International Journal of Agricultural Management and Development
Available online on: www.ijamad.iaurasht.ac.ir
ISSN: 2159-5852 (Print)
ISSN:2159-5860 (Online)
Research Paper

Modeling of Climate Change Effects on Groundwater Resources: The Application of Dynamic Systems Approach

Mostafa Teimoori [a], Sayed Mehdi Mirdamadi [b], Sayed Jamal F Hosseini [c]*

Received: 05 October 2017,
Accepted: 13 August 2018

Abstract

The purpose of the present study was the simulation of climate change effects on groundwater resources in Iran by using the dynamic systems approach. The approach was performed through system dynamics modeling process including problem explanation, system description, model development, model testing, and the use of the model for policy analysis. The impact of the application of various exogenous scenarios including drought scenarios, management of water supply and population growth was assessed and the behavior of variables of water resources volume and per capita volume of renewable water of the Southern Khorasan Province was simulated by Vensim software for the 2013-2041 period. Data were collected by referring to relevant organizations like South Khorasan Regional Water Organization, South Khorasan Agricultural Organization, and Statistical Center of Iran and the input data of the model were fed into the model in an Excel worksheet. The results showed that the water resource exploitation management scenario had a significant positive effect on the balance of aquifers of South Khorasan Province so that the balance of the province aquifers in the scenario of controlling water resources exploitation has been significantly different from the scenario of the lack of control of different drought in all the studied years. In addition, the results of examination of the province's renewable water showed that droughts have had a negative impact on the volume of renewable water of the province and droughts together with population growth have reduced the province per capita renewable water.

Keywords:
Virtual water, agricultural sector, water resource management, simulation, Hirmand Catchment

[a] Department of Rural Development, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Department of Agricultural Extension and Education, Science and Research Branch, Islamic Azad University, Tehran, Iran
[c] Department of Agricultural Extension and Education, Science and Research Branch, Islamic Azad University, Tehran, Iran
* Corresponding author's email: m.teimoori1982@yahoo.com

INTRODUCTION

It is clear that some degree of climate change during the next century is now inevitable (Dessai et al., 2005). Climate change and droughts are recognized as an environmental disaster and have attracted the attention of environmentalists, ecologists, hydrologists, meteorologists, geologists, and agricultural scientists (Mishra & Singh, 2010). Rural communities in the developing world are at high risk from climate change, and adaptation has become crucial in developing sustainable livelihoods (Parry, 2009; Smith and Wandelm, 2006; Sapkota et al., 2016). Water scarcity has been frequently occurring these days in many parts of the world, partly because water demand has increased manifold due to the growth in population and expansion of agricultural, energy and industrial sectors, and partly because of climate change and contamination of water supplies (Bates et al., 2008; Mishra and Singh, 2011). Due to increasing population growth over the last decades, governments have emphasized more exploitation of water resources in order to meet the increasing water demand. They have tried to supply water resources in response to growing demand (Radif, 1999). On the other hand, the annual accessible water in the world is just 2001 m^3 that is predicted to decrease to the critical level of 1700 m^3 in next two decades (Ratnakar & Govardhan, 2006). Global statistics show that in the near future, many parts of the world will encounter water scarcity and it is believed to be the biggest problem in the world. The year 2003 is named as 'freshwater global year' implying the importance of sustainable optimum use of this precious resource. The growing population has raised water demand, making the problem of water scarcity worse; besides, the volume of accessible freshwater is decreasing (Nuruzi and Chizari, 2006).

Iran is a developing country, located in a dry and semi-dry region, and face water scarcity problem. It has been indicated that the total volume of reproducible water resources in Iran is 88.5 billion m^3 of which 93.5 percent, i.e. 83 billion m^3, is consumed by the agricultural sector, 4.5 billion m^3 is utilized for the domestic and drinking uses, and the rest is consumed by industries and other sectors (Keshavarz & Sadeghzadeh, 2000). According to the criteria of the International Water Management Institute (IWMI), Iran confronts intensive water crisis (Ehsani & Khaledi, 2003).

Besides natural water scarcity, another challenge in dry countries like Iran is water resource management and optimum utilization. Due to the decline of precipitation and the frequent droughts in recent years, it is necessary to optimize water consumption as well as research on the application of proper techniques for favorable water management in order to decrease the negative impacts of drought. Improving agricultural water productivity, food security, and sustainable supply of food requires increasing water consumption efficiency, refining management structure, and optimizing water utilization (Kijne, 2001). Droughts impact both surface and groundwater resources and can lead to reduced water supply, deteriorated water quality, crop failure, reduced range productivity, diminished power generation, disturbed riparian habitats, and suspended recreational activities; as well, they affect a host of economic and social activities (Riebsame et al., 1991). Droughts also affect water quality as moderate climate fluctuations can alter hydrologic regimes with substantial effects on lake chemistries (Webster et al., 1996). Sediments, organic matters, and nutrients are transported to surface waters by runoff, a pathway that is interrupted during droughts (Mishra & Singh, 2010).

These changes can result in over-farming, degradation of land resources, and increased pressure on wild species and exposure to zoonotic diseases (Fields, 2005). Globally, climate policies of developed nations including increased reliance on biofuels may have a detrimental impact on staple food markets and consequently, the nutrient needs of already malnourished populations (Boddiger, 2007; Hahn et al., 2009). One of the key features of vulnerability is its dynamic nature that may change as a result of changes in the biophysical as well as the socioeconomic characteristics of a particular region (Adger & Kelly, 1999). Hence, vulnerability assessments should be ongoing processes in order to highlight the spatial and temporal scales of the vulnerability of a region (Luers, 2005; Antwi-Agyei et al., 2012).

The province of Southern Khorasan, which has an arid and semi-arid climate, has been suffering from more severe droughts in recent years. This has impaired the income of the rural households, made their living conditions more undesirable, and trapped more rural households in poverty (Teimoori et al., 2014). Regarding the importance of agriculture in the development of the province, the high dependence of agriculture on water, and the optimal management of water, the findings can provide the authorities and policymakers with strategies to improve local agriculture and access to sustainable rural development.

