Vienna Yearbook of Population Research 2024 (Vol. 22), pp. 337–376
https://doi.org/10.1553/p-gjfn-7z5k

RESEARCH ARTICLE

Integrated water-population interactions framework: An application to assess water security in Iran

Zahra Soltani[1], **Mohammad Jalal Abbasi-Shavazi**[1,2,3] **and Ali Bagheri**[4]

ABSTRACT While dynamic water security models related to food and livelihood security have advanced significantly in recent decades, the inclusion of demographic variables in these models is often limited to merely population growth. As many countries have either completed or are in the process of completing the demographic transition, population growth alone may no longer be the predominant demographic variable influencing water security models. Therefore, there is a discernible need for more comprehensive water security models to consider the simultaneous impact of various demographic variables on different aspects of water security. Inspired by the contemporary environmental demography perspectives, we introduce a generic integrated framework for integrated water-population interactions (IWPI) which explores the overlooked impacts of demographic transitions on different aspects of water security. Demographic shifts can impact food and water consumption and agricultural employment. Recognizing these dynamics is essential as countries advance through demographic transitions and face mounting pressures on water resources. The Integrated Water-Population Interaction (IWPI) framework was implemented in Iran through the Water-Population System Dynamics (WPSD) model. The model shows that population size, household composition and urbanization significantly affect domestic water consumption. It also reveals how changes in educational and occupational structures impact livelihood security and food self-sufficiency under water constraints. We introduce a novel population metric for water security assessment in Iran, offering policy-makers a tool to assess and address water insecurities that can affect the population in different ways. Our findings recommend realistic food self-sufficiency targets, flexible water resource planning and policies that integrate population dynamics with water, food and livelihood security to ensure sustainable outcomes in Iran.

KEYWORDS Demographic transition • Food security • Livelihood security • Sustainable development • System dynamics modelling • Iran

✉ Zahra Soltani, zahra.soltani@ut.ac.ir
1 Faculty of Social Sciences, University of Tehran, Tehran, Iran
2 Vienna Institute of Demography (OeAW), International Institute of Applied System Analysis (IIASA), Wittgenstein Centre for Demography and Global Human Capital (IIASA, OeAW, University of Vienna), Laxenburg, Austria
3 Australian National University, Canberra, Australia
4 Tarbiat Modares University, Tehran, Iran

Introduction

In recent decades, researchers have devised a diverse array of tools and models aimed at gauging local and global water security in order to meet human needs. Noteworthy examples of such efforts include Falkenmark et al. (1989) and Kummu et al. (2010), who proposed assessing water shortages by examining the quantity of potentially available water relative to the population it serves, or Gleick (1996), who advocated for a fundamental water requirement standard of one person per day. Although these early indicators continue to be utilized for policy-making, they have faced substantial criticism. Their primary drawback is their linear and static interpretation of the relationship between the population and water resources, which fails to account for the intricate interplay of diverse climates, economies and cultures (Cohen, 1995; Falkenmark, 2013). Conversely, contemporary and intricate definitions of water security have also emerged that surpass the capabilities of earlier and more simplistic models to adequately assess these nuanced dimensions of water security. Nowadays, water security at a large scale, such as at the country level, is defined as the sustainable access to a substantial quantity of clean water, not only to meet domestic needs, but also to support food production and sustainable livelihoods (Grey and Sadoff, 2007; Hanjra and Qureshi, 2010; Tarlock and Wouters, 2010; UN-Water, 2013; Flörke et al., 2013). Various system dynamics models have emerged to address growing concerns about interrelated water, food and livelihood security in different global regions (Sterman, 2002; Hjorth and Bagheri, 2006; Hussey and Pittock, 2012; Albrecht et al., 2018). While these models include population as a key influencing variable, they often focus solely on population size changes or growth rates in predicting water security, while overlooking the other significant impacts of demographic variables on resource consumption and limitations. Can these models, which oversimplify population dynamics and fail to account for the complexities of water security, truly support decisions that lead to effective water, food, population and employment policies that ensure the safety of the population? It appears that they cannot.

With the reduction of the world population growth rate, environmental demographers have shifted their focus beyond issues of population size and growth rates to recognize the impact of other demographic variables on the intricate interplay of population and environmental dynamics. Attention has been drawn to factors such as population distribution, composition trends, household changes and migration, highlighting their direct or indirect connections to environmental dynamics (MacKellar et al., 1995; Pebley, 1998; Hunter, 2000; Lutz et al., 2002). In recent years, the adoption of system dynamics as a theoretical framework in environmental demography has prompted heightened scrutiny of the demographic dynamics shaping the relationship between population and the environment (Hunter, 2000; Lutz et al., 2002; Curran and de Sherbinin, 2004; Hummel et al., 2013; Hunter and O'Neill, 2014). Despite these theoretical advancements in environmental demography, a specific framework for enhancing water security models by systematically considering the interplay of different demographic variables and facets of water security has yet to be developed (Lutz et al., 2014 a, b; Lutz and Striessnig, 2015; KC and Lutz, 2017; Hayes and Adamo, 2014).

Consequently, we opted to combine novel environmental demography approaches and water resource management theories, leading to the creation of a conceptual framework of

https://doi.org/10.1553/p-gjfn-7z5k

Integrated Water-Population Interactions (IWPI). This framework incorporates methods, techniques and relevant data from both fields. Developing an Integrated Water-Population Interrelations framework has the potential to provide a comprehensive structure that captures the dynamic interdependencies between the crucial aspects of water and population, considering factors such as changes in age structures, households, urbanization trends and consumption patterns. By incorporating these variables, the inherent complexity within the nexus of water resources and population dynamics is more fully addressed, establishing a robust foundation for analysis. The framework needs to be customized by developing a Water Population System Dynamic (WPSD) model for each application according to the modeling purpose and the data availability. The WPSD model can significantly contribute to tackling water-related challenges by serving as a valuable tool for policy-makers. By providing scenario analysis and predicting potential intervention impacts, these models can empower stakeholders to make informed decisions, and can thus facilitate the formulation of effective policies for the sustainable management of water resources.

In this paper, we provide a practical application of the theoretical IWPI framework by introducing a methodology for constructing a WPSD model and its adoption to measure water security in the case of Iran.

Iran is situated in an arid to semi-arid region, and has experienced significant population growth during its demographic transition (Abbasi-Shavazi et al., 2009). Thus, Iran faces pronounced water resource limitations due to population pressure (Madani, 2014; Madani et al., 2016; Mesgaran and Azadi, 2018). Despite a recent deceleration in population growth, Iranian policy-makers aspire to enhance the country's water security. However, the impact of various demographic variables on the water security situation remains unknown to them. Simultaneously, they are deeply concerned about identifying optimal policy measures to achieve a balanced coexistence between population livelihoods, water resources and food security. As demonstrated in this paper, the WPSD model developed within the Integrated Water-Population Interrelations framework proves effective in addressing the significant water security challenges Iran faces.

Our overarching goal of developing an integrated framework to address the dynamic interactions between water and population is operationalized through three distinct objectives: first, developing a methodology to build a model that can consider the interlinkage of various demographic factors and water dynamics, and showing its application to the case of Iran in the context of declining population growth; second, developing a population metric for water policy-makers to anticipate future water insecurity exposure by predicting the number of people who are exposed to different aspects of water insecurity; and, finally, evaluating the impact of diverse water and agricultural policies on population vulnerability to water-related challenges. These objectives are elaborated upon in the subsequent sections.

Review of the literature

In this section, we will begin by examining the evolution of environmental demographic approaches and their impacts on water-security dynamics. Then, we will explore the trends in the development of water security models. These two sections will provide a foundation

https://doi.org/10.1553/p-gjfn-7z5k

for a more comprehensive understanding of the third part of our literature review, which focuses on the interconnection between water security and population dynamics.

The evolution of environmental demographic approaches and their impacts on water security dynamics

Demography has come a long way since its inception, starting with Thomas Malthus's influential work, "An Essay on the Principle of Population" in 1798. Initially, demography primarily examined the relationship between population and natural resources. However, in the decades that followed, it shifted its focus to quantitative studies of vital events such as mortality, fertility and migration, along with advancements in data collection methods (Caldwell, 1996; Lee and Anderson, 2002).

As Davis (1990) and Pebley (1998) discussed, prior to the 1950s, environmental issues had not been central to demography. A turning point in population studies occurred in the mid-20th century, driven by developments in transportation and health, which led to a demographic transition in many countries and rapid global population growth. These trends reignited concerns similar to Malthus', with scientists like Hardin (1968) and Ehrlich (1970), Ehrlich and Holdren (1971) and Holdren and Ehrlich (1974) raising new demographic environmental concerns.

Since the 1970s, researchers have begun exploring the intersections between population, economy and the environment. The book "*The Limits to Growth,*" through its adept portrayal of the interdependencies of population dynamics and variables such as food resources, contributed significantly to the advancement of integrated models delineating the interactions between population and the environment (Meadows et al., 1972). In addition, the introduction of the system dynamics approach and models by pioneers like Forrester (1961, 1968, 1971) led to the development of various models in scientific disciplines aiming to identify the adverse effects of population growth on natural resources (Seidl and Tisdell, 1999; Adams, 2001; Stephenson et al., 2013).

In the next decades, some environmental demographers, while recognizing that the population growth rate posed a significant threat to the environment (Davis, 1990; Keyfitz, 1992; Ehrlich et al., 1993; Ehrlich, 2014), criticized the oversimplification of solely focusing on this factor. They advocated shifting to paradigms connecting population dynamics, such as distribution, composition, household changes and migration, with environmental dynamics like climate change, land use change and water shortages (MacKellar et al., 1995; Pebley, 1998; Hunter, 2000; Lutz et al., 2001; Lutz et al., 2001 and 2002). Indeed, they made efforts to tackle the sustainability question by adopting a comprehensive approach.

In the pursuit of achieving sustainability amid shifts in demographic trends and environmental changes, various models have been employed (Stephenson et al., 2013; Hummel et al., 2013). Environmental demographers have emphasized using system dynamics frameworks and models to address the complexities of contemporary problems (MacKellar et al., 1995; Hunter, 2000; Lutz et al., 2002; Curran and de Sherbinin, 2004; Hummel et al., 2013; Hunter and O'Neill, 2014). Empirical experiments have highlighted that population size is not the sole demographic variable influencing natural resource constraints, noting

https://doi.org/10.1553/p-gjfn-7z5k

that factors like educational composition and age–sex structure also play decisive roles (Lutz et al., 2014b; Lutz and Striessnig, 2015; KC and Lutz, 2017). Despite these theoretical advancements, studies adopting dynamic system approaches have largely concentrated on examining the impact of demographic factors on carbon emissions or on levels of vulnerability and adaptability to climate change (Hayes and Adamo, 2014; McLeman, 2010; Lutz et al., 2014a; Lutz and Striessnig, 2015). The complex dynamic interactions between water and population using the system dynamics approach have often been overlooked by environmental demographers.

Trends in the development of water security models

Over the last few decades, researchers have developed various tools and models to assess water security at local and global scales with the aim of meeting human needs. The first generation of water indicators primarily focused on the physical availability of water and its relation to population numbers or growth (*e.g.,* Falkenmark et al., 1989; and Kummu et al., 2010; Gleick, 1996). However, these indicators oversimplified the complex interplay of water and population, while neglecting components like climate, economy and culture.

To address these limitations, the second generation of water models emerged, which utilized population indicators to gauge society's capacity to cope with water shortages. For instance, the Social Resource Water Stress/Scarcity Index integrated the Hydrological Water Stress/Scarcity Index with the UNDP Human Development Index and demographic-economic variables to evaluate the adaptive capacity to combat water scarcity (Appelgren and Klohn, 1999; Ohlsson, 2000). Additionally, the Water Poverty Index or Agriculture Water Poverty Index considered demographic, social and economic aspects affecting water supply and demand (Sullivan, 2002; Forouzani and Karami, 2011).

While the first and second generations of models facilitated international water shortage comparisons and monitored water shortages over time, the third generation, exemplified by the Water-Energy-Food (WEF) nexus models, gained prominence among policy-makers. These models aimed to enhance water security by addressing the water-energy-food interrelationships, especially at the country or the regional level (Sullivan et al., 2003).

Furthermore, the development of concepts like water footprint and virtual water enabled nexus and system dynamics models to tackle water security challenges over the past two decades (Hoekstra and Chapagain, 2006; Mekonnen and Hoekstra, 2011; Hoekstra et al., 2011). According to Hoekstra (2017), the concepts of virtual water and water footprint are helpful for analyzing water use, allocation, consumption and shortage in global terms. Alongside the development of water security models and tools, the definition of water security at a large political scale, such as at the country level, was developed. Nowadays, water security at the country level is defined as sustainable access to clean water for domestic, food production and livelihood needs in order to promote human well-being and socioeconomic development (Grey and Sadoff, 2007; Flörke et al., 2013). Thus, a water security framework must be designed to address critical aspects of water security, including meeting domestic and urban water needs, ensuring food security, supporting sustainable livelihoods and safeguarding water resources and biodiversity against depletion and natural hazards

https://doi.org/10.1553/p-gjfn-7z5k

(Gleick, 1996; Boberg, 2005; Grey and Sadoff, 2007; Wye Group, 2011, UN-Water, 2013; Wyman, 2013; UNESCO, 2014).

Understanding the interconnection of water security and population dynamics

In order to develop a conceptual framework for constructing a WPSD model, we delve into the intricate relationship between water security and population dynamics. First, our attention is directed toward comprehensively tackling distinct dimensions of water security. Second, we provide a brief overview of the interconnections between various demographic patterns and different aspects of water security.

