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Role of knowledge in water crisis management: A Bayesian network model approach

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Abstract

Water is the most critical natural resource in the world and one of the scarce inputs of the agriculture sector in arid and semi-arid areas, including Iran. Consecutive droughts, lower groundwater levels, and lower water quality are among the concerns of farmers and policymakers in Iran. Therefore, the impacts of various factors, including the knowledge-based economy index on the water crisis in Iran were investigated. We applied the Bayesian Network for modeling water crisis management. In doing so, we identified the key factors related to water crisis management using the U.N. indicators. The composite index of the knowledge-based economy was calculated using knowledge assessment methodology. The results of the U.N. indicator indicated that Iran is in a state of severe water crisis. The modeling results showed that advances in the knowledge-based economy index could alleviate the water crisis. Also, we found that increased economic growth could exacerbate the water crisis. Sensitivity analysis showed that drought has the most significant impact on the water crisis. Therefore, planning and policymaking to advance the various components of the knowledge-based economy and moving towards sustainable development can help manage the water crisis. The components of the knowledge-based economy comprised innovation, knowledge and human resources, information and communication infrastructures, and economic incentives and institutional regimes.

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Introduction

Water is an essential natural resource in the world that plays a vital role in the ecosystem and the development of countries (Rosegrant et al., 2009; Duarte et al., 2013; Zhang et al., 2020). The development of water resources is crucial for food security around the world (Rosegrant et al., 2002). The agriculture sector is the largest user of water in the world. According to the statistics provided by the United Nations Food and Agriculture

Organization (FAO), almost 70% of the global water withdrawal belongs to the agriculture sector (AQUASTAT, 2016).

Coping with water shortage has always been a major challenge in arid and semi-arid climates (Mokhtari et al., 2019). Iran is located in the hot and dry region of the world (Taheri et al., 2019). According to the long-term mean, rainfall in this country is about 403 billion cubic meters, about 70% of which is out of reach due to evapotranspiration and is virtually unavailable. The remaining 30% is equivalent to 130 billion cubic meters of water potential of the country, and all planning should be based on this amount (Ashofteh and Vojdanifard, 2015). Iran is widely exposed to the drought phenomenon (Abbasi et al., 2019). Drought affects human life, water resources, and agricultural sectors (Koohi et al., 2021). Droughts finally lead to a socio-economic crisis (Surendran et al., 2019). Thus, in areas where droughts occur, access to water becomes a major concern for local residents and government officials (Craig et al., 2019). The agriculture sector accounts for almost 92 percent of the total water use in Iran (AQUASTAT, 2004). Consecutive droughts have caused excessive exploitation of groundwater resources. The reduction of groundwater levels and the quality of water used in agriculture has caused political, cultural, and socio-economic concerns (Mokhtari et al., 2019). Therefore, policies have been adopted by Iranian policymakers to use this scarce resource optimally. Thus, in accordance with Article 35 of the Sixth Five-Year Economic, Social and Cultural Development Plan Act of the Islamic Republic of Iran, the government is obliged to deal with the water crisis and sustainability, increase production in the agriculture sector, balance the aquifers, increase productivity and restore water balance during 2017-2021 through two important steps:

1) Increase productivity of crops with competitive potential, high export value, low water requirement, and low salinity and drought-tolerant cultivars and adherence to appropriate cropping patterns and
2) Develop new irrigation methods (Plan and Budget Organization, 2017).

Many researchers believe that economy knowledge is one of the most important ways to solve the social, economic, technological, and political challenges that societies face, and knowledge in the economy is a major factor of production and economic growth (Popov and Kochetkov, 2019). In Iran, knowledge-based economy has attracted the attention of policymakers, in recent years. So, in the vision of the Islamic Republic of Iran, knowledge-based development has been identified as the primary development strategy.

So far, no study has investigated the impact of the knowledge-based economy index on water crisis management in Iran. In various studies, the effects of different components of knowledge-based economy on productivity (Fu et al., 2018; Morris, 2018; Baumann and Kritikos, 2016; Kurt and Kurt, 2015; Lam and Lam, 2005) and water productivity and use (Xue and Ren, 2016; Ali et al., 2016) have been investigated. The overall objective of this study is to find out whether advancing the knowledge-based economy index and increasing economic growth will lead to a reduction in the water crisis. For this purpose, a Bayesian network model has been used, which helps to understand the causal and independent relationships between the influential factors and the uncertainty associated with these factors. Therefore, a model has been designed to determine the impacts of the knowledge-based economy index and increasing economic growth on the water crisis, and suggest policy recommendations to manage the water crisis in Iran.