MATERIALS AND METHODS

System dynamics (SD) has a long history as a modeling paradigm. Its origins can be sought in the work of Forrester (1961), who developed it to provide an understanding of strategic problems in complex dynamic systems. By giving insight into feedback processes, SD models provide system users with a better understanding of the dynamic behavior of systems (Teimoori, 2014).

In an SD context, the models are applied to problems where the issue can be represented as a problematic trend over time. As with any problem-solving process, this is an iterative process. Results at any stage can be fed back into the previous steps. For example, step 4 that builds confidence in the model may require iteration back to step 2 to refine the system description. Only by the first five steps, one may be able to build a model for decision support within an organization. The application of the model for public communication is composed of six steps:

1. Define the problem
2. Describe the system
3. Develop the model
4. Build confidence in the model
5. Use the model for policy analysis
6. Use the model for public outreach (Stave, 2003).

The SD approach is based on the theory of feedback processes. A feedback system is influenced by its own past behavior (Teimoori, 2014).

For this purpose, the required data was collected from database of related organizations like South Khorasan Regional Water Organization, South Khorasan Agricultural Organization, and Statistical Center of Iran and was analyzed using MS-Excel, SPSS and Vensim Software packages and the behavior of the desired variables from 2005 to 2041 were simulated and represented in different figures.

RESULTS AND DISCUSSION

Define the problem

The first step is to identify one or more key variables whose behavior over time defines the problem. The graph of these indicator variables is used as a reference graph in step 4 to test whether the model adequately represents the system generating the problem (Stave, 2003), SD focuses on investigating or modeling a specific problem rather than investigating the whole system guiding participants to identify and agree on the goal of the process by answering the question: What is the problematic behavior or behaviors we are trying to change it (Stave, 2002). Rainfall volume in South Khorasan Province from 1995 to 2012 shows a significant decrease so that rainfall that was about 210 mm in 1995 declined to 100 mm in 2012, implying 37% reduction in precipitation.

Describe the system

Describing a system means identifying the system structure that appears to be the source of a problematic trend. This involves extracting essential elements and connections from the real system that produces the observed or anticipated behavior. The final representation of key variables and causal links is called dynamic hypothesis; *i.e.,* the structure that is thought to explain the dynamic behavior in question. This structure serves as the basis for creating the simulation model (Stave, 2003).

Dynamic hypothesis

Modeling has emerged as a key technology for visualizing and anticipating the processes and impacts of climate change and climate variability on agricultural production systems. Combinations of General Circulation Models, Regional Circulation Models, crop models, soil models, agro-ecological system models, and economic models have been used to illustrate potential impacts of climate change in the coming decades based on various climate scenarios (Lahsen, 2005; Thornton et al., 2010). The Causal Loop Diagram of the research based on the model's subsystems is presented in Figure 1.

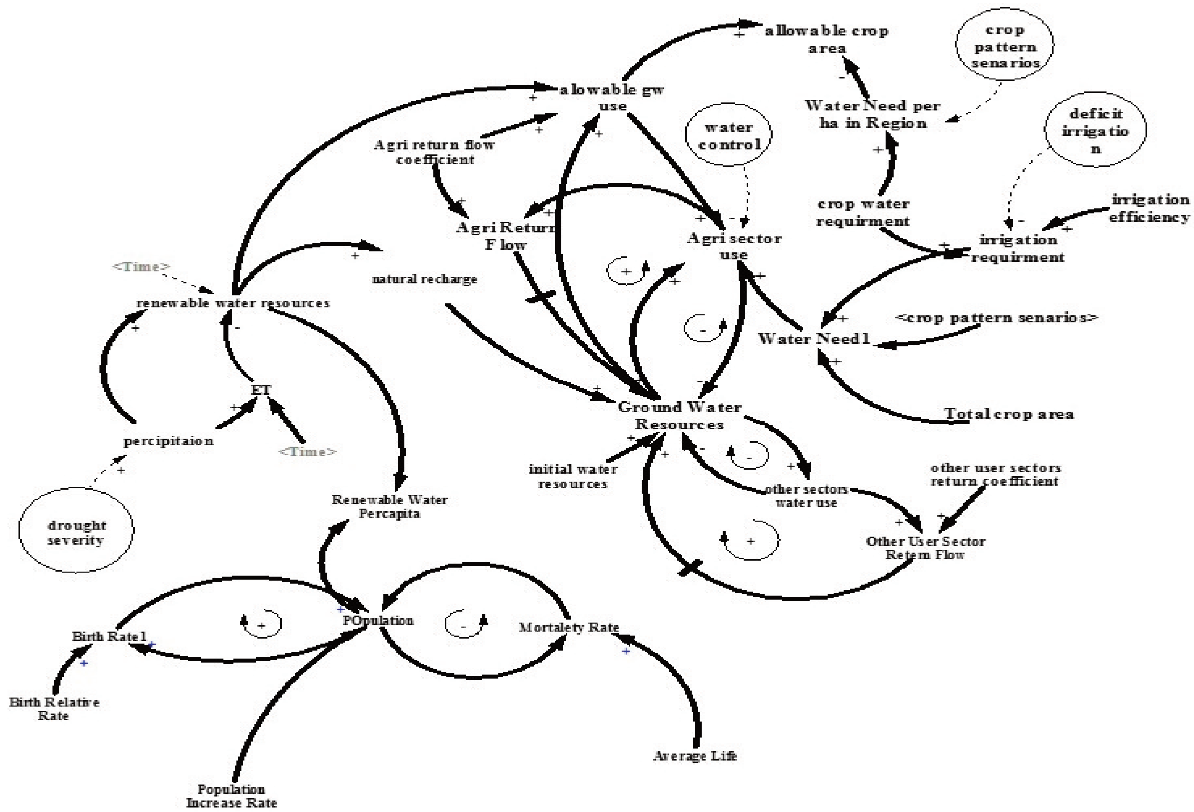

Figure 1. Causal loop diagrams

Develop the model

In the model development stage, the dynamic hypothesis is represented as a set of stocks and information flows (Stave, 2003), The Stock and Flow Diagram of the research is depicted in Figure 2.