Ensuring water security involves meeting the diverse needs of the population, ranging from domestic water requirements to the water needed for food and livelihood security. Access to safe and affordable water for drinking, hygiene, sanitation and food preparation is fundamental (Gleick, 1996; Grey and Sadoff, 2007; UN-Water, 2013). The interconnection between water and food security, highlighted by the FAO (2000), emphasizes the necessity of ensuring sufficient and reliable water access for agricultural production, which is crucial for addressing global food needs (Ehrlich et al., 1993; Wyman, 2013). However, contemporary interpretations distinguish between food security and self-sufficiency, emphasizing global trade dynamics (Wiedmann and Lenzen, 2018). Livelihood security, which is another facet of water security according to UN-Water (2013), involves ensuring sustainable access to water for livelihood activities, and is distinct from the poverty definition of the World Bank (2001). The pivotal role of water in agriculture becomes apparent when seeking to support rural livelihoods, especially in the context of decreasing per capita land area due to population growth, by emphasizing the importance of reliable irrigation for increased crop productivity and income (Ellis, 1998; Shah, 1998; 2007; Hasnip et al., 2001). Beyond agriculture, water plays a vital role in various economic sectors, including industries and manufacturing, where job security is contingent on water availability (Grey and Sadoff, 2007; Dickin and Di Mario, 2017).

On the other hand, the significance of demographic elements to water security has been acknowledged in the 20th and 21st centuries. The association between population trends and water scarcity is notably exemplified in crises like that in Syria (Ehrlich, 2014). Global concerns about water shortages posing substantial threats to peace and security are particularly emphasized in regions undergoing demographic transitions, such as Western Asia and Northern Africa (World Economic Forum, 2016; Postel, 2000; Kummu et al., 2010; Gleick, 1993 and 1996; Weeks, 2016: p. 11; Madani et al., 2016). While most studies concentrate on the impact of population size on resource constraints, this section delves into the nuanced role of various demographic variables in influencing water consumption, shortage and security. Population size remains a pivotal factor in water security models, even as global growth rates decline, and it continues to shape environmental demography (Fischer and Heilig, 1997). Additionally, household numbers and sizes emerge as influential factors in water security, especially in light of the current trend of rising household numbers, which is driven by a combination of population growth and decreasing household size. This trend not only significantly influences per capita water demand, but also has pronounced effects in rural

https://doi.org/10.1553/p-gjfn-7z5k

areas, where agriculture prevails. The proliferation of households, outpacing population growth, results in amplified land use, heightened water consumption for irrigation and increased land fragmentation (Curran and de Sherbinin, 2004; MacKellar et al., 1995; Keilman, 2003; Soltani and Abbasi-Shavazi, 2022). There is also increasing recognition that demographic composition, which encompasses age–sex structures and educational levels, shapes water consumption patterns and influences adaptation to water shortages (Ohlsson, 2000; Forouzani and Karami, 2011; Lutz et al., 2014b; Muttarak and Lutz, 2014). Furthermore, the dynamics of rural–urban migration and urbanization significantly impact water resources, affecting consumption levels and altering pressures on water resources in diverse regions (Boberg, 2005; McDonald et al., 2014; World Water Assessment Programme, 2009; Cohen et al., 2013). Urban areas, which are characterized by higher per capita water consumption, can strain local water resources, leading to agricultural water reallocation, diminished rural livelihoods and induced migration, creating a cyclical pattern of escalating urbanization and heightened pressure on regional water resources.

Developing an Integrated Water-Population Interactions (IWPI) framework: A comprehensive approach to assessing water security in the context of demographic transitions

As outlined in the preceding sections, both environmental demography and studies related to water resource management have increasingly embraced the utilization of dynamic system approaches and methodologies in their investigations in recent years. This adoption of dynamic system methodologies has paved the way for the development of our customized model, the Water-Population System Dynamics (WPSD) model, which is applied to measure water security in Iran.

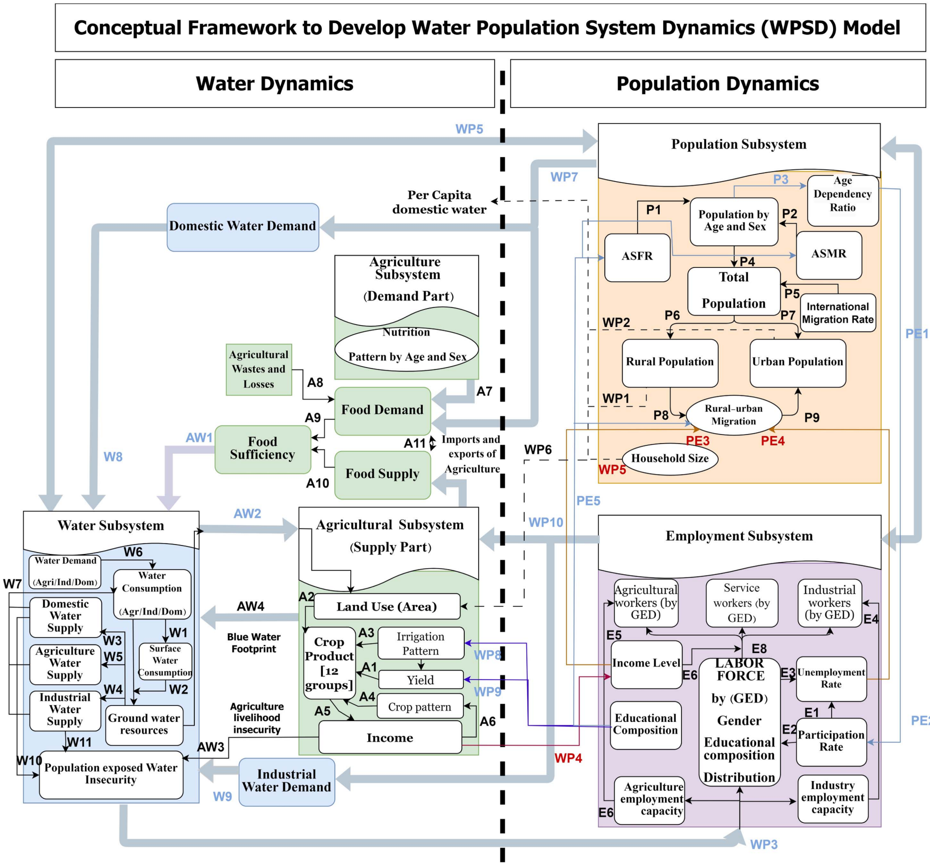
While the interactions between population and water dynamics are evident, the intermediary aspects involving employment dynamics and agricultural dynamics play a pivotal role (Hunter, 2000; Kristensen, 2004). As illustrated in Figure 1, in the Integrated Water-Population Interactions (IWPI) framework as developed in this paper, four distinct subsystems are considered: population, employment, agriculture and water. The framework has been suggested in a generic integrated form corresponding to the insights from the literature. It needs to be customized for modeling applications in each case according to the modeling purpose, data availability and the importance of each component in the case under study.

The dynamics of employment are primarily shaped by demographic factors, with some degree of influence stemming from water dynamics. Therefore, these dynamics are regarded as components of the population dynamics section of the model. Similarly, agricultural dynamics are significantly impacted by water dynamics, with some influence from population dynamics, and are thus categorized as part of the water dynamics section of the model.

Initially, we highlight the key characteristics of each subsystem, as shown in Figure 1. Subsequently, we delineate the two constituents of water and population dynamics.

https://doi.org/10.1553/p-gjfn-7z5k

Figure 1 The Integrated Water-Population Interactions (IWPI) conceptual framework



Toward the end of this section, we will provide a concise illustration of the dynamic assumptions underpinning the model.

Introducing the subsystems

The most important specific characteristics of each subsystem shown in Figure 1, without considering the other subsystems, are described as follows:

Population subsystem

The population subsystem engages with demographic factors through a comprehensive approach. Age-specific fertility and mortality rates play a pivotal role in estimating the

https://doi.org/10.1553/p-gjfn-7z5k

population within each age–sex group [connectors P1 and P2 in Figure 1], facilitating the calculation of age dependency ratios [P3] and total population numbers [P4]. If the net international migration rate significantly influences the total population, it is advisable to incorporate this variable into the analysis [P5]. Additionally, the subsystem incorporates the dynamic element of rural–urban migration rates, simulating consequential shifts in population distribution between urban and rural areas. In other words, the urban and rural population numbers can be obtained based on the percentage of the urban and the rural population in the total population [P6 and P7]. At the same time, the rural–urban migration (or urban–rural migration) has an impact on the changes in the urban and rural populations [P8 and P9]. This simulation allows for a nuanced understanding of the evolving demographic landscape. Furthermore, critical attention is given to variations in the sizes and numbers of households, recognizing their significance as pivotal variables within the subsystem. This approach ensures a nuanced understanding of population dynamics, encompassing factors that span populations, households, migration patterns and age–sex structures.

Employment subsystem

The employment subsystem encompasses key features integral to a comprehensive understanding of labor dynamics. First and foremost, it involves the meticulous estimation of the student population, taking into account gender, rural–urban distribution and educational levels. Subsequently, it engages in the calculation of the numbers of individuals entering the labor force after each educational level, employing GED (Gender, Educational Composition, Distribution) parameters encompassing gender, educational level and rural or urban distribution to stimulate workforce dynamics. The subsystem further delves into the estimation of unemployed and employed individuals by considering the participation rates and unemployment rates [E1, E2 and E3] and the potential employment capacity across three primary occupational sectors – services, agriculture and industry – according to the GED classification [E4, E5 and E6]. Additionally, the employment subsystem involves the reconstruction of income levels, which can affect the number of employed individuals among distinct occupational groups, all stratified by GED. Lastly, the employment subsystem evaluates the value preferences of the labor force in selecting from the three major occupational sectors, accounting for income levels as a determining factor [E7 and E8]. In amalgamating these components, the subsystem provides a nuanced and comprehensive analysis of the multifaceted aspects of employment dynamics.

Agricultural subsystem

The agricultural subsystem is designed to undertake several integral functions essential for understanding agricultural trends. Foremost among these is the precise estimation of variable changes related to agricultural supply [supply part]. This involves a detailed assessment of factors such as yield, land use, irrigation patterns and crop varieties, and how they affected the production of cereals, rice, potatoes, beans, vegetables, fruit,

https://doi.org/10.1553/p-gjfn-7z5k

oilseeds, sugar, industrial seeds and fodder plants, as well as trends in meat and dairy production [A1, A2, A3, A4, and A5]. In addition, the agricultural subsystem [supply part] aims to determine the income derived from the sale of agricultural products, and calculates the minimum amount of land needed to cultivate each product, thereby ensuring the livelihood security of rural households [A5]. Crop production income can be a determining factor when choosing the cultivation pattern [A6]. Additionally, the agricultural subsystem [demand part] engages in the simulation of net food demand, carefully considering the nutrition pattern by age and sex [A7]. This simulation approximates gross food necessity by accounting for net food demand adjusted for the waste and losses of agricultural products [A8]. Furthermore, the subsystem plays a pivotal role in calculating the degree of self-reliance in generating required food products in every country across various primary food groups for the population. It estimates food sufficiency by considering the difference between food supply and food demand [A9 and A10]. It also assesses import requirements and export potentials within the agricultural sector for each food group, thus providing valuable insights into the nation's food security. In essence, these multifaceted functions contribute to a holistic analysis of the agricultural sector encompassing production dynamics, food demand, trade potentials and rural livelihood sustainability.

Water subsystem

The water subsystem is structured to fulfil critical functions necessary for a comprehensive understanding of water resource management. First and foremost, it is tasked with accurately estimating annual surface water extraction quantities, differentiating between domestic, industrial and agricultural purposes [W1]. Concurrently, it engages in an assessment of the utilization of non-renewable underground water resources, acknowledging the environmental implications of such extractions [W2]. Furthermore, the subsystem evaluates the impact of diminishing non-renewable underground water resources on the overall water supply for domestic, industrial and agricultural consumption [W3, W4 and W5]. It also undertakes the calculation of water consumption within the agricultural, domestic and industrial sectors, facilitating a comparative analysis of the water demands and water supply in each sector [W6 and W7].

Moreover, the water subsystem assumes a proactive role in identifying populations exposed to water insecurity due to water supply restrictions, including domestic water insecurity, food insecurity and potential livelihood insecurity, within the industrial and agricultural domains. The population faces direct impacts from water supply restrictions that can result in domestic water insecurity and livelihood insecurity in the industrial sector [W8, W9, W10 and W11]. Conversely, food insecurity and agricultural livelihood insecurity, driven by water scarcity, are influenced indirectly through agricultural variables, which will be elaborated upon in subsequent sections. This comprehensive assessment extends to quantifying the total population exposed to water insecurity in a given country. In essence, the multifaceted functions of the water subsystem contribute to a nuanced understanding of water dynamics, facilitating informed decision-making and strategic planning for sustainable water resource management.

https://doi.org/10.1553/p-gjfn-7z5k

Interrelationship between the subsystems

Interrelationship between the subsystems within the population dynamics section

The complicated interrelationships between the population and employment subsystems within the population dynamics sector are elucidated through various key facets. First, changes in the demographic composition (the numbers of people in different age and sex groups) are expected to gradually influence the attributes of the labor market [PE1]. This nuanced relationship is further emphasized through the evaluation of demographic shifts using the index of change in the age dependency ratio [PE2], a factor expected to dynamically impact the labor market participation rate across all gender, educational and rural–urban distribution categories, as suggested before (Muenz, 2007; Scherbov et al., 2014). Building upon the conceptual frameworks proposed by Lee (1966) and Todaro (1969), the interconnected dynamics unfold as changes in income levels and employment capacity, and the differences in income and in the probability of employment between urban and rural areas (which has an inverse relationship with the unemployment rate), play significant roles in shaping the dynamics of rural-to-urban migration [PE3 and PE4]. This comprehensive understanding of the interplay of demographic shifts, labor market participation, income differentials and migration dynamics contributes to a nuanced exploration of the population-employment nexus within the broader context of population dynamics.

Education [PE5] is a pivotal factor influencing fertility rates, mortality and rural–urban migration. Scholars have observed that among the socioeconomic indicators, education consistently stands out as the most influential predictor of demographic behavior, particularly regarding fertility (Bongaarts, 2003; Cleland, 2002, Lutz et al., 2014a). While establishing a clear causal or linear connection between mortality and education is challenging, evidence suggests that mortality declines are greater among people with higher than with lower educational levels (Case and Deaton, 2017; Meghir et al., 2018). The impact of education on rural–urban migration is complicated, as it can both stimulate migration by creating urban job opportunities and enhance the resilience of rural communities to challenges such as water shortages and climate change, potentially mitigating forced migration (Connor et al., 2023; Hunter & Nawrotzki, 2016).