Materials and Methods

Research stages

The research stages taken in this study are shown in Figure 1. The statistics to calculate the components of the knowledge-based economy have been obtained from various statistical sources, including World

Bank statistics and World Governance Indices (WGI); the statistics to calculate agriculture sector water productivity, economic growth rate, economic growth rates of various sectors (industry and agriculture), inflation rate and liquidity are drawn from Time Series Database of Central Bank of Iran, Water Statistical Yearbook and Water Resources Management Company of Iran; the statistics to calculate water crisis index are from Water Statistical Yearbook and Water Resources Management Company of Iran; the statistics on area equipped for irrigation under pressure (ha) are from the Iranian Ministry of Agriculture Jihad statistics "Volume II"; and the Standardized Precipitation Index (SPI) statistics are from the National Center for Drought and Crisis Management (2017). The period covered in this study is 2001-2016.

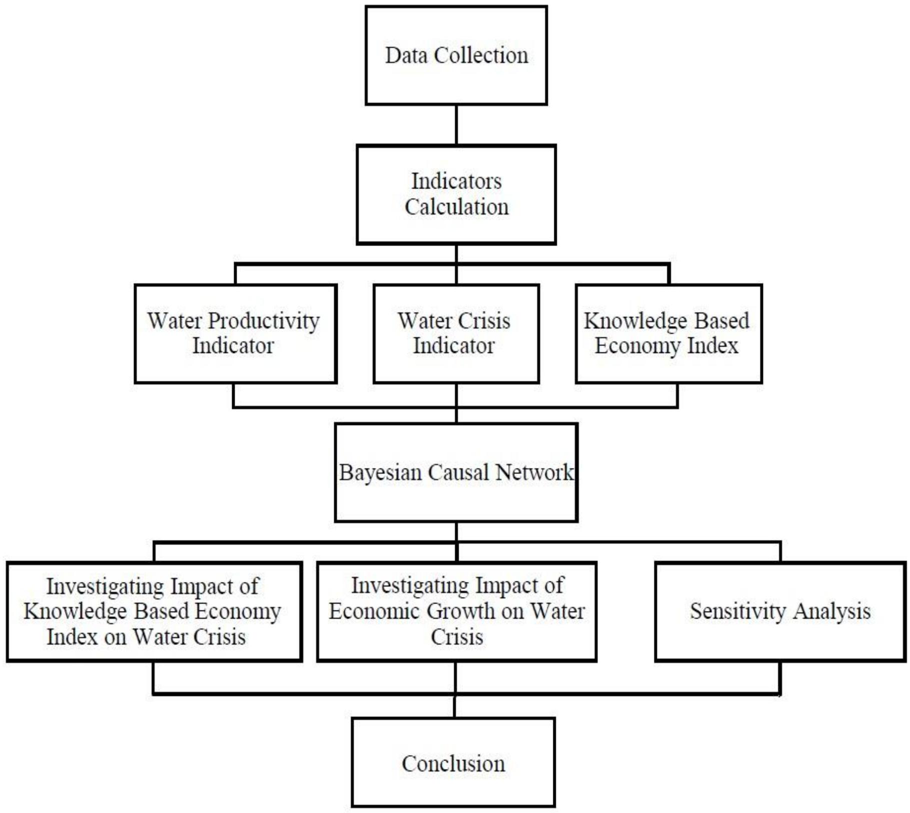

Figure 1. Flowchart of the proposed framework

Water crisis measurement

This section introduces the indicators used to assess the water crisis.

Falkenmark indicator

Falkenmark (1989) defined water crisis based on per capita amount of annual renewable water resources in each country, as follows (Table 1):

Table 1. Falkenmark indicator

Indicator (m^3/capital/year)	Class
> 1700	No Stress
1000 – 1700	Stress
500 – 1000	Scarcity
< 500	Absolute Scarcity

Source: Nepomilueva, 2017

International water management institute (IWMI) indicators

The International Water Management Institute uses the following two indicators simultaneously to study the status of water resources.

1) Percentage of current exploitation to total annual water resources, and
2) Percentage of future water exploitation compared to current water exploitation (Babran and Honarbakhsh, 2008; Nepomilueva, 2017).

U.N. indicator

The U.N. Commission on Sustainable Development has identified the percentage of exploitation from renewable water sources as an indicator of measuring water crisis (Table 2).

Table 2. U.N. indicator

Indicator (%)	Class
> 40	Severe crisis
$20 - 40$	Mean crisis
$10 - 20$	Balanced crisis