Build confidence in the model

Before using the model to identify and test policy options, it must be validated against the observed or anticipated trend. If the model reproduces the problematic trend and represents the system as stakeholders understand the real system actually works, we assume that the model contains the critical elements generating the problem. If it does not reproduce the reference graph, the modelers must go back to the second step to revise the dynamic hypothesis or model structure (Stave, 2003). In order to validate the model, the observational and estimated data of the volume of groundwater resources are compared whose results are illustrated in Figure 3 that indicates the accuracy of the model's performance.

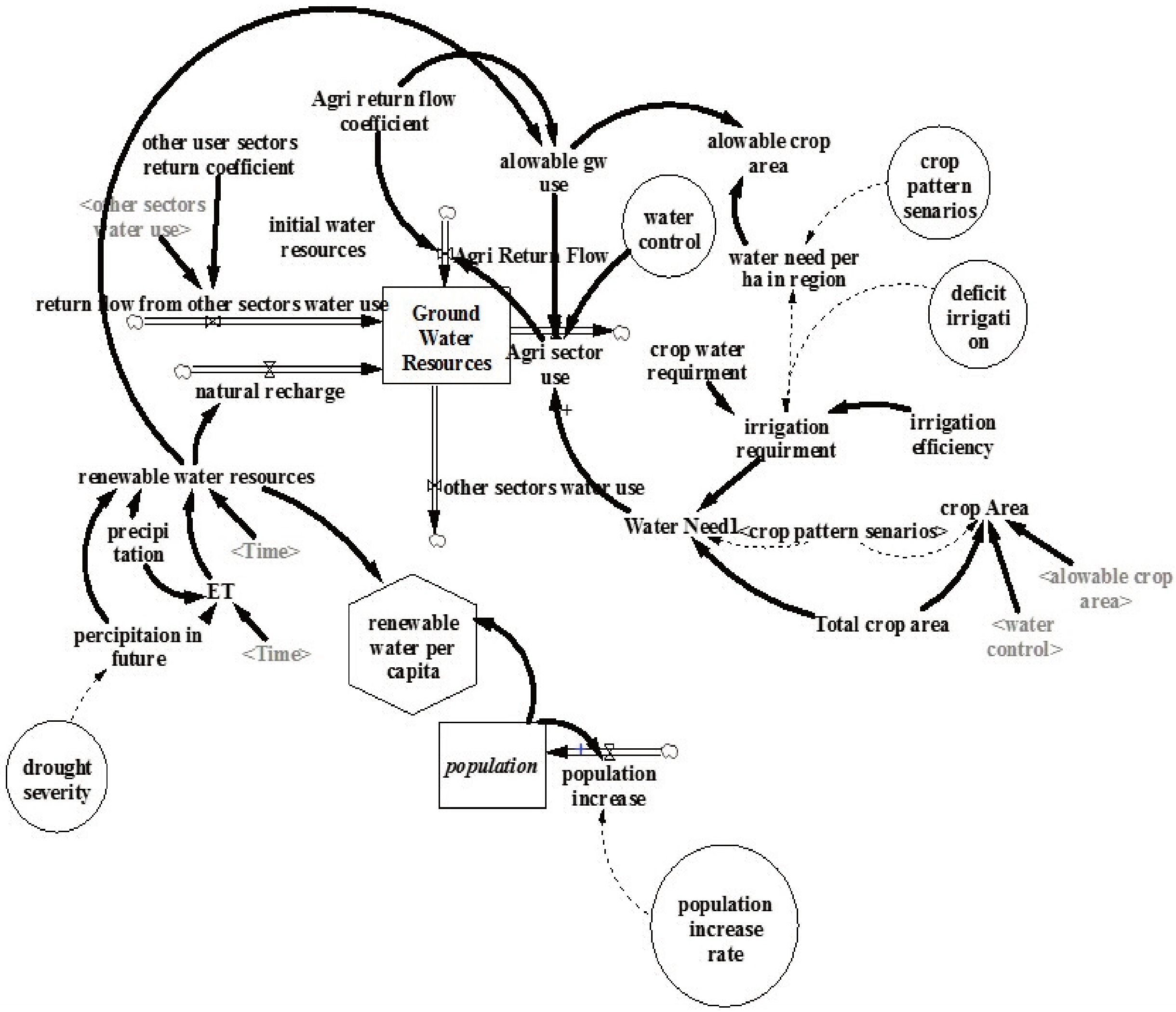

Figure 2. Stock and flow diagram

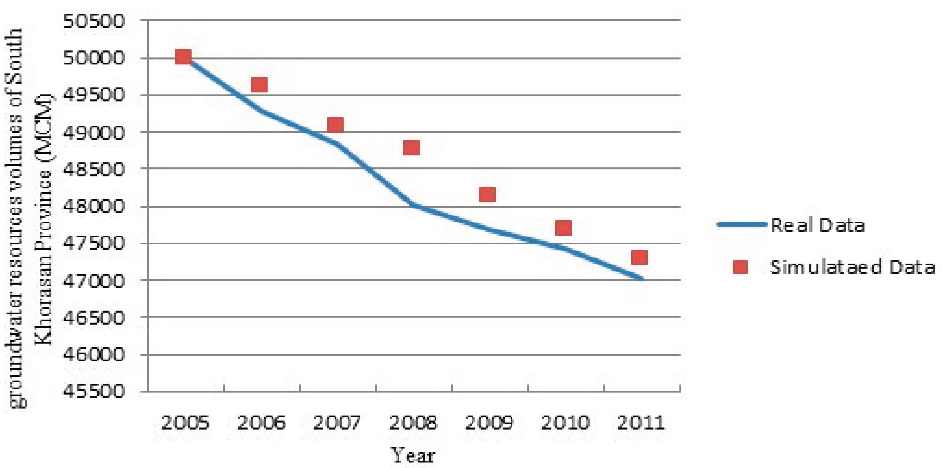

Figure 3. The Validation of the model against the real and simulated data of groundwater resources volumes

Also, independent t-test was used to compare real data and simulated data of the studied variables. The results are presented in Table 1. Accordingly, there is no significant difference between real data and simulated data of variables of groundwater resources volumes in South Khorasan Province as per the statistics.