Interrelationship between the subsystems within the water dynamics section

The inherent interrelationships between the water subsystem and the agricultural subsystem in the domain of water dynamics are clarified through a thorough analysis of the essential factors. As indicated below, these linkages are especially conspicuous when evaluating the security of food and livelihoods within the agricultural sector. Additionally, the concept of the water footprint serves to forge a closer connection between these two subsystems.

Notably, Wiedman and Lenzen (2018), Wyman (2013) and Boberg (2005) pointed out the ramifications of uncontrolled depletion of non-renewable underground water resources for agricultural irrigation, emphasizing the potential for significant groundwater losses and reductions of cultivated land area, and their adverse effects on agricultural stability and food security. These insights, aligned with theoretical foundations laid out by

https://doi.org/10.1553/p-gjfn-7z5k

Godfray et al. (2010) and Hanjra and Qureshi (2010), have contributed to the recognition of food security as an integral component of water security [AW1 and AW2].

Furthermore, the allocation of water for agricultural activities has profound implications for rural livelihoods, given the substantial role of agriculture in rural employment. Access to reliable irrigation infrastructure has been identified as pivotal for establishing sustainable livelihoods among rural populations (Ellis, 1998; Shah, 1998; 2007; Hasnip, 2001; Wye Group, 2011), especially in contexts where population growth has led to reductions in per capita land availability. Reliable access to irrigation systems has been linked to increased crop yields (Boserup, 1965 and 1981), higher incomes and enhanced livelihood security for rural residents. In alignment with contemporary water security definitions (Grey and Sadoff, 2007; UN-Water, 2013), the IWPI framework incorporates agricultural livelihood security as a core component within the broader framework of water security. Assessment of this component involves examining whether the available land area for each farming household, based on cultivation patterns and irrigation methods, generates sufficient income to sustain livelihoods [AW3].

Moreover, the utilization of the water footprint concept emerges as a valuable tool in assessing agricultural water consumption [AW4]. The water footprint, which denotes the volume of water used during the production of an agricultural product through evaporation and transpiration, provides insights into the relationship between agricultural water usage and available water resources in different countries (Hoekstra and Chapagain, 2006; Mekonnen and Hoekstra, 2011; Hoekstra et al., 2011; Hoekstra, 2017). This concept is intricately integrated into the framework, enhancing its capacity to evaluate and address the complex interplay of agricultural practices and water resource dynamics on a global scale.

Interrelationship between the population dynamics section and the water dynamics system

First of all, unlike Meadows *et al.*'s model, our framework demonstrates that the mortality rates and the population sizes of countries are not significantly affected by water-related constraints on food production, thanks to the ability to import food products. Meadows' model, by contrast, assumes that global biological capacity directly influences mortality rates during food shortages (Meadows et al., 1972). However, urbanization and rural–urban migration are significant population trends that are impacting water resources. Urbanization influences water consumption levels and per capita domestic water consumption [WP1 and WP2], while redistributing populations through rural–urban migration can alter water resource pressures across regions (Boberg, 2005; McDonald et al., 2014; World Water Assessment Programme, 2009). The growing demand for water in urban areas may lead to the reallocation of agricultural water resources to meet urban domestic water needs, which could, in turn, result in reduced agricultural water supply, reduced agriculture employment capacity [WP3], decreased agriculture income levels [WP4] and adverse effects on rural livelihoods, prompting rural-to-urban migration [WP5]. These dynamics could perpetuate a cycle of increasing urbanization and growing pressure on regional water

https://doi.org/10.1553/p-gjfn-7z5k

resources, which is often categorized as forced migration due to water insecurity, with the consequent risks of poverty and marginalization (Cohen et al., 2013). The IWPI framework seeks to recreate the indirect impact of insufficient agricultural water resources in rural areas on rural–urban migration rates by considering how it affects variables such as the unemployment rates and the income levels of rural households.

Furthermore, in the framework, we suggest placing particular emphasis on the variable of family size when considering the interconnection between water dynamics and population dynamics [WP6]. This approach is recommended because the research indicates that smaller household sizes and growth in household numbers that outpaces overall population growth can exacerbate environmental issues, particularly water shortages (Curran and de Sherbinin, 2004; MacKellar et al., 1995; Keilman, 2003). In rural areas, where agriculture prevails, the expansion of rural households leads to increased land use for farming, greater water consumption for irrigation and land fragmentation, resulting in unsustainable levels of long-term water exploitation (Soltani and Abbasi-Shavazi, 2022). Additionally, smaller household sizes coupled with higher numbers of households can boost water consumption and per capita water consumption (Martin, 1999; Boberg, 2005; Nauges and Whittington, 2010). In the framework, all the aspects discussed involve the reconfiguration of the interconnection between household size and the variables within the water dynamics sector.

Subsequently, as different population subgroups exhibit distinct behaviors (Hunter, 2000), the consumption of natural resources, including water resources, can be profoundly impacted by the demographic composition, and especially the age–sex composition, of the population. Research has demonstrated that both the quantity and the patterns of water and food consumption are influenced by the age–sex structure of the population (Aigner-Walder et al., 2012). This relationship between dietary and consumption patterns and the age–sex structure can lead to changes in a country's water footprint, including in the volume of water used for domestic purposes and the volume of water used in the production of food consumed by the population [WP7] (Hoekstra and Chapagain, 2006). These presuppositions have been employed to establish the relationship between the age–sex composition of the population and the variables of the water dynamics sector (especially the food demand variable). Additionally, there is an emphasis on the role of public education in mitigating the adverse effects of environmental hazards, as education can yield direct benefits, such as enhanced cognitive and problem-solving skills and improved knowledge and risk perception, along with changes in yields, irrigation patterns and labor force participation [WP8, WP9, and WP10] (Lutz et al., 2014b; Muttarak and Lutz, 2014; Soltani et al., 2019). Hence, within our framework, we posited that education serves as a criterion for determining individuals' preferences when entering various labor market sectors. Consequently, as the educational composition of the workforce undergoes shifts, the composition of the labor market changes as well.

The final point is that in the modern world, water plays a crucial role in various forms of production, including in industries (Grey and Sadoff, 2007). Industries and manufacturing are significant consumers of water and resources, and the employment opportunities within these sectors are contingent upon the accessibility of the water resources needed to meet their requirements. Deficiencies in the water supply could result in livelihood insecurity

https://doi.org/10.1553/p-gjfn-7z5k

for individuals employed in these sectors (Dickin and Di Mario, 2017). Our decision to include industrial livelihood security as part of water security in the framework is influenced by such an approach.

Adapting the IWPI framework for a Water-Population System Dynamics (WPSD) model to measure water security in Iran

In this section, we aim to adapt the IWPI framework to a practical application that may be used in developing a Water-Population System Dynamics (WPSD) model to measure water security. The model has been customized to illustrate the challenges that may be encountered in analyzing the interconnected dynamics of water resources and Iran's population in the short-term future. This section is divided into two parts: (1) introducing the Iranian context and (2) outlining the fundamental model's outcomes.

Introducing the context of Iran

The Middle East and North Africa (MENA) region is widely recognized as the most water-stressed area in the world. Climate change has severely impacted the availability of water resources in this region, which is characterized by rising temperatures, decreasing precipitation and increasing evapotranspiration. However, in many countries in the Middle East, climate change is not the sole challenge facing the water sector (Droogers et al., 2012). Population growth and economic development, which drive higher demand for irrigation and domestic and industrial water uses, pose even greater challenges. A critical issue for the Middle East is enhancing agricultural production to support the rapidly growing population (Falkenmark and Lannerstad, 2005; Rosegrant et al., 2009).

Iran, the most populous country in Western Asia, faces significant water security challenges due to its arid and semi-arid climate, which limits its freshwater resources. The country's average annual rainfall is merely one-third of the global average, while its evaporation potential is three times higher than the global average (Energy Ministry of Iran, 2016). Over 70% of water resources from precipitation are lost through evaporation (Iran Water Resources Management Company, 2018). Iran's considerable climatic diversity complicates its water management efforts. Despite historical engineering innovations such as qanats and irrigation systems, substantial population growth over the past century has led to a severe water crisis (Ardakanian, 2005). With the population increasing from approximately 10 million in 1920 to around 85 million in 2023, per capita water resources have drastically diminished (Saraei, 1998; Statistical Center of Iran, 2021). In recent decades, supply-oriented strategies such as drilling deep-pumped wells, building dams and inter-basin water transfers have been implemented to address water stress. However, these measures have led to the unsustainable exploitation of water (Madani, 2014; Saatsaz, 2020).

The direct impact of population growth on water resources management in Iran has primarily been the increased demand for domestic water in urban centers. However, the agricultural sector remains the primary water user, receiving 90% of the total allocated water

https://doi.org/10.1553/p-gjfn-7z5k

(Moridi, 2017). Population growth in Iran, as well as the expanded global market for agricultural products, have indirectly increased the demand for agricultural products, expanded irrigated lands and increased the need for job opportunities and income, particularly within the agricultural sector. Poorly designed policies, such as those supporting food self-sufficiency and water subsidies, have further exacerbated pressure on water resources (Saatsaz, 2020). Consequently, water consumption in Iran has consistently exceeded the country's initial water stress threshold by approximately fourfold. This imbalance between water demand and sustainable supply has accelerated a water crisis affecting millions of people (Gleick, 1994). Currently, Iran's annual water consumption is estimated to be around 96 billion cubic meters (BCM), which is about 8% higher than its total renewable water resources (89 BCM) and approximately 80% higher than the scarcity threshold level (about 53 BCM) (Mesgaran and Azadi, 2018). This crisis is evidenced by groundwater over-abstraction, over-drafted aquifers and the shrinking and drying up of water bodies, as well as escalating interregional and inter-sectoral conflicts over water (Madani, 2014; Saatsaz, 2020).

In addition to internal water conflicts, regional disputes further complicate Iran's water security. The political instability in Afghanistan has led to increased international migration to Iran (UNHCR, 2021; Hosseini-Chavoshi and Abbasi-Shavazi, 2023), raising concerns about the capacity of urban water supply systems to accommodate additional immigrants.

The relationship between population dynamics, politics and Iran's water security extends beyond mere population size and geographical factors to include various demographic factors, such as livelihood composition, educational levels, age–sex structure and household size. These factors significantly affect water consumption, especially in agriculture, where low water productivity is a notable issue. The reduction of water resources for agriculture has raised concerns about increased rural–urban migration in Iran (Ministry of Energy, Iran, 2016). As Iran has shifted from having a predominantly young population to having a mainly middle-aged, active population, water consumption has increased, but the future impact of the age–sex structure on water use remains uncertain. Although literacy and educational levels have improved, the farming population remains largely elderly and has low literacy, hindering the adoption of less water-intensive cultivation methods. Additionally, while population growth has halted, the rise in the number of households due to decreasing household sizes continues to put pressure on water resources (Statistical center of Iran, 2021).

Policy responses have often failed to adequately consider these demographic characteristics. Demographic shifts, rural–urban migration and difficulties in adopting less water-intensive crops further complicate water management. Changes in population distribution, educational levels, household size and age structure contribute to increasing water insecurity. As Iran's demographic transition concludes and its population growth declines, the influence of these demographic factors on water security is expected to become more pronounced. However, the mechanisms through which these changes affect water security have received limited attention. Iran's efforts to address water security are hindered by the lack of a comprehensive framework that integrates population, water resources, livelihoods and food security. Policy responses often overlook the demographic characteristics of agricultural users, resulting in ineffective outcomes.

https://doi.org/10.1553/p-gjfn-7z5k

Moreover, measures like those promoting self-sufficiency are criticized for not balancing population food needs with water resource sustainability. A comprehensive understanding of the interplay of population components and water security is essential for effective water management.

Methodology

Method and data

Aligned with our IWPI framework, this study employs System Dynamics Modeling to facilitate decision-making processes regarding Iran's complex water issues, which are intricately linked with population dynamics. Although our focus is on Iran, similar models can be tailored to the specific conditions and data limitations of other countries, addressing the complexities of decision-making in water resource policies in places where demographic changes influence water exploitation trends and pose water security risks.

As emphasized by Stave (2002), system dynamics models aim to link existing knowledge with necessary actions (Hjorth and Bagheri, 2006), rather than to serve as forecasting tools. Despite their generally lower forecasting power compared to models in specific scientific fields (Beckage et al., 2011), dynamic models are crucial for providing policy options for multidisciplinary issues (Stave, 2002). Recognizing the model's limitations, the authors agree with the perspective of the Club of Rome (Meadows et al., 1972) that despite its imperfections and preliminary state, the model is sufficiently developed to be useful to decision-makers.

To develop the model, we undertook a distinctive project, gathering numerous data sources across various disciplines, which are described in Table 1. Primary data sources include the Statistical Center of Iran, with datasets from the Agriculture Census, the Population and Housing Census, the Rural Households, Income and Expenditure Survey and the Purchase Price of Agricultural Products Survey. Additionally, data from the Ministry of Agriculture, the Ministry of Energy and the Ministry of Health and Medical Education of Iran are incorporated into the model to facilitate comprehensive analysis and forecasting.

In addition to the data, statistical software R was utilized for analyzing 2% sample data from censuses and statistical surveys conducted by the Statistical Center of Iran[1]. This analysis extracts rural–urban migration rates and labor force participation rates categorized by age, sex and educational status. Model validation is carried out through various tests, including the dimensional consistency test, the parameter sensitivity test and the behavior-reproduction test.