Table 1
The Comparison of Real Data and Simulated Data of Variables of Groundwater Resources Volumes in South Khorasan Province as per the Statistics.

Variables	Mean	t	*P*-value
Real data of variables of groundwater resources volumes	48196	-0.850	0.468[ns]
Simulated data of variables of groundwater resources volumes	48651		

ns= non significant

Use the model for policy analysis

When the model structure has been validated, it can be used to test the effect of policy interventions on the problem. This includes studying the model structure to identify policy levers followed by the simulation of the effect of those changes (Stave, 2003).

In this regard, given the inevitable effects of drought on groundwater resources, the effects of various scenarios of drought including normal drought (severity normal), 20% increase in drought severity (severity 20%), 30% increase in drought severity (severity 30%), 40% increase in drought severity (severity 40%) in terms of control and lack of control over the exploitation of water resources, over balance of the aquifer and per capita renewable water of South Khorasan Province in various scenarios of population including reduced fertility (1.3 child) (population scenario 1 (ps1)), stabilization of fertility (1.8 child) (population scenario 2 (ps2)), rising to the level of substitution (2.1 person) (population scenario 3 (ps3)) and exceeding the level of substitution (2.5 person) (population scenario 4 (ps4)) from 2013 to 2041 were simulated.

Volume of groundwater resources

Figures 4 and 5 show the effect of drought scenarios on water supply management (controlled and uncontrolled exploitation of these resources), in cropping pattern and irrigation conditions and investment on the present situation, on the balance of the province aquifers. As is evident in Figure 4, if the current conditions of farming continue, droughts increase in severity, and no control is exercised over the exploitation of water resources, the decline of aquifer volume under the drought scenarios will be aggravated, and the increased severity of droughts will accelerate the decline of the aquifer level because, in more severe droughts, farmers exploit groundwater resources without restrictions to meet their water requirement, putting more pressure on groundwater resources, whereas the recharge rates of aquifers are reduced due to the reduced level of rainfall in these more severe drought conditions.

Aquifer size of the province under different drought scenarios and under the control of exploitation (Figure 5) indicates that in this case, the reduced size of the aquifer has been following an increasing trend because, in these conditions, the utilization rate of the agriculture sector has been controlled, but it has not been practiced in other sectors like domestic, industrial, etc. and these sectors have unrestrictedly used groundwater resources.

Also, the comparison of the volume of groundwater resources in droughts of varying severity in Figure 6 is considerable and shows that the volume of groundwater resources in more severe droughts will be greater in the 2041 outlook because the amount of renewable water of the province will decrease as droughts grow in severity (Figure 6). As a result, the amount of the allowable exploitation of groundwater resources by farmers has been reduced too. This shows that the decreased level of over-exploitation of the renewable groundwater resources (36% of surface sources), resulting in the improvement of water resources in the more severe droughts.

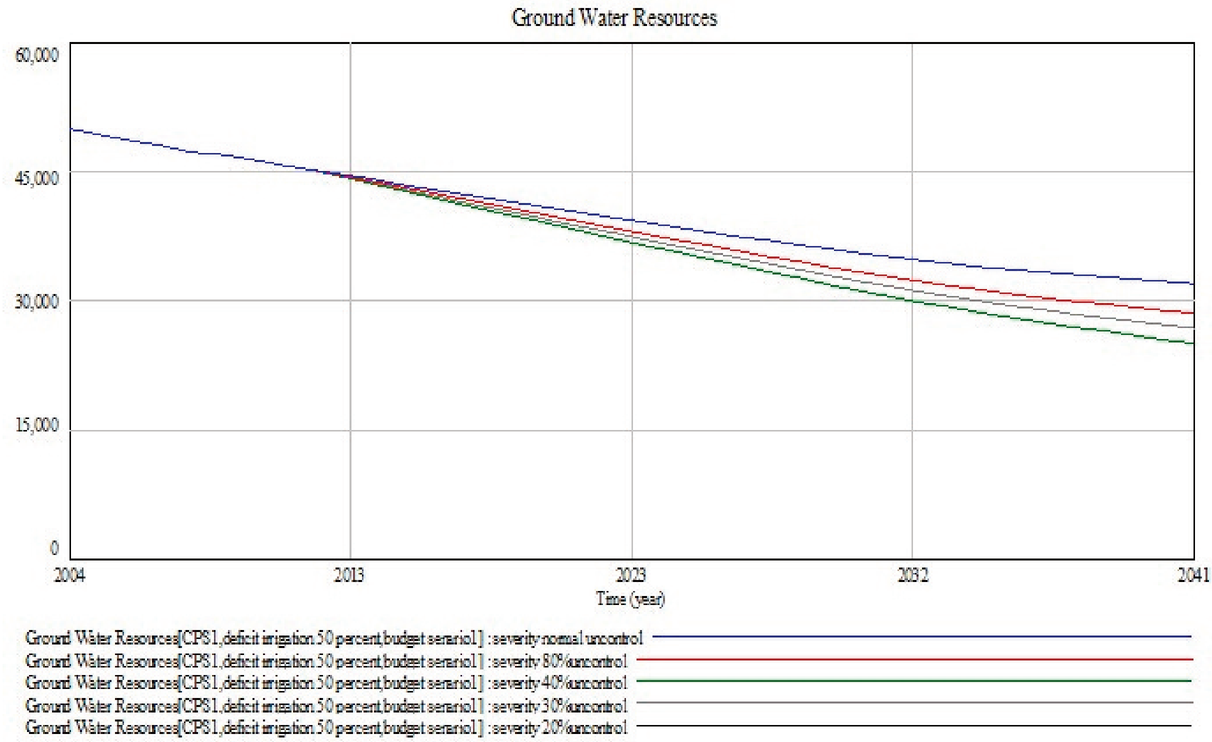

Figure 4. The effect of drought scenarios under control over exploitation of water resources on cropping patterns and irrigation status quo on balance of the province aquifers (MCM)

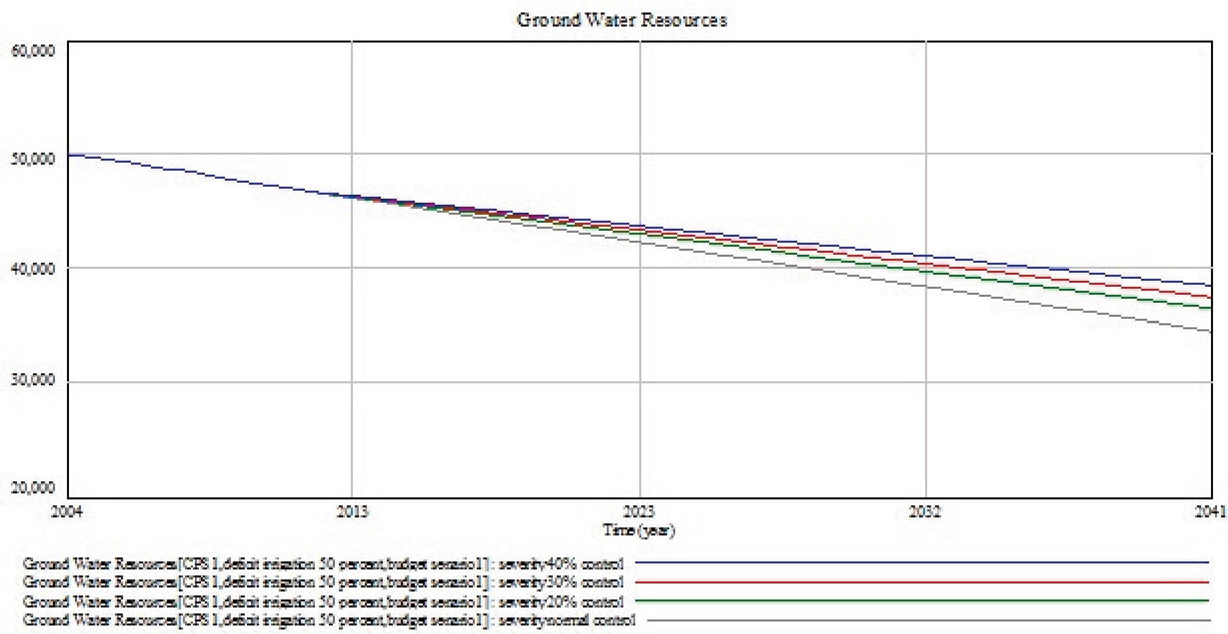

Figure 5. The effect of drought scenario with no control over exploitation of water resources on cropping patterns and irrigation status quo on balance of the province aquifers (MCM)

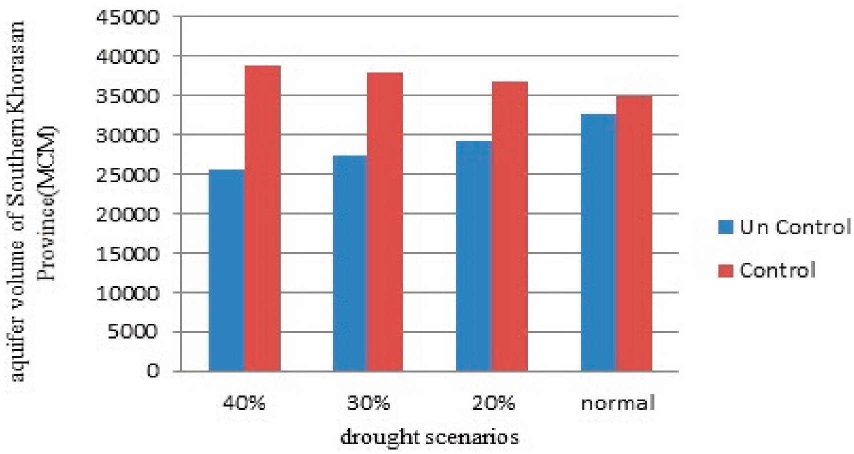

Figure 6. The effect of drought scenarios under control non- control over the exploitation of water resources of the province in the outlook of 2041

Population

Population growth of the province based on growth scenarios presented by Statistical Center of Iran [including reduced fertility (1.3 children), stabilization of fertility (1.8 children), rise to the level of substitution (2.1 persons) and increase more than the level of substitution (2.5 persons) were simulated up to 2041 and the results are shown in Figures 7 and 8. The simulation results show that the population growth in South Khorasan Province in all the studied scenarios up to 2041 has followed an increasing trend and among the different scenarios, the rate of population growth in the fourth scenario (increase more than the level of substitution) was higher. In contrast, the first scenario (reduced fertility, 1.3 children) had the lowest growth. Figure 8 also shows that in case the fourth scenario is applied, the population growth in South Khorasan Province in the 2014 outlook equals 866,708 people and in case the first scenario is applied, the province population will be 773,045. Also, the province population in the two scenarios of stabilization of fertility (1.8 children) and rise to the level of substitution (2.1 persons) will be 806,954 and 833,331, respectively.