The modeling period spans 30 years, from 2011 to 2041, with the initial eight years (2011 to 2018) dedicated to model calibration and the subsequent years (2018 to 2041)

1 Some of the input data for our simulations were obtained directly from published census results tables. However, certain inputs required by the model were not available in the published census tables, necessitating the use of 2% sample data from the 2011 and 2016 censuses.

https://doi.org/10.1553/p-gjfn-7z5k

Table 1 The details of the main data and sources utilized in the WPSD model of Iran

Data	Data sources
The quantity of crop production, yield, and the area of dry and irrigated lands	Ministry of Agriculture-Jihad of Iran (2019a). *Agricultural statistics yearbook Volume 1 - Crops*
The quantity of livestock	—. (2019b). *Agricultural statistics yearbook Volume II*
The quantity of production and the area of dry and irrigated lands	—. (2019c). *Agricultural statistics yearbook, volume three*
The quantity of protein and diary production	—. (2020a). Review on production process of Iranian protein products
The yield of products	—. (2020b). *Review on harvest level and production rate statistics of crops*
The cost of planting crops	—. (2020c). Agriculture Information Bank
Population by age, sex, literacy level, student status, employment status (unemployed or employed in agriculture, service and industry sectors); Households by geographic location (urban or rural)	Statistical Center of Iran (2007, 2012a and 2017a). The results of the population and housing censuses of Iran
The rural–urban immigration rates by age and sex and educational composition	—. (2012b and 2017b). 2% sample data of the population and housing censuses
Per capita land area of farms, the number of farmers, ranchers and gardeners	—. (2014, 2015). The results of the agricultural census of 2013
Average household income and expenses by geographic location, employment and education status	—. (2019a). *Income and expenditure survey report*
Employment status (unemployed or employed in agriculture, service and industry sectors)	—. (2017c). *Summary of the results of the labor force survey*
The selling price of each kilogram of crops	—. (2019b). *Purchase price of agricultural products survey report*
The amount of precipitation; The evaporation rate from surface and underground water resources; The returned water from domestic consumption, industry and agriculture	Iran Water Resources Management Company (2014). National Synthesis of Comprehensive Water Studies of the Country
The amount of renewable surface and underground water	—. (2019a). Allowable water in Iran
The withdrawal rate from surface and underground water sources; The consumption of domestic, industrial and agricultural users	—. (2019b). The results of the statistics of the country's water resources and consumption
Current nutrition pattern; The optimal pattern of nutrition according to age and sex groups	Ministry of Health and Medical Education of Iran (2019). National food and nutrition security document

(table continues)

https://doi.org/10.1553/p-gjfn-7z5k

Table 1 (*continued*)

The other data sets and sources:
Export and import statistics of agricultural products (Tehran Chamber of Commerce Industries, Mines and Agriculture, 2020).
Articles related to the estimation of waste and losses of agricultural products (Keshavarz et al., 2016; Gustafsson et al., 2013)
Articles and theses related to estimating the water footprint of food and agricultural products in Iran (Hoekstra et al., 2011; Mirzaie-Nodoushan et al., 2020).
Project for modeling and predicting mortality rates in Iran: 1979-2047 (Eini-Zeinab, 2014)

focused on forecasting. To enhance the transparency of the model, the causal diagrams and key equations used in its development are detailed in the online supplementary material sections S1 and S2 (available online at https://doi.org./10.1553/p-gjfn-7z5k). Section S3 (supplementary material) describes the comparison of the model results to available historical data.

Developing a Water-Population System Dynamics (WPSD) model for measuring water security in Iran through customization of the IWPI framework

In undertaking this distinctive project inspired by our IWPI framework, we gathered statistical sources across various disciplines and integrated them into a comprehensive model comprising over 1,000 distinct equations. To customize the IWPI framework for developing a WPSD model for Iran, given the data availability and the objectives of our case study, we built the model based on the following assumptions.

Population subsystem customization. Despite the model's robust capability to reconstruct various demographic factors – such as population growth, age structure, household changes, student population and labor force population across different economic subgroups, as well as rural–urban migration – certain population trends and dynamics were excluded. Specifically, the WPSD model designed for Iran did not account for the complicated dynamics of international migration. This exclusion arose from the complexity of Iran's migratory patterns, which include substantial levels of emigration leading to brain drain and intermittent inflows, particularly of refugees and immigrants from Afghanistan. The United Nations data indicates that Iran's annual net migration figures have stabilized around zero (United Nations Department of Economic and Social Affairs, Population Division, 2024). However, since 2020, political changes in Afghanistan have led to significant levels of legal and illegal migration to Iran. The exclusion of these forms of migration from the model was due to initial data limitations and their perceived insignificance based on international data. Additionally, the limited data and the cross-sectional nature of these migration waves, along with the uncertainty of Iran's immigration policies, led to the decision to exclude the impact of international migration from the model. Nonetheless, we recognize that if temporary immigrants continue to reside in Iran, their domestic water and food needs, as well as their impact on the job structure, particularly in agriculture, could critically influence the population's exposure to water insecurity.

https://doi.org/10.1553/p-gjfn-7z5k

Additionally, it is noteworthy that while the effects of age structure changes on employment and migration rates were considered, other dynamics, such as the impact of increased education on mortality and fertility rates, were not included due to data limitations and the potential for unnecessary complexity.

Employment subsystem customization. In simulating employment processes across various economic sectors, some economic relationships –such as the selling price of agricultural products, the production cost of agricultural products and the income levels of various occupational groups – were reconstructed based on data from a single year due to significant economic fluctuations and the challenges in predicting inflation and price changes. Therefore, the employment potential in different sectors was reconstructed based on historical trends and water resource constraints. Given that economic sanctions over the past decade have constrained the growth capacity of Iran's industrial sector, our model reflects the limited ability of the industrial sector to absorb a larger workforce, in line with these past trends.

Water subsystem customization. The model primarily relied on the water balance model, a cornerstone of water resource planning in Iran, incorporating general parameters such as precipitation, runoff coefficient and surface and groundwater flows between Iran and its neighbors. However, due to insufficient data, developments related to the exploitation of shared water resources were excluded. The model treated Iran's water resources as a single unit, disregarding regional differences critical for water security because of its overarching policy-making objectives. Consequently, it did not account for regional variations in water distribution facilities and access. Additionally, climate change impacts were excluded due to data and modeling constraints.

Agricultural subsystem customization. The water footprint of agricultural products was estimated using the latest statistical data (Mirzaie-Nodoushan et al., 2020), but potential efficiency improvements in reducing the water footprint were not considered. A significant challenge was the lack of comprehensive data on agricultural product losses and waste in Iran. Approximations were made using research on horticultural and agricultural product losses (Keshavarz et al., 2016) and global data from FAO publications (Gustafsson et al., 2013). The country was divided into regions for loss estimates, but uncertainties about the estimates of losses and waste, as well as the current nutrition pattern, posed serious issues during the modeling phase.[2]

Assessing water security in Iran by applying a population metric

Prior to the widespread use of the term "water security," various tools were developed to measure water conditions, focusing primarily on the hydrology of freshwater resources. These tools varied in their spatial and temporal resolution, and ranged from single to multiple dimensions. Most were developed at the federal, provincial and regional levels, with fewer being developed at the country level (Octavianti and Staddon, 2021; Plummer et al., 2012).

2 For further details on the underlying assumptions and causal connections within the WPSD model, please see Section S1 (supplementary material).

Currently, water security at a large scale, such as at the country level, is defined as sustainable access to an adequate quantity of clean water for domestic needs, food production and sustainable livelihoods (Grey and Sadoff, 2007; Hanjra and Qureshi, 2010; Tarlock and Wouters, 2010; UN-Water, 2013; Flörke et al., 2013).

Even though these aspects significantly impact populations, many water security models have underestimated the population at risk. Our model focuses on quantifying water security for various policies by estimating the population exposed to different water risks.

For Iran, we identified four major water security concerns for policy-makers: food security, domestic water supply security and the security of agricultural and industrial livelihoods. Our objective was to determine the appropriate policy to enhance water security using a metric based on estimating the population at risk under different scenarios. We prioritized assessing not only which population groups are exposed to specific risks, but also the total number of people exposed to various water-related threats on average.

To achieve this, we developed a population metric (see equation 1) to evaluate the impact of different policies on reducing or increasing the number of people affected by water security risks in Iran[3].

$$PEWI = \frac{PEDWI + PEFI + PEILI + PEALI}{4} \quad (1)$$

where

PEWI: Population exposed to water insecurity
PEDWI: Population exposed to domestic water insecurity
PEFI: Population exposed to food insecurity
PEILI: Population exposed to industrial livelihood insecurity due to water shortage
PEILA: Population exposed to agricultural livelihood insecurity

The newly introduced metric has been designed to address the specific needs of water-related policy-making in Iran. A central assumption in its development is the equal importance of all aspects of water security, with the objective of adopting policies that, on average, reduce the number of individuals exposed to water risk. This approach has also been applied to the creation of other metrics, tailored to the unique conditions of each region. Additionally, specific demographic indicators concerning water security can be developed to facilitate temporal and spatial comparisons, although this objective falls outside the primary scope of this article.

Scenarios and policies

Scenarios

The WPSD model's utilized scenarios are detailed in Table 2. In the context of demographic considerations, as illustrated in Table 2, three scenarios have been formulated based on the trajectory of fertility trends. It is noteworthy that the potential influence of alterations in

3 For more explanations on the variables outlined in equation 1, the reader is referred to Section S2 (supplementary material).

https://doi.org/10.1553/p-gjfn-7z5k

Table 2 Description of the scenarios utilized in the WPSD model of Iran

Scenario	Main scenarios	Details of the scenarios	Description of the scenarios
Scenario 1	No effect of changes in household size on per capita domestic water consumption	Low fertility	The effects of changes in household size on changes in per capita water consumption have been neglected. In addition, the total fertility rate is projected to gradually decline from 2.01 children per woman at the beginning of the simulation period in 2011 to 1.5 children per woman in 2041, the final year of the simulation.
Scenario 2		Medium fertility	The effects of changes in household size on changes in per capita water consumption have been neglected. In addition, the total fertility rate remains constant at 2.01 children per woman throughout the entire simulation period.
Scenario 3		High fertility	The effects of changes in household size on changes in per capita water consumption have been neglected. In addition, the total fertility rate is projected to gradually rise from 2.01 children per woman at the beginning of the simulation period in 2011 to 2.5 children per woman in 2041, the final year of the simulation.
Scenario 4	Positive effect of changes in household size on per capita domestic water consumption	Low fertility	The decrease in household size is assumed to increase per capita domestic water consumption. Specifically, per capita water consumption increases in proportion to the third root of the percentage change in household size, while the total fertility rate is projected to gradually decline from 2.01 children per woman at the beginning of the simulation period in 2011 to 1.5 children per woman in 2041, the final year of the simulation.
Scenario 5 (base scenario)		Medium fertility	The decrease in household size is assumed to increase per capita domestic water consumption. Specifically, per capita water consumption increases in proportion to the third root of the percentage change in household size, and the total fertility rate remains constant at 2.01 children per woman throughout the simulation period.
Scenario 6		High fertility	The decrease in household size is assumed to increase per capita domestic water consumption. Specifically, per capita water consumption increases in proportion to the third root of the percentage change in household size, while the total fertility rate is projected to gradually rise from 2.01 children per woman at the beginning of the simulation period in 2011 to 2.5 children per woman in 2041, the final year of the simulation.

https://doi.org/10.1553/p-gjfn-7z5k

women's educational levels on fertility rates was deliberately omitted to mitigate additional complexities. Two distinct scenarios were analyzed regarding the impact of household size reduction on per capita urban and rural water consumption. According to the literature and explanations related to the IWPI framework, it has been established that a reduction in household size leads to an increase in per capita water consumption. This increase occurs due to a reduction in shared uses and the prevalence of non-shared water uses in smaller household units, as well as an increase in water wastage within distribution networks. Various statistics indicate differing severities of the impact of decreased household size on per capita domestic water consumption across different countries. In this model, it was proposed that two scenarios – no effect of changes in household size on per capita domestic water consumption and a third-root effect of such changes – should be considered for both urban and rural areas. As outlined in Table 2, these two scenarios were regarded as the primary scenarios and were integrated with three scenarios related to varying levels of fertility in the model subsequently applied to Iran. Comprising three population scenarios and two nutritional scenarios, a total of six distinct scenarios were combined. The baseline scenario was established by selecting the average fertility scenario and the 50% effect of changes in household size on per capita domestic water consumption. In our model, we successfully reconstructed population dynamics, including such variables as age–sex structure, educational composition, occupational composition and population distribution in urban and rural areas. Although these dynamics indirectly influence water resources, their effects were not included as separate scenarios due to their indirect nature.

Policies

As indicated, the model has the capability to assess the impact of various policies on the enhancement of water security, specifically with regard to diminishing the population susceptible to water insecurity. Explanations regarding the policies employed in the model are described in Table 3.

The results of applying the WPSD model for Iran

Understanding the influence of demographic patterns on water security is essential for crafting effective policies to enhance water security. As a result, our initial focus in presenting the WPSD model's findings centers on the demographic dynamics within Iran. In the second part, we estimate the population exposed to water insecurity, encompassing aspects like agricultural and industrial livelihood, food security and access to domestic water. Finally, in the third part of this section, we demonstrate how the model can assist policy-makers in crafting effective strategies to enhance water security within Iran.

The primary aspects of population trends in the WPSD model for Iran

Population, household and age–sex composition. In the WPSD model for Iran, we explored three scenarios representing varying levels of fertility. The model's findings

https://doi.org/10.1553/p-gjfn-7z5k

Table 3 Description of the policies utilized in the WPSD model of Iran

Policy type	Policy title	Description of policies
1. Water resource planning	Active water planning	The concept of active water resource planning entails establishing a management system capable of adapting goals related to water, and allowing adjustments based on the perception of water insecurity. When calculating the population exposed to domestic or industrial water insecurity, the water resource planning model adjusts to allocate up to five times the required water for the population at risk for domestic or industrial use in the subsequent year.
	Passive planning (base policy)	Water resource planning completely ignores the perceptions of the population exposed to the risk of domestic and industrial water insecurity.
2. Evolving objectives in food security	Goal of 100% self-sufficiency (base policy)	Self-sufficiency in food production is a primary objective of Iran's agricultural policies. Consequently, we assessed the population at risk of food insecurity based on a 100% food self-sufficiency policy. However, this policy has faced criticism from water sector policy-makers due to severe water resource limitations, rendering it seemingly unattainable.
	Goal of 90% self-sufficiency	In recent years, the policy of self-sufficiency in the production of food products has been criticized by policy-makers in the water sector, who have argued that it is impossible to implement due to the serious limitations in water resources. We tried to move outside the dual goals of self-sufficiency or lack of self-sufficiency in the production of food products in the country, and instead aimed to find out how many people would be exposed to the risks of water insecurity if the goal was 90% self-sufficiency for food products.
	Goal of 80% self-sufficiency	We tried to move outside the dual goals of self-sufficiency or lack of self-sufficiency in the production of food products in the country, and instead aimed to find out how many people would be exposed to the dangers of water insecurity if the goal was 80% self-sufficiency for food products.
3. Modification of dietary patterns	Current nutrition pattern (base policy)	It is assumed that the current pattern of nutrition in the country will continue.
	Change the nutrition pattern	The Ministry of Health in Iran has issued an optimal nutrition pattern that diverges from the existing dietary norms (according to the nutritional needs of the population in different age–sex groups, a special food composition has been recommended). This policy explores the possibility of transitioning away from the current nutrition pattern to the one recommended by the Ministry of Health over the 30-year simulation period.

(table continues)

https://doi.org/10.1553/p-gjfn-7z5k

Table 3 (*continued*)

Policy type	Policy title	Description of policies
4. Reassessment of cultivation priorities	No specific crop cultivation priority (base policy)	There is no specific cultivation priority on the agenda; both food security and household livelihood are equally important.
	Cultivation priority based on food security	The priority of cultivation is determined based on self-sufficiency needs. However, the annual cultivation pattern of any agricultural product can change substantially based on historical experiences.
	Cultivation priority based on providing livelihood security	The priority of cultivation is determined by the need to improve household livelihoods. However, the annual cultivation pattern of any agricultural product can change substantially based on historical experiences.
5. Mitigating agricultural waste and losses	No reduction (base policy)	If the cost of importing agricultural products exceeds the cost of exporting them, there is no potential for investment in reducing waste and losses of these products.
	Reduction of waste and loss	The gradual reduction of waste and losses in the agricultural sector during the 30-year simulation period aims to decrease agricultural waste and losses by up to 50% of the current levels.

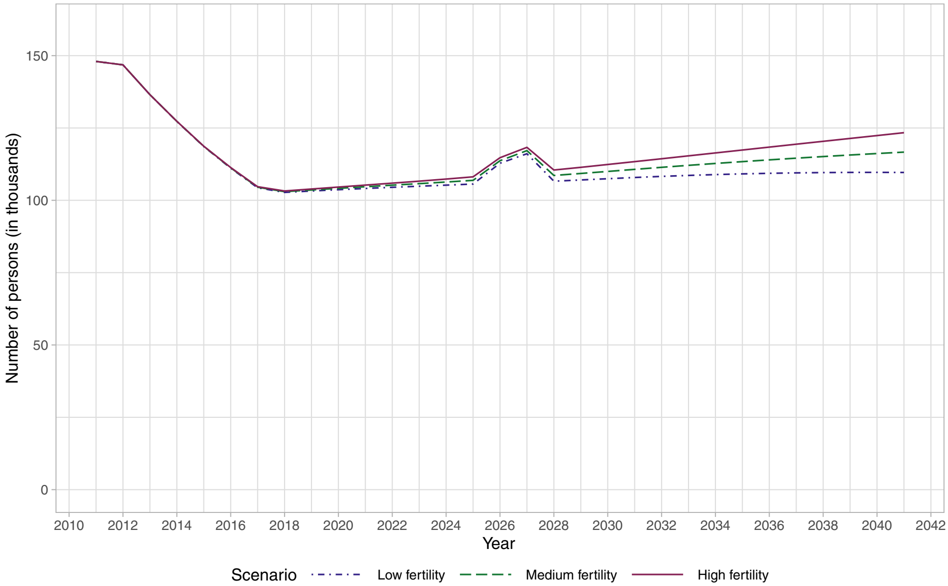
suggest that by 2041 (the concluding year of the modeling), Iran's population is projected to fall to between 91.79 and 100.73 million, depending on the chosen population scenario. However, these demographic trends do not occur uniformly across all demographic subgroups. For instance, over the three decades of simulation (from 2011 to 2041), the rural population is expected to remain steady or to slightly decrease or to increase from approximately 21.44 million to between 19.86 and 22.06 million, depending on the demographic scenario. Importantly, these variables were considered independent of the water dynamics within the model.

Furthermore, it is projected that the ratio of age dependency will increase from approximately 0.41 to more than 0.56 across various scenarios. Other notable shifts in variables include alterations in the sex ratio (the number of males to the number of females), initially exceeding one in the early stages of the simulation but gradually declining to approximately 0.96 in the concluding years of the simulation. Simultaneously, the quantity of households will undergo a substantial transformation. Over the 30-year simulation period, the number of households is expected to surge from 20.63 million to between 34.51 and 37.86 million, depending on the fertility scenario.

Educational and livelihood compositions. In the preceding sections, we categorized labor market segments in our model based on gender, residence and educational level. The analysis of the model's outcomes reveals that the different demographic scenarios have minimal effects on the numbers of illiterate individuals in urban and rural areas, with a gradual decline expected in both settings. A consistent decrease in the number of individuals

https://doi.org/10.1553/p-gjfn-7z5k

Figure 2 The annual number of rural–urban migrants during the simulation period



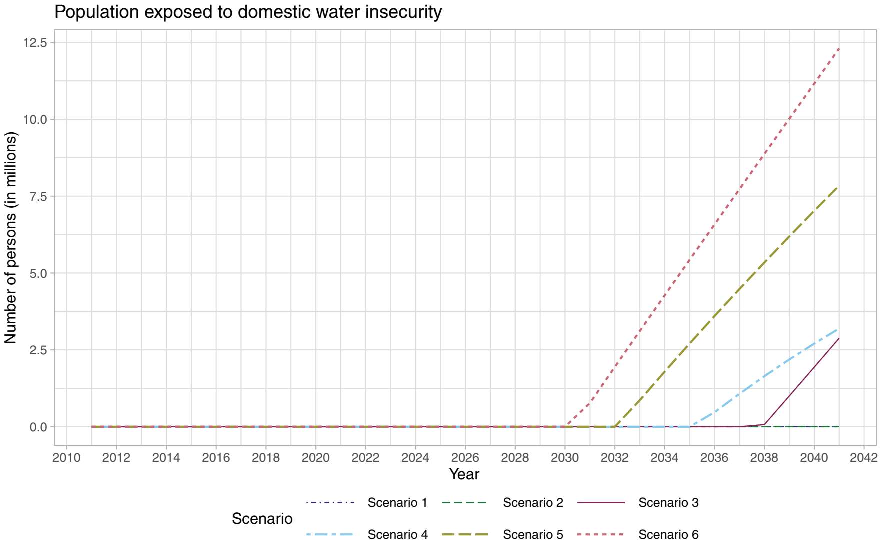
with primary education is observed across various demographic scenarios, driven by rising literacy rates and the retirement from the workforce of prior generations with lower educational levels. Notably, the most significant impact of these scenarios is found in the active populations with secondary education or higher, as an increase in the number of active individuals with higher education is expected among both rural and urban populations, while the number of active individuals with secondary education is likely to increase among women but to decrease among men.

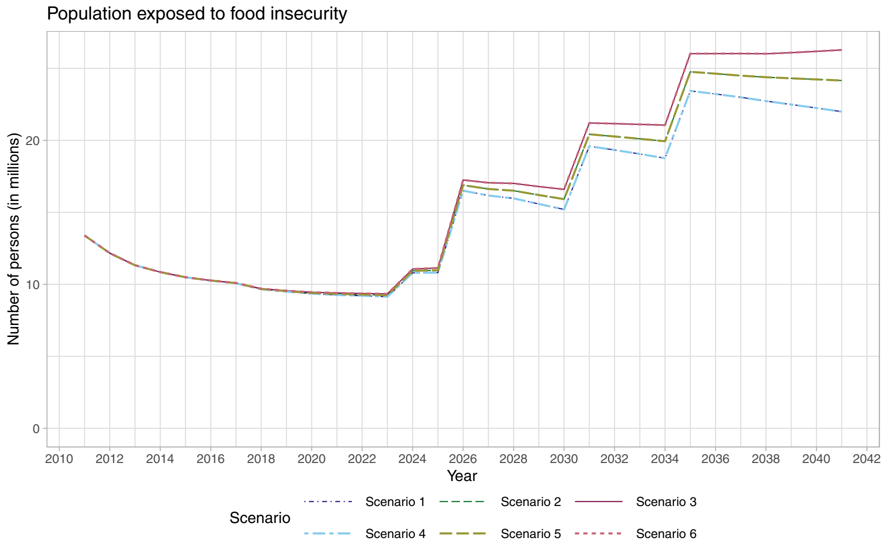
The labor force dynamics depicted in the reconstructed model are influenced by dynamic changes, and these changes, in turn, affect these dynamics. The industrial sector in Iran, which is characterized by below average income levels, typically has less prominence in the labor market than other sectors, making it more sensitive to shifts in the active population estimates in various demographic scenarios. Conversely, in line with the model's assumptions and considering the higher income levels associated with the service sector, employment in this sector takes precedence in the forecasting period, leading to a gradual increase in the numbers of service employees in both urban and rural areas. Importantly, due to a reduction in the population of individuals with low literacy levels and constraints on agricultural sector employment linked to water resource limitations, employment in agriculture is expected to decline progressively in both rural and urban populations.

Rural–urban migration trends. Regarding the number of rural–urban migrants shown in Figure 2, it should be noted that this number is influenced by factors beyond water resources. At the beginning of the simulation period, the pattern of declining numbers of people

https://doi.org/10.1553/p-gjfn-7z5k

Figure 3 Estimated number of the population exposed to the risk of domestic water insecurity, food insecurity, agricultural livelihood insecurity and water insecurity in Iran throughout the three-decade simulation period



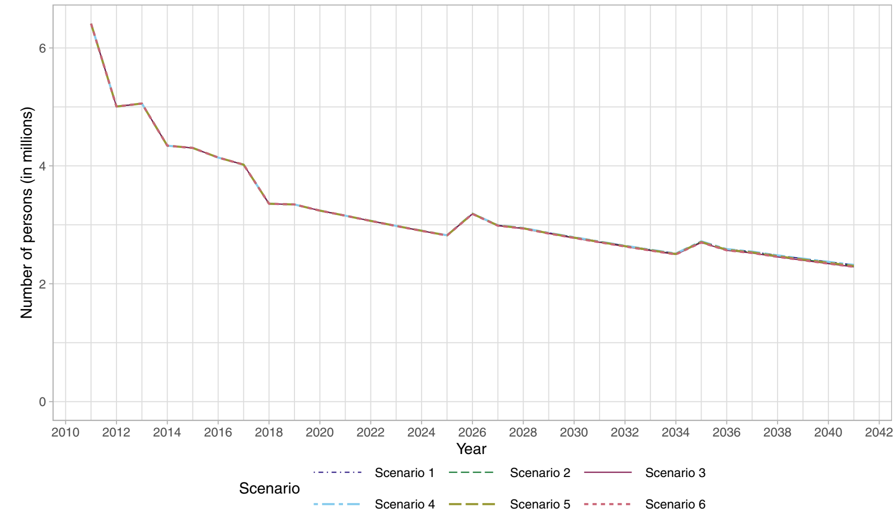


(figure continues)

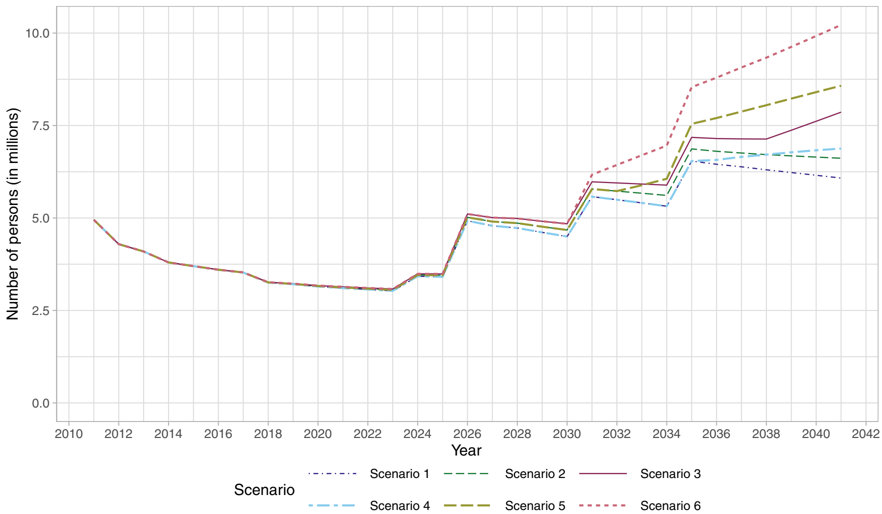
https://doi.org/10.1553/p-gjfn-7z5k

Figure 3 (*continued*)

Population exposed to agricultural livelihood insecurity



Population exposed to water insecurity



*Scenario 1: Low fertility scenario and **no** effect of changes in household size on per capita domestic water consumption*
*Scenario 2: Medium fertility scenario and **no** effect of changes in household size on per capita domestic water consumption*
*Scenario 3: High fertility scenario and **no** effect of changes in household size on per capita domestic water consumption*
Scenario 4: Low fertility scenario and effect of changes in household size on per capita domestic water consumption
Scenario 5: Medium fertility scenario and effect of changes in household size on per capita domestic water consumption
Scenario 6: High fertility scenario and effect of changes in household size on per capita domestic water consumption

https://doi.org/10.1553/p-gjfn-7z5k

being exposed to agricultural livelihood insecurity (illustrated in Figure 3) aligns with the declining trend of rural-to-urban migration. However, in the future, given the increasing educational levels of the rural workforce and the higher rates of migration among educated rural individuals seeking better employment and livelihood opportunities, the number of rural–urban migrants is expected to rise across all scenarios. This is despite the overall decreasing trend in the population exposed to agricultural livelihood insecurity.