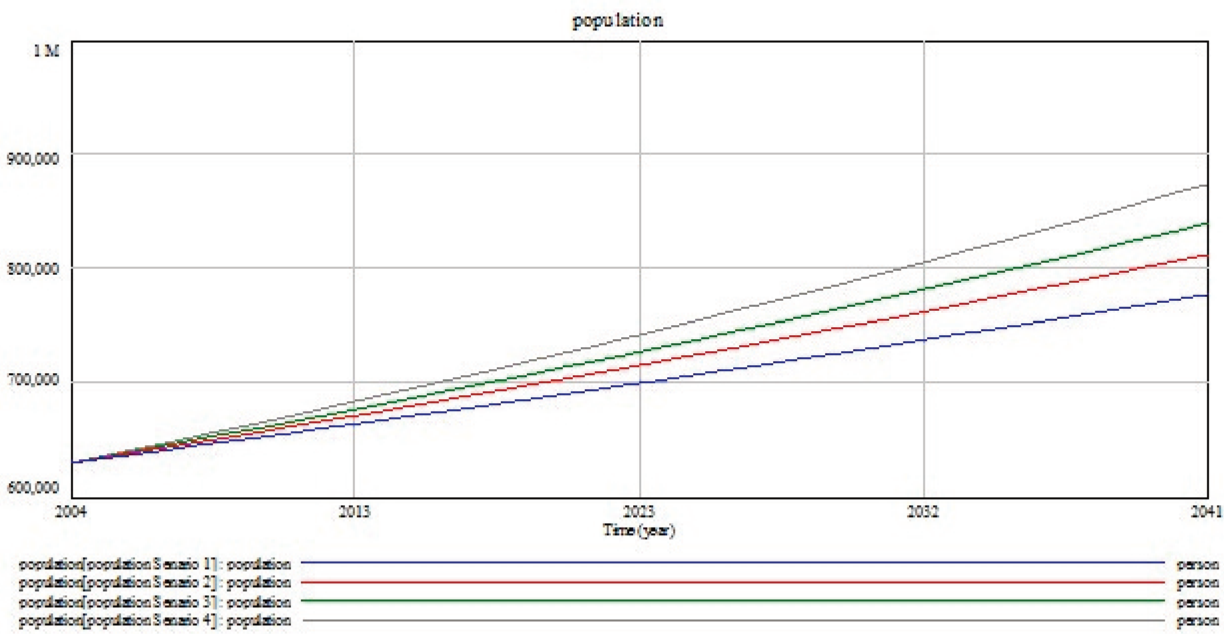

Figure 7. The rate of population growth of the province based on the population growth scenarios

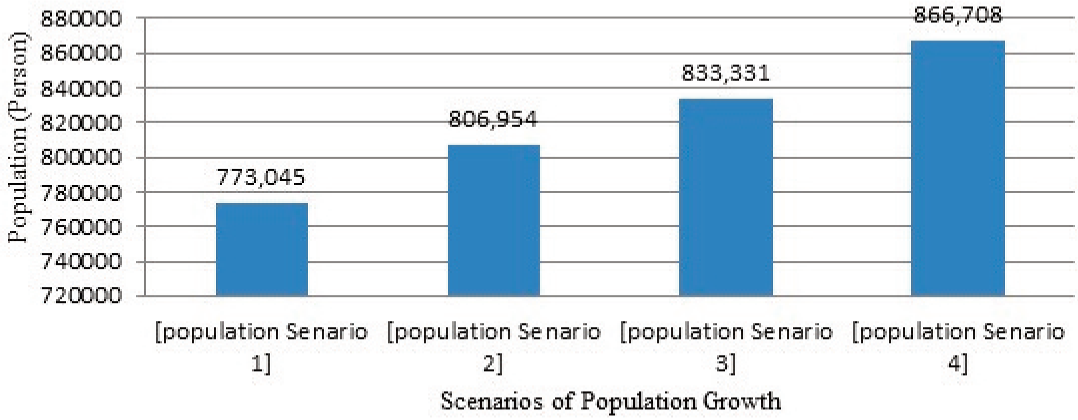

Figure 8. The province population in 2014 outlook based on the scenarios of population growth

Renewable water

A review of the variations of per capita renewable water in scenarios of population growth in South Khorasan Province shows that in the simulated years, given drought and population growth, the trend of per capita renewable water of the province was descending and per capita renewable water has declined with the increase in population (Figure 9).

Also, the changes in per capita renewable water in different scenarios of drought under the current population growth rate are significant (Figure 10). The figure shows that per capita renewable water was lower in more severe droughts.

The comparison of per capita renewable water at present and in the 2041 outlook in different scenarios of drought and population growth is presented in Figure 11. Accordingly, in all scenarios of drought and population, per capita renewable water in 2041 will significantly differ from that of the year 2011 and this can challenge policies of population growth.

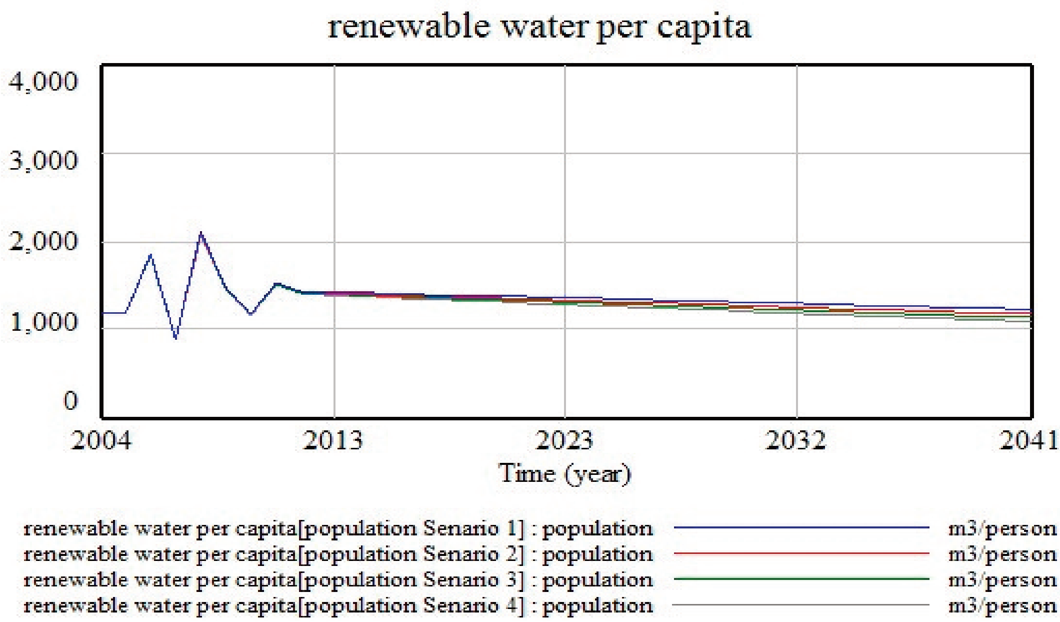

Figure 9. The variations in per capita renewable water in population growth scenario in drought-normal scenarios