Nevertheless, the relationship between the proportion of the population at risk of agricultural livelihood insecurity and rural–urban migration is not entirely severed. For instance, in 2026, as depicted in Figure 3, the number of people exposed to livelihood insecurity reaches its peak. Correspondingly, an increase in rural–urban migrants is evident in Figure 2.

The principal characteristics encompassing the population dynamics within the WPSD model of Iran

The utilization of the conceptual framework allowed us to address another primary inquiry in this research. Specifically, it enabled us to ascertain, considering Iran's demographic trends – encompassing population size, age, and gender distribution, household count and educational and occupational structure – which segments of the population will face water-related insecurities (including livelihood, domestic water and food security) over the next three decades. The model's findings are shown in Figure 3. As illustrated in Figure 3, applying the WPSD model to Iran reveals that domestic water insecurity and food insecurity within the population during the 30-year period from 2011 to 2041 are significantly influenced by different demographic dynamics under different scenarios. Those dynamics are described further below.

Population exposed to domestic water insecurity. As depicted in Figure 3, in the initial years of the simulation, no part of the population is at risk of domestic water insecurity despite the population dynamics. This result indicates that the total water resources available for planning can meet the domestic water needs of the population, even under various demographic scenarios. However, our model did not account for regional differences in access to water supply and distribution facilities, nor did it evaluate domestic water security from this perspective. Instead, it focused solely on the general aspects of the country's water resource planning.

Despite demographic dynamics – such as population growth and changes in geographical distribution (rural or urban), and specifically more intense urban population growth, which is associated with higher per capita domestic water consumption, and without considering the effects of household size changes on per capita water consumption – the country's allowable water resources are sufficient for domestic needs. However, in all three scenarios where the effect of reduced household size on increased water consumption was included, and in the high fertility scenario without accounting for household size changes in the last decade, domestic allocable water proved insufficient. Consequently, depending on the scenario, between three and 12 million people are projected to face the risk of domestic water insecurity, as defined earlier.

https://doi.org/10.1553/p-gjfn-7z5k

Population exposed to food insecurity. In the WPSD model, the assessment of the population's food requirements considered variables such as age and sex composition and specific dietary needs across various age–sex groups. Additionally, losses and waste in the agricultural sector for each product were individually accounted for. The model underscores that the most pressing water-related concern from 2011 to 2041 is the inadequacy of water resources to meet the population's food requirements, assuming the goal of self-sufficiency in food production. While the use of non-renewable underground water resources is expected to reduce the population vulnerable to food insecurity from 13.39 million in 2011 to around nine million in 2023, the sector's production capacity gradually diminishes due to unsustainable resource exploitation. Consequently, the population susceptible to food insecurity, relying on internal agricultural production, is projected to increase, reaching a range of 21.99 to 26.28 million people under different demographic scenarios.

Population exposed to agricultural livelihood insecurity. According to the WPSD model results, transformations in the educational composition of the working-age population in Iran, coupled with a decline in water resource capacity, will gradually diminish the potential for employment within the agricultural sector, thereby reducing the workforce engaged in this sector. Simultaneously, the reduction in the size of rural households leads to a decrease in the number of dependents relying on farming within each household. Consequently, over the 30-year modeling period, the population vulnerable to livelihood insecurity within the agricultural sector, encompassing farmers and their dependents, will undergo a gradual decline. Specifically, this population is projected to decrease from approximately 6.41 million individuals in the initial year of the simulation (2011) to approximately 3.2 million, reaching a range of 2.28 to 2.32 million people under various scenarios by the culmination of the simulation in 2041.

Population exposed to industrial livelihood insecurity. The model posits that the inclination of the working-age population to seek employment in the industrial sector hinges on the average incomes of industrial workers in Iran compared to those of workers in other sectors. Given that industrial sector workers generally earn lower incomes, the working-age population is less inclined to pursue employment in this sector when other opportunities exist. Furthermore, throughout the transition of the population from middle age to old age, the labor market strain across various economic sectors will diminish. However, if the industrial sector workers continue to earn lower incomes than workers in other sectors, there will not be a compelling incentive to boost employment in this sector, and the expansion of industrial facilities and increased pressure on water resources by industrial plants is unlikely. Through the assumptions outlined, the model illustrates that, based on the model's simulations spanning from 2011 to 2041, no part of the population faces livelihood insecurity within the industrial sector.

Total population exposed to water insecurity. The total population exposed to water insecurity is the average number of individuals in the population who are exposed to different aspects of water insecurity. As shown in Figure 3, the model's projected outcomes demonstrate a nuanced trajectory. Initially, over the simulation period from 2011 to 2041, the average population exposed to water insecurity, including for livelihood, domestic, and food requirements, exhibits a declining trend. However, this trajectory is later influenced by

https://doi.org/10.1553/p-gjfn-7z5k

two significant factors: unsustainable underground water resource utilization, leading to reduced agricultural production capacity and employment opportunities, and an escalating demand for domestic water surpassing planned provisions. Consequently, the population at risk of water insecurity is expected to expand, increasing from 4.95 million individuals at the simulation's outset to a range of 6.08 to 10.22 million individuals under diverse demographic and nutritional scenarios by the end of the simulation.

How the WPSD model of Iran can be applied to inform decision-makers

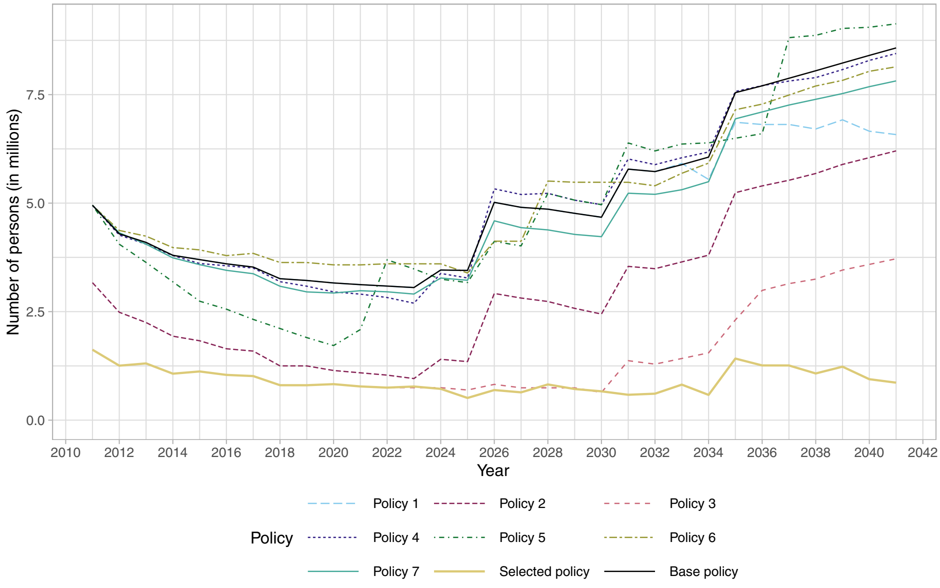
Figure 4 illustrates our assessment of various policy options that can be proposed by Iranian policy-makers to reduce the population at risk of water insecurity using the WPSD model. The findings indicate that due to population dynamics – such as population growth, increased urbanization and decreased household sizes leading to more households – the demand for domestic water exceeds the currently allowable domestic water. Consequently, active and flexible domestic water planning (policy 1 in Figure 4) emerges as a crucial strategy to reduce the population at risk of water insecurity, potentially decreasing the number of people at risk in 2041 from 8.69 million to 6.51 million. Regarding food security (policies 2, 3 and 4 in Figure 4), achieving 100% self-sufficiency in food production appears unattainable given Iran's water resource constraints. This level of self-sufficiency is only viable during the first decade of our simulation. We recommend that policy-makers adopt more realistic food security goals, such as 90% or 80% self-sufficiency, which could reduce the population at risk of water insecurity to between 6.23 and 3.89 million by 2041.

Another significant challenge faced by water and agriculture policy-makers in Iran is the apparent disconnection between water resource limitations and the Ministry of Health's dietary recommendations. Despite increasing awareness of water resource constraints in recent years, the Ministry of Health has not prioritized the development of a water-efficient food pattern. The current pattern recommended by the Ministry (policy 4 in Figure 4) is ineffective in significantly reducing the population exposed to water insecurity. By 2041, this policy is projected to reduce the number of people at risk by only about 100,000. According to the WPSD model, maintaining the current food pattern with a goal of 100% self-sufficiency in food production poses critical issues, particularly for cereal and rice production, which are essential for population livelihood. If the Ministry of Health's recommended food model was adopted, a reduction in cereal consumption would be required, which would help to increase self-sufficiency. However, if the recommendation to consume more red meat, eggs and dairy products was adopted, the nation's self-sufficiency in producing these essential food products would be compromised. This reduction in self-sufficiency is evident in most simulation years, even under scenarios of low fertility and population growth, underscoring the need for reassessing the food pattern in the context of Iran's water limitations.

Policies aimed at modifying cultivation patterns to improve food security and farmers' livelihoods (policies 5 and 6 in Figure 4) were found to be ineffective. It seems that an increase in one aspect of water security (for example, in food security) leads to a decrease in another aspect of water security (for instance, in livelihood security). Therefore, shifting the cultivation pattern to enhance food security could significantly reduce agricultural

https://doi.org/10.1553/p-gjfn-7z5k

Figure 4 Estimated number of the population at risk of water insecurity under different policies



Note: All policies cover the base scenario described in Table 2. Therefore, it is assumed the decrease in households increases per capita domestic water consumption, and the total fertility rate remains constant at 2.01 throughout the simulation period.
Base policy: It is assumed that the current pattern of nutrition in the country will continue; the water resource planning completely ignores the perceptions of the population exposed to the risk of domestic and industrial water insecurity. The goal of 100% self-sufficiency is considered. There is no specific cultivation priority on the agenda, and if the cost of importing agricultural products exceeds the cost of exporting them, there is no potential for investment in reducing waste and losses of these products.
Policy 1: Active water planning
Policy 2: Change food security to the goal of 90% self-sufficiency
Policy 3: Change food security to the goal of 80% self-sufficiency
Policy 4: Change the nutrition pattern
Policy 5: Change the cultivation priority based on food security
Policy 6: Change the cultivation priority based on livelihood security
Policy 7: Reduction of waste and losses of agricultural products
Selected policy: A combination of the policy of changing food security to the goal of 80% self-sufficiency, active domestic water planning, reducing waste and losses of agricultural products and changing the cultivation pattern to livelihood security

income, thereby increasing the number of farmers facing livelihood insecurity. Changing the cultivation pattern to enhance farmers' livelihood security is more effective than focusing solely on food security, as it could reduce the population at risk of water insecurity by 360,000 by the end of the simulation period.

The evaluation of policy 7, as depicted in Figure 4, focused on the impact of gradually reducing agricultural product losses and waste on mitigating water insecurity risks. It was found that this policy could decrease the number of people exposed to water insecurity by up to 800,000 annually.

Integrating the selected policy options, even under the medium fertility scenario, and considering the changes in household size affecting per capita water consumption, provides a promising outlook for Iran. The population exposed to water risk could drop to less than two million in all simulation years, and to below one million in most years.

Conclusion

While many countries deal with the challenge of meeting escalating demands for water and food during their demographic transitions, it is noteworthy that the significance of demographic transitions has received limited attention in discussions on water and food security. Demographic transitions, which are marked by declining mortality and fertility rates leading to initial population growth, have far-reaching effects extending beyond mere population size. These transitions encompass shifts in age distribution, alterations in food and nutritional patterns and changes in water consumption dynamics. They also influence employment patterns, particularly in the agricultural sector. Consequently, as countries progress into the latest stages of the demographic transition when their population growth rates decline, the role of other demographic factors related to water becomes increasingly pivotal. Understanding the complicated interplay of population dynamics, water resources, food production and water-dependent livelihoods is imperative.

With its evolution over the years, demography, and particularly environmental demography, has provided a foundation for enhancing models of water security. Environmental demographers have shifted their approach from oversimplification to a more complex system dynamics perspective, recognizing the influence of various demographic variables beyond population size on natural resource consumption. Inspired by this evolving approach, as well as by extensive literature and research on demography and water resources management, a generic Integrated Water-Population Interaction (IWPI) framework was proposed. The framework needs to be customized in every application according to the modeling purpose and data availability. To show its application, the framework was adapted to the case of water security in Iran using the Water-Population System Dynamics (WPSD) model.

The application of the WPSD model in Iran demonstrated that population size, household size changes and urbanization ratios significantly impact drinking water consumption. Changes in educational and occupational composition, influenced by the age dependency ratio and household size, affect livelihood security due to limited water resources. Additionally, the age–sex structure and population size influence food self-sufficiency under water limitations. These impacts were illustrated through separate scenarios or indirect relationships within the model, which also mapped rural–urban migrations driven by water resource constraints. A key achievement of the WPSD model was the development of a new population metric to evaluate water security dimensions.

The WPSD model's integration of population, water, employment and agricultural dynamics offers comprehensive policy options for harmonizing these factors. Based on

https://doi.org/10.1553/p-gjfn-7z5k

the results of the WPSD model of Iran, it is recommended that water policy be adapted for active and flexible domestic water resource planning. The goal of achieving 100% self-sufficiency in food is unrealistic, while a more achievable target is 80% self-sufficiency, accompanied by reductions in agricultural losses and waste. Nutrition policy-makers should consider the impact of dietary patterns on food self-sufficiency under water limitations. The model demonstrates that changes in cultivation patterns have varied effects on water security, highlighting the need for policies that consider all dimensions to effectively reduce water insecurity. Therefore, the WPSD model of Iran has the potential to tackle significant policy questions concerning the population's water security. To fully address the various dimensions of water security, further development of the model, including considering the impacts of climate change and technological advancements, and accounting for subnational water security differences and international migration, is recommended.

In conclusion, the IWPI framework and the WPSD model and the new population metric to evaluate the water security offer a structured approach to tackle the multifaceted challenges of water security by considering the intricate relationship between population and water variables. This approach underscores the need for holistic policies and interventions that account for the interplay of population growth, employment opportunities, agricultural practices and water resource management in achieving sustainable water, food and livelihood security. By introducing a novel concept of water security that gauges insecurity in meeting domestic water, food and livelihood needs for different population segments, this approach enables policy-makers to evaluate policy effects on the water-population balance, particularly in countries experiencing demographic transitions. The new population metric can be customized to assess water insecurities by quantifying populations exposed to different aspects of water insecurity in different conditions, and consolidating them into a composite metric. The proposed framework and model, elaborated upon in this article, can be offered as a comprehensive tool for analyzing water-food-livelihood security, especially in arid and semi-arid regions where undergoing the demographic transition has increased pressure on water resources.

Supplementary material

Available online at https://doi.org/10.1553/p-gjfn-7z5k.

Supplementary file 1. Model description (S1), mathematical formulation of the model (S2), comparison of model results to historical data (S3)

Acknowledgements

The authors would like to express their gratitude to the esteemed editor and reviewers for their valuable suggestions and comments.

ORCID iDs

Zahra Soltani https://orcid.org/0000-0002-8423-6189

Mohammad Jalal Abbasi-Shavazi https://orcid.org/0000-0002-8647-376X

Ali Bagheri https://orcid.org/0000-0003-4518-6884

References

Abbasi-Shavazi, M. J., McDonald, P., and Hosseini-Chavoshi, M. (2009). *The fertility transition in Iran: Revolution and reproduction*, Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3198-3

Adams, W. M. (2001). *Green Development: Environment and Sustainability in the Third World* (2nd ed.). Routledge. https://doi.org/10.4324/9780203440896

Aigner-Walder, B., and Döring, T. (2012). The effects of population ageing on private consumption — A simulation for Austria based on household data up to 2050. *Eurasian Econ Rev 2*, 63–80. https://doi.org/10.14208/BF03353833

Albrecht, T. R., Crootof, A., and Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, *13*(4), 043002. https://dx.doi.org/10.1088/1748-9326/aaa9c6

Appelgren, B., and Klohn, W. (1999). Management of water scarcity: A focus on social capacities and options. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *24*(4), 361–373. https://doi.org/10.1016/S1464-1909(99)00015-5

Ardakanian, R. (2005, March). Overview of water management in Iran. In *Water Conservation, Reuse, and Recycling: Proceeding of an Iranian-American workshop* (pp. 18–33). The National Academies Press, Washington, DC.

Beckage, B., Gross, L. J., and Kauffman, S. (2011). The limits to prediction in ecological systems. *Ecosphere*, *2*(11), 1–12. https://doi.org/10.1890/ES11-00211.1

Boberg, J. (2005). *Liquid assets: How demographic changes and water management policies affect freshwater resources*. Rand Corporation. https://doi.org/10.7249/MG358

Bongaarts, J. (2003). Completing the fertility transition in the developing world: The role of educational differences and fertility preferences. *Population Studies*, *57*(3), 321–335. https://doi.org/10.1080/0032472032000137835

Boserup, E. (1965). *The conditions of agricultural growth: The economics of agrarian change under population pressure*. Routledge. *https://doi.org/10.4324/9781315070360*

Boserup, E. (1981). *Population and technological change: A study of long-term trends*. University of Chicago Press.

Caldwell, J. C. (1996). Demography and social science, *Population Studies*, *50*(3), 305–333, https://doi.org/10.1080/0032472031000149516

Cleland, J. (2002). Education and future fertility trends, with special reference to mid-transitional countries. *Population Bulletin of the United Nations, Special Issue: Completing the fertility transition* (pp. 183–194). New York: Department of Economic and Social Affairs, United Nations. https://researchonline.lshtm.ac.uk/id/eprint/17865

Case, A., and Deaton, A. (2017). Mortality and morbidity in the 21st century. *Brookings papers on economic activity* 397–476. https://doi.org/10.1353/eca.2017.0005

Cohen, I. S., Spring, Ú. O., Padilla, G. D., Paredes, J. C., Inzunza Ibarra, M. A., López, R. L., and Díaz, J. V. (2013). Forced migration, climate change, mitigation and adaptive policies in Mexico: Some functional relationships. *International Migration*, *51*(4), 53–72.

Connor, D. S., Hunter, L., Jang, J., and Uhl, J. H. (2023). Family, community, and the rural social mobility advantage. *Research in Social Stratification and Mobility*, *87*, 100844. https://doi.org/10.1111/j.1468-2435.2012.00743.x

Cohen, J. E. (1995). Population growth and Earth's human carrying capacity. *Science*, *269*(5222), 341–346. https://doi.org/10.1126/science.7618100

Connor, D. S., Hunter, L., Jang, J., and Uhl, J. H. (2023). Family, community, and the rural social mobility advantage. *Research in Social Stratification and Mobility*, *87*, 100844. https://doi.org/10.1016/j.rssm.2023.100844

Curran, S. R., and de Sherbinin, A. (2004). Completing the picture: The challenges of bringing "consumption" into the population–environment equation. *Population & Environment*, *26*(2), 107–131. https://doi.org/10.1007/s11111-004-0837-x

Davis, K. (1990). Population and resources: Fact and interpretation. *Population and Development Review*, *16*, 1–21. https://doi.org/10.2307/2808060

Dickin, S., and Di Mario, L. (2017). *Water security is job security: Water as an enabler for livelihoods*. In: Devlaeminck, D., Adeel, Z., Sandford, R. (Eds) The human face of water security. Water security in a new world. Springer, Cham. https://doi.org/10.1007/978-3-319-50161-1_6

https://doi.org/10.1553/p-gjfn-7z5k

Droogers, P., Immerzeel, W. W., Terink, W., Hoogeveen, J., Bierkens, M. F. P., Van Beek, L. P. H., and Debele, B. (2012). Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences*, *16*(9), 3101–3114. https://doi.org/10.5194/hess-16-3101-2012

Ehrlich, P. (1970). *The population bomb*. New York Times, 47.

Ehrlich, P. R. (2014). Human impact: The ethics of I=PAT. *Ethics in Science and Environmental Politics*, *14*(1), 11–18. https://doi.org/10.3354/esep00151

Ehrlich, P. R., Ehrlich, A. H., and Daily, G. C. (1993). Food security, population and environment. *Population and Development Review*, *19*(1), 1–32. https://doi.org/10.2307/2938383

Ehrlich, P. R., and Holdren, J. P. (1971). Impact of population growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. *Science*, *171*(3977), 1212–1217. https://doi.org/10.1126/science.171.3977.1212

Eini-Zeinab, H. (2014). *Modeling and predicting mortality rates in Iran: 1979-2047*. (In Persian), Statistical Research Center, Tehran.

Ellis, F. (1998). Household strategies and rural livelihood diversification. *The Journal of Development Studies*, *35*(1), 1–38. https://doi.org/10.1080/00220389808422553

Falkenmark, M., Lundqvist, J., and Widstrand, C. (1989). Macro scale water scarcity requires micro scale approaches. *Natural Resources Forum*, *13*(4), 258–267. https://doi.org/10.1111/j.1477-8947.1989.tb00348.x

Falkenmark, M., and Lannerstad, M. (2005). Consumptive water use to feed humanity – curing a blind spot. *Hydrology and Earth System Sciences 9* 15–28. https://doi.org/10.5194/hess-9-15-2005

Falkenmark, M. (2013). Adapting to climate change: Towards societal water security in dry-climate countries. *International Journal of Water Resources Development*, *29*(2), 123–136. https://doi.org/10.1080/07900627.2012.721714

Fischer, G., and Heilig, G. K. (1997). Population momentum and the demand on land and water resources. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *352*(1356), 869–889. https://doi.org/10.1098/rstb.1997.0067

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change*, *23*(1), 144–156. https://doi.org/10.1016/j.gloenvcha.2012.10.018

FAO. (2000). *New dimensions in water security: Water, society and ecosystem services in the 21st century*. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/012cecd8-eb32-4928-ae7c-b05907a56dfe/content

Forouzani, M., and Karami, E. (2011). Agricultural water poverty index and sustainability. *Agronomy for Sustainable Development*, *31*(2), 415–431. https://doi.org/10.1051/agro/2010026

Forrester, J. (1961). *Industrial dynamics*. Cambridge, MA: The MIT Press. (Reprinted by Pegasus Communications, Waltham, MA).

Forrester, J. W. (1968). Industrial dynamics—After the first decade. *Management Science*, *14*(7), 398–415. https://doi.org/10.1287/mnsc.14.7.398

Forrester, J. W. (1971). Counterintuitive behavior of social systems. *Theory and Decision*, *2*(2), 109–140. https://doi.org/10.1007/BF00148991

Gleick, P. H. (1993). Water and conflict: Fresh water resources and international security. *International security*, *18*(1), 79–112. https://doi.org/10.2307/2539033

Gleick, P. H. (1994). Water, war & peace in the Middle East. *Environment: Science and policy for sustainable development*, *36*(3), 6–42. https://doi.org/10.1080/00139157.1994.9929154

Gleick, P. H. (1996). Basic water requirements for human activities: Meeting basic needs. *Water International*, *21*(2), 83–90. https://doi.org/10.1080/02508069608686494

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*(5967), 812–818. https://doi.org/10.1126/science.1185383

Grey, D., and Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water Policy*, *9*(6), 545–57. https://doi.org/10.2166/wp.2007.021

Gustafsson, J., Cederberg, C., Sonesson, U., and Emanuelsson, A. (2013). The methodology of the FAO study: Global food losses and food waste-extent, causes and prevention. *FAO* 20011a. SIK. Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

https://doi.org/10.1553/p-gjfn-7z5k

Hanjra, M. A., and Qureshi, M. E. (2010). Global water crisis and future food security in an era of climate change. *Food Policy*, *35*(5), 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006
Hasnip, N., Mandal, S., Morrison, J., Pradhan, P., and Smith, L. (2001). *Contribution of irrigation to sustaining rural livelihoods*, KAR Project R 7879. HR Walingford/DFID, UK. https://eprints.hrwallingford.com/456/1/odtn109.pdf
Hardin, G. (1968). The tragedy of the commons. *Science*, *162*(3859), 1243–1248. https://doi.org/10.1126/science.162.3859.1243
Hayes, A. C., and Adamo, S. B. (2014). Introduction: Understanding the links between population dynamics and climate change. *Population and Environment*, *35*, 225–230. https://doi.org/10.1007/s11111-014-0208-1
Health Ministry of Iran (2019). *National food and nutrition security document*. (In Persian).
Hjorth, P., and Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures*, *38*(1), 74–92. https://doi.org/10.1016/j.futures.2005.04.005
Hoekstra, A. Y., and Chapagain, A. K. (2006). Water footprints of nations: Water use by people as a function of their consumption pattern. In E. Craswell, M. Donnell, D. Bossio, S. Demuth, and N. Giesen (Eds), *Integrated Assessment of Water Resources and Global Change: A north-south analysis*. (pp. 35–48). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5591-1_3
Hoekstra, A. Y., Chapagain, A. K., Mekonnen, M. M., and Aldaya, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Routledge.
Hoekstra, A. Y. (2017). Water footprint assessment: Evolvement of a new research field. *Water Resources Management*, *31*(10), 3061–3081. https://doi.org/10.1007/s11269-017-1618-5
Holdren, J. P., and Ehrlich, P. R. (1974). Human population and the global environment: Population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force. *American Scientist*, *62*(3), 282–292. https://www.jstor.org/stable/27844882
Hosseini-Chavoshi, M., and Abbasi-Shavazi, M. J. (2023). Breaking a vicious cycle: Education as the solution to Afghanistan's woes. *Migration Policy Practice*, *12*(1): 11–17.
Hummel, D., Adamo, S., de Sherbinin, A., Murphy, L., Aggarwal, R., Zulu, L., Liu, J., and Knight, K. (2013). Inter- and transdisciplinary approaches to population–environment research for sustainability aims: A review and appraisal. *Population and Environment*, *34*, 481–509. https://doi.org/10.1007/s11111-012-0176-2
Hunter, L. M. (2000). *The environmental implications of population dynamics*. Santa Monica: RAND.
Hunter, L. M., and Nawrotzki, R. (2016). Migration and the environment. In M. J. White (Ed.), *International handbook of migration and population distribution*, 465–484. https://doi.org/10.1007/978-94-017-7282-2_21
Hunter, L. M., and O'Neill, B.C. (2014). Enhancing engagement between the population, environment, and climate research communities: The shared socio-economic pathway process. *Population and Environment*, *35*, 231–242. https://doi.org/10.1007/s11111-014-0202-7
Hussey, K., and Pittock, J. (2012). The Energy–Water Nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society*, *17*(1). https://doi.org/10.5751/ES-04641-170131
Iran Water Resources Management Company (2014). *National Synthesis of Comprehensive Water Studies of the Country Report*. (In Persian), Ministry of Energy, Tehran.
Iran Water Resources Management Company (2018). *Report on the status of Iran's water resources and consumption*. Ministry of Energy, Tehran. (In Persian).
Iran Water Resources Management Company (2019a). *Allowable water of Iran Report*. (In Persian), Ministry of Energy, Tehran.
Iran Water Resources Management Company (2019b). *The results of the statistics of the country's water resources and consumption report*. (In Persian), Ministry of Energy, Tehran.
KC, S., and Lutz, W. (2017). The human core of the shared socio-economic pathways: Population scenarios by age, sex, and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004
Keilman, N. (2003). The threat of small households. *Nature*, *421*, pp 489–490. https://doi.org/10.1038/421489a
Keshavarz, A., Shariatmadar, M., Khosravi, A., Sheikhi Mehrabadi, A., Biki Khoshk, A., Shabani, M., Bakhshaish, M., Kianpour, R., and Afkari, B. (2016). Estimation of economic value of water lost due to

https://doi.org/10.1553/p-gjfn-7z5k

agricultural wastes & losses (irrigated and horticultural) from harvest to before consumption. *Water and Sustainable Development*, *3* (1), 73–82. (In Persian) https://doi.org/10.22067/jwsd.v3i1.59431

Keyfitz, N. (1992). Completing the worldwide demographic transition: The relevance of past experience. *Ambio 21*(1), 26–30. https://doi.org/10.2307/4313860

Kristensen, P. (2004). *The DPSIR framework*. National Environmental Research Institute. European Environment Agency. Denmark. Paper presented at the UNEP workshop on vulnerability assessment of water resources to environmental change, Nairobi, Kenya, September 27–29.