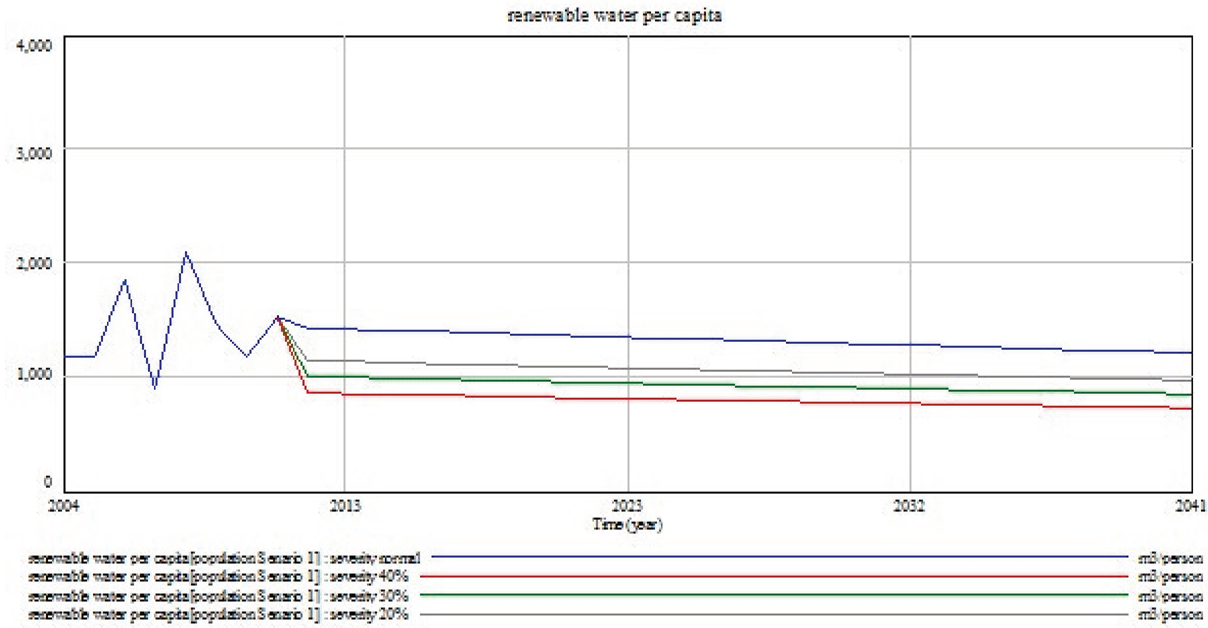

Figure 10. The variations in per capita renewable water in drought scenarios while maintaining the current population growth rate

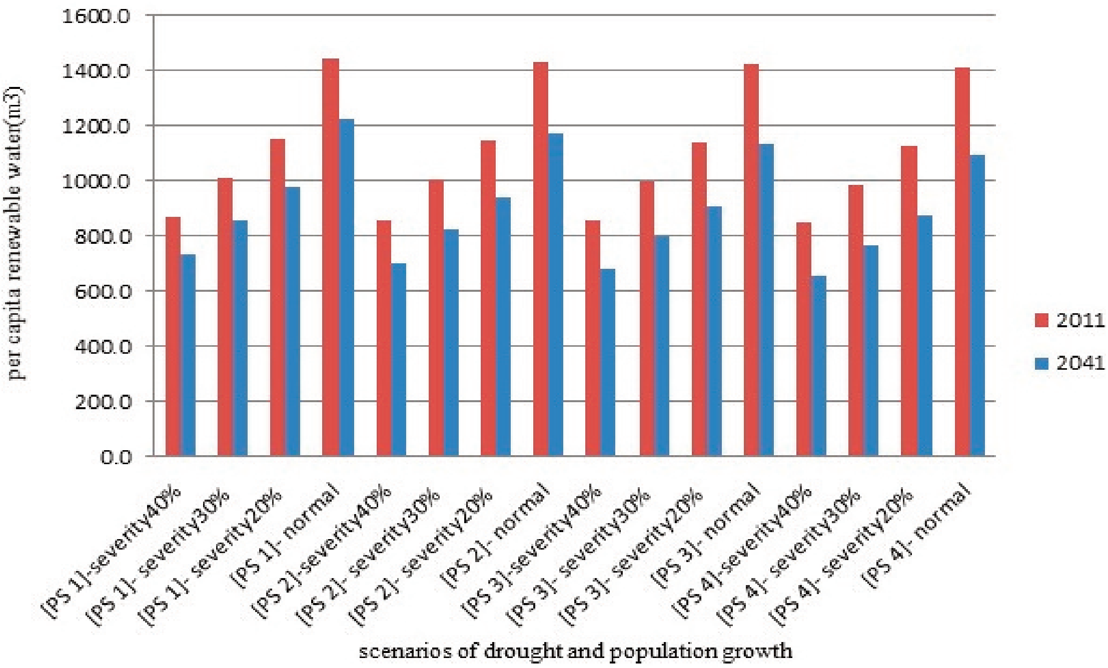

Figure 11. Per capita renewable water at present and in the 2041 outlook under different drought and population growth scenarios

CONCLUSION AND RECOMMENDATIONS

The research findings reveal that if droughts grow in severity in the coming years, but no change happens in the current agricultural practices in agriculture of South Khorasan Province in terms of cropping patterns, low irrigation, rate of development of pressurized irrigation systems, and lack of control over exploitation of water resources, droughts will have negative effects on the volume of groundwater resources because in these conditions, farmers will compensate the shortage of rainfall by further extraction of groundwater resources, and the adverse impacts of drought will appear at the level of groundwater resources.

Also, the application of the scenario of control over the exploitation of water resources in normal drought conditions suggests that in the drought conditions, control over exploitation of water resources has prevented the depletion of groundwater because, in these conditions, farmers would be able to adapt with drought and manage available water with higher efficiency. So, it could be stated that in case the current situation of South Khorasan (normal drought) continues, exercising the scenario of control over the exploitation of water resources will be helpful because, in these conditions, farmers will be able to compensate the shortage of water by optimal management.

But assuming 20% more severe drought, the application of the scenario of control over exploitation of water will restrict farmers' exploitation of the groundwater resources, and this will reduce the rate of groundwater balance loss and this will lead to improvements in aquifer volume of the province.

The results of studying the province renewable water show that droughts have had a negative impact on the volume of renewable water so that the volume of renewable water has reduced as droughts have become more severe. However, droughts with increased rates of the population have reduced per capita renewable water of the province.

The comparison of per capita renewable water at present and in the 2041 outlook in different scenarios of drought and population growth indicates that in all scenarios of drought and population, per capita renewable water in 2041 will have significant difference from that in 2011 and given the importance of water for human life, renewable water scarcity can act as a barrier to population growth and challenge policies of population growth.

Given the dramatic effect of exercising scenario of control over the exploitation of water resources on the volume of the province groundwater, it can be said that this scenario in drought conditions of South Khorasan Province can act as an efficient policy and be functional in this condition. So, it can be inferred that the scenario of control over the exploitation of water resources is an effective solution to the existing situation of groundwater and its management.

ACKNOWLEDGEMENTS

Authors would like to thank all participants in this research who contributed to achieving the intended objectives and purposes.

REFERENCE

Adger, W. N., & Kelly, P. M. (1999). Social vulnerability to climate change and the architecture of entitlements. *Mitigation and Adaptation Strategies for Global Change, 4*(3-4), 253-266.

Antwi-Agyei, P., Fraser, E.D.G., Dougill, A.J., Stringer, L.C., & Simelton, E. (2012). Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data. *Applied Geography, 32*, 324-334.

Bates, B., Kundzewicz, Z.W., Wu, S., & Palutikof, J. (2008). Climate change and water, Technical Paper of the Intergovernmental Panel on Climate Change, IPCC, Secretariat, Geneva, 210 pp.

Boddiger, D. (2007). Boosting biofuel crops could threaten food security. *Lancet, 370*, 923–924.

Dessai, S., Lu, X., & Risbey, J. S. (2005). On the role of climate scenarios for adaptation planning. *Global Environmental Change, 15*(2), 87–97.

Ehsani, M., & Khaledi, H. (2003). *Productivity of agriculture water, National Committee of Irrigation & Drainage in Iran*. Tehran, Iran (In Persian).

Fields, S. (2005). Why Africa's climate change burden is greater. *Environmental Health Perspectives, 113*, A534–A537.

Forrester, J. W. (1961). *Industrial Dynamics*. MIT Press, Cambridge, MA. Gagnon, B., G.

Keshavarz, A., & Sadeghzadeh, Z.W. (2000). *Water Use Management in Agriculture.* Agricultural Engineering Research Institute Tehran. (In Persian).

Hahn, M.B., Riederer, A.M. & Foster, S.O. (2009). The Livelihood Vulnerability Index: A Pragmatic Approach to Assessing Risks from Climate Variability and Change: A Case Study in Mozambique. *Global Environmental Change, 19*, 74-88.

Kijne, J.W. (2001). Lessons learned from the change from supply to demand water management*. Water Policy, 2,* 109-123.

Lahsen, M. (2005). Seductive simulations? Uncertainty distribution around climate models. *Social Studies of Science, 35*, 895-922.

Luers, A.L. (2005). The surface of vulnerability: an analytical framework for examining environmental change. *Global Environmental Change, 15,* 214-223.

Mishra, A.K., & Singh, V.P. (2010). A review of drought concepts. *Journal of Hydrology 391*, 202–216.

Mishra, A.K., & Singh, V.P. (2011). Drought modeling – A review. *Journal of Hydrology, 403*, 157–175.

Nuruzi, A., & Chizari, M. (2006). Factors affecting the acceptance of sprinkler irrigation in Namavand. *Agricultural Economy and Development, 5*, 23-29. (In Persian).

Parry, M. (2009). Climate change is a development issue, and only sustainable development can confront the challenge. *Climate and Development, 1*(1), 5-9.

Radif, A. (1999). Integrated water resource management (IERM). *Desalination, 124*, 145-153.

Ratnakar, R., & Govardhan, D.S. (2006). Participatory irrigation management the AP-WELL project: INDO-DUTCH teamwork. [On-line] retrieved from http://www.aiaee.org/2006/Accepted/555.pdf.

Riebsame, W.E., Changnon, S.A., Karl, T.R. (1991). *Drought and Natural Resource Management in the United States: Impacts and Implications of the 1987–1989 Drought*. Westview Press, Boulder, CO, p. 174.

Sapkota, P., Keenan, R.J., Jana-Axinja Paschen, J. A., & Ojha, H. R. (2016). Social production of vulnerability to climate change in the rural middle hills of Nepal. *Journal of Rural Studies, 48*, 53-64.

Smith, B., & Wandelm, J. (2006). Adaptation, adaptive capacity and vulnerability**.** *Global Environmental Change, 16*(3), 282-292.

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*, 303–313.

Stave, K.A., (2002). Using system dynamics to improve public participation in environmental decisions. *System Dynamics Review, 18*(2), 139–167.

Teimoori, M., Mirdamadi, S.M., Farajollah hosseini, S. J., Rahimi Sourah, S., & Afshar Kazmi, M.A. (2014). Survey of Poverty Line- Vulnerability of Rural Households and the Determining factors in the Province of Southern Khorasan, Iran. *International Journal of Plant, Animal and Environmental Sciences*, *4*(3), 395-402.

Teimoori, M. (2014). *Modeling of vulnerability reduction scenarios of South Khorasan Province farmers against drought using dynamic systems approach*. Published thesis, Department of Agricultural Development, Islamic Azad University, Science and Research Branch. Pp.51.

Thornton, P.K., Jones, P.G., Alagarswamy, G., Andresen, A., Herrero, M. (2010). Adapting to climate change: agricultural system and household impacts in East Africa. *Agricultural Systems, 103,* 73–82.

Webster, K.E., Kratz, T.M., Bowser, C.J., & Adagnuson, J.J. (1996). The influence of landscape position on lake chemical responses to drought in Northern Wisconsin. *Limnol. Oceanog*r, *41*(5), 977–984.

How to cite this article:

Teimoori, M., Mirdamadi, S.M., & Hosseini, S.J. (2019). Modeling of climate change effects on groundwater resources: the application of dynamic systems approach. *International Journal of Agricultural Management and Development, 9*(2), 107-118.

URL: http://ijamad.iaurasht.ac.ir/article_665021_cb4384bc056751920a6e96d34ab8e64e.pdf