Kummu, M., Ward, P. J., de Moel, H., and Varis, O. (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters*, *5*(3), 034006. https://doi.org/10.1088/1748-9326/5/3/034006

Lee, E. S. (1966). A theory of migration. *Demography*, *3*, 47–57. https://doi.org/10.2307/2060063

Lee, R., and Anderson, M. (2002). Malthus in state space: Macro economic-demographic relations in English history, 1540 to 1870. *Journal of Population Economics*, *15*(2), 195–220. https://doi.org/10.1007/s001480100091

Lutz, W., Sanderson, W., and Scherbov, S. (2001). The end of world population growth. *Nature*, *412*(6846), 543–545. https://doi.org/10.1038/35087589

Lutz, W., Prskawetz, A., and Sanderson, W. C. (Eds) (2002). Population and environment: Methods of analysis. *Population and Development Review*, *28*(Supplement), 225–250. http://www.jstor.org/stable/i356664

Lutz, W., Butz, W. P., and KC, S. (Eds) (2014a). *World population and human capital in the 21st century*, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198703167.001.0001

Lutz, W., Muttarak, R., and Striessnig, E. (2014b). Universal education is key to enhanced climate adaptation. *Science*, *346*(6213), 1061–1062. https://doi.org/10.1126/science.1257975

Lutz, W., and Striessnig, E. (2015). Demographic aspects of climate change mitigation and adaptation. *Population Studies*, *69*(sup1), S69–S76. https://doi.org/10.1080/00324728.2014.969929

MacKellar, F. L., Lutz, W., Prinz, C., and Goujon, A. (1995). Population, households, and CO_2 emissions. *Population and Development Review*, *21*(4), 849–865. https://doi.org/10.2307/2137777

Madani, K. (2014). Water management in Iran: What is causing the looming crisis? *Journal of Environmental Studies and Sciences*, *4*(4), 315–328. https://doi.org/10.1007/s13412-014-0182-z

Madani, K., AghaKouchak, A., and Mirchi, A. (2016). Iran's socio-economic drought: Challenges of a water-bankrupt nation. *Iranian Studies*, *49*(6), 997–1016. https://doi.org/10.1080/00210862.2016.1259286

Malthus, T. R. (1798). *An essay on the principle of population*. History of Economic Thought Books, McMaster University Archive for the History of Economic Thought, number malthus1798.

Martin, N. (1999). *Population, households and domestic water use in countries of the Mediterranean Middle East* (Interim Report IR-99-032). International Institute for Applied Systems Analysis (IIASA) https://pure.iiasa.ac.at/id/eprint/5910/1/IR-99-032.pdf

McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T. Grill, G., and Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, *27*, 96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022

McLeman, R. (2010). Impacts of population change on vulnerability and the capacity to adapt to climate change and variability: A typology based on lessons from "a hard country". *Population and Environment*, *31*, 286–316. https://doi.org/10.1007/s11111-009-0087-z

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. (1972). *The limits to growth*. A Report For the Club of Rome's Project On the Predicament of Mankind. Universe Books, New York.

Meghir, C., Palme, M., and Simeonova, E. (2018). Education and mortality: Evidence from a social experiment. *American Economic Journal: Applied Economics*, *10*(2), 234–256. https://doi.org/10.1257/app.20150365

Mekonnen, M., and Hoekstra, A. Y. (2011). *National Water Footprint Accounts: The green, blue, and grey water footprint of production and consumption* (Value of Water Research Report Series No. 50). UNESCO-IHE, Delft, the Netherlands.

Mesgaran, M. B., and Azadi, P. (2018). A national adaptation plan for water scarcity in Iran. In *Working paper 6, Stanford Iran 2040 Project,* Stanford University, August 2018.

Ministry of Agriculture-Jihad of Iran. (2019a). *Agricultural statistics yearbook Volume 1 - Crops* (years 1993–2018). (In Persian), Tehran.
Ministry of Agriculture-Jihad of Iran. (2019b). *Agricultural statistics yearbook Volume II* (years 1993–2018). (In Persian), Tehran.
Ministry of Agriculture-Jihad of Iran. (2019c). *Agricultural statistics yearbook, volume three - horticultural products* (years 1993–2018). (In Persian), Tehran.
Ministry of Agriculture-Jihad of Iran. (2020a). *Review on harvest level and production rate statistics of crops*. (In Persian), Tehran.
Ministry of Agriculture-Jihad of Iran. (2020b). *Review on production process of Iranian protein products*. (In Persian), Tehran.
Ministry of Agriculture-Jihad of Iran. (2020c). *Agriculture Information Bank*. (In Persian), Tehran.
Ministry of Energy, Iran (2016). *Report of the International Conference on Water Security in Human Settlements*. Iran. Tehran: April 21–22, 2016. (In Persian), Tehran.
Ministry of Health and Medical Education of Iran. (2019). *National document of nutrition and food security (2013–2021)*. Report by the Community Nutrition Improvement Office and Work Environment Health Center, Ministry of Health and Medical Education of Iran. (In Persian), Tehran.
Mirzaie-Nodoushan, F., Morid, S., and Dehghanisanij, H. (2020). Reducing water footprints through healthy and reasonable changes in diet and imported products. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2020.04.002
Moridi, A. (2017). State of water resources in Iran. *International Journal of Hydrology*, *1*(4), 1, 111–114. https://doi.org/10.15406/ijh.2017.01.00021
Muenz, R. (2007). *Aging and demographic change in European societies: Main trends and alternative policy options* (Vol. 703). World Bank, Social Protection Advisory Service.
Muttarak, R., and Lutz, W. (2014). Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society*, *19*(1). https://doi.org/10.5751/ES-06476-190142
Nauges, C., and Whittington, D. (2010). Estimation of water demand in developing countries: An overview. *The World Bank Research Observer*, *25*(2), 263–294. https://doi.org/10.1093/wbro/lkp016
Octavianti, T., and Staddon, C. (2021). A review of 80 assessment tools measuring water security. *Wiley Interdisciplinary Reviews: Water*, *8*(3), e1516. https://doi.org/10.1002/wat2.1516
Ohlsson, L. (2000). Water conflicts and social resource scarcity. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *25*(3), 213–220. https://doi.org/10.1016/S1464-1909(00)00006-X
Pebley, A. R. (1998). Demography and the environment. *Demography*, *35*, 377–389. https://doi.org/10.2307/3004008
Plummer, R., de Loë, R., and Armitage, D. (2012). A systematic review of water vulnerability assessment tools. *Water Resources Management*, *26*, 4327–4346. https://doi.org/10.1007/s11269-012-0147-5
Postel, S. L. (2000). Entering an era of water scarcity: The challenges ahead. *Ecological applications*, *10*(4), 941–948. https://doi.org/10.1890/1051-0761(2000)010[0941:EAEOWS]2.0.CO;2
Rosegrant, M. W., Ringler, C., and Zhu, T. (2009). Water for agriculture: Maintaining food security under growing scarcity. *Annual review of Environment and Resources*, *34*, 205–222. https://doi.org/10.1146/annurev.environ.030308.090351
Saatsaz, M. (2020). A historical investigation on water resources management in Iran. *Environment, Development and Sustainability*, *22*(3), 1749–1785. https://doi.org/10.1007/s10668-018-00307-y
Scherbov, S., Sanderson, W. C., and Mamolo, M. (2014). Quantifying policy trade-offs to support aging populations. *Demographic Research*, *30*, 579–608. https://doi.org/10.4054/DemRes.2014.30.20
Saraei, H. (1998). Iran's demographic transition: Preliminary considerations. *Social Science Quarterly*. *5*(9). 1–18. https://dorl.net/dor/20.1001.1.17351162.1376.5.9.1.1 (In Persian).
Seidl, I., and Tisdell, C. A. (1999). Carrying capacity reconsidered: From Malthus' population theory to cultural carrying capacity. *Ecological Economics*, *31*(3), 395–408. https://doi.org/10.1016/S0921-8009(99)00063-4
Shah, T. (1998). Water against poverty: Livelihood-oriented water resources management. *Water Nepal*, *6*(1), 117–143.

https://doi.org/10.1553/p-gjfn-7z5k

Shah, T. (2007). The groundwater economy of South Asia: An assessment of size, significance, and socio-ecological impacts. *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*, 7–36. https://doi.org/10.1079/9781845931728.0007

Soltani, Z., Abbasi-Shavazi, M. J., Bagheri, A., and Koosheshi, M. (2019). The effect of demographic variables on the estimation of agricultural water consumption in Iran (2007–2014). *Journal of Population Association of Iran*, *14*(28), 171–204. (In Persian)

Soltani, Z., and Abbasi-Shavazi, M. J. (2022). Analysis of how the livelihood security of rural households is affected by crop area and cultivation patterns, to reduce water and livelihood risks in Iran. *Journal of Environmental Hazards*, *9*(2), pp. 169–187. (In Persian)

Statistical Center of Iran. (2007). *The results of the population and housing censuses of Iran in 2006*. https://amar.org.ir/

Statistical Center of Iran. (2012a). *The results of the population and housing censuses of Iran in 2011*. https://amar.org.ir/

Statistical Center of Iran. (2012b). *2% sample data of population and housing censuses in 2011*. https://amar.org.ir/

Statistical Center of Iran. (2014). *The results of the agricultural census of 2013*. https://amar.org.ir/

Statistical Center of Iran. (2015). *Detailed results of the national agricultural census of the entire country* - 2013. https://amar.org.ir/

Statistical Center of Iran. (2017a). *The results of the population and housing censuses of Iran in 2016*. https://amar.org.ir/

Statistical Center of Iran. (2017b). *2% Sample data of population and housing censuses in 2016*. https://amar.org.ir/

Statistical Center of Iran. (2017c). *Summary of the results of the labor force survey project*. https://amar.org.ir/

Statistical Center of Iran. (2019a). *Income and expenditure survey report*. https://amar.org.ir/

Statistical Center of Iran. (2019b). *Purchase price of agricultural products survey report*. https://amar.org.ir/

Statistical Center of Iran. (2021). *Population and household projection report*. https://amar.org.ir/

Stave, K. A. (2002). Using system dynamics to improve public participation in environmental decisions. *System Dynamics Review: The Journal of the System Dynamics Society*, *18*(2), 139–167. https://doi.org/10.1002/sdr.237

Stave, K. A. (2003). A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *Journal of Environmental Management*, *67*(4), 303–313. https://doi.org/10.1016/S0301-4797(02)00205-0

Stephenson, J., Crane, S. F., Levy, C., and Maslin, M. (2013). Population, development, and climate change: Links and effects on human health. *The Lancet*, *382*(9905), 1665–1673. https://doi.org/10.1016/S0140-6736(13)61460-9

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review: The Journal of the System Dynamics Society*, *18*(4), 501–531. https://doi.org/10.1002/sdr.261

Sullivan, C. (2002). Calculating a Water Poverty Index. *World Development*, *30*(7), 1195–1210. https://doi.org/10.1016/S0305-750X(02)00035-9

Sullivan, C. A., Meigh, J. R., and Giacomello, A. M. (2003). The Water Poverty Index: Development and application at the community scale. *Natural Resources Forum*, *27*(3), 189–199. https://doi.org/10.1111/1477-8947.00054

Tarlock, A. D. and Wouters, P. (2010). Reframing the water security dialogue. *Journal of Water Law*, *20*(2/3), 53–60. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2359854

Tehran Chamber of Commerce Industries, Mines and Agriculture. (2020). Export and import statistics dataset. https://service.tccim.ir/

Todaro, M. P. (1969). A model of labor migration and urban unemployment in less developed countries. *The American Economic Review*, *59*(1), 138–148.

UN-Water (2013). *Summary for decision-makers*. Available online: http://www.unwater.org/app/uploads/2017/05/water_security_summary_Oct2013.pdf.

UNESCO (2014). *IHP-VIII: water security: Responses to local, regional, and global challenges (2014–2021)*. https://unesdoc.unesco.org/ark:/48223/pf0000225103

United Nations Department of Economic and Social Affairs, Population Division. (2024). Iran (Islamic Republic of): Annual natural change and net migration. In “World Population Prospects 2024”. United Nations. Retrieved [07/24/2024], from [https://population.un.org/wpp/Graphs/DemographicProfiles/Line/364]

UNHCR. (2021). Operational Data Portal on the Afghanistan Situation. United Nations High Commissioner for Refugees. Available at ~https://data.unhcr.org/en/situations/afghanistan#:~:text=Refugee%20Situations,-COVID%2D19&text=The%20humanitarian%20situation%20inside%20Afghanistan,of%20origin%20since%20June%202021

Weeks, J. R. (2016). *Population: An introduction to concepts and issues* (12th ed.). Cengage Learning, Boston, MA, 461–468.

Wiedmann, T., and Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, *11*(5), 314–321. https://doi.org/10.1038/s41561-018-0113-9

World Bank (2001). World Development Report 2000/2001: Attacking Poverty. Ravi Kanbur and Nora Lustig (Eds). https://documents1.worldbank.org/curated/en/230351468332946759/pdf/World-development-report-2000-2001-attacking-poverty.pdf

World Economic Forum. (2016). *The global risks report* (11th ed.). World Economic Forum. https://reports.weforum.org/global-risks-2016/

World Water Assessment Programme (2009). *The United Nations world Water Development Report 3: Water in a changing world*. Paris: UNESCO, and London: Earthscan.

Wye Group (2011). *Statistics on rural development and agricultural household income*. Food and Agriculture Organization of the United Nations (FAO). Available online: https://catalogue.unccd.int/532_am087e.pdf

Wyman, R. J. (2013). The effects of population on the depletion of fresh water. *Population and Development Review*, *39*(4), 687–704. https://doi.org/10.1111/j.1728-4457.2013.00634.x

https://doi.org/10.1553/p-gjfn-7z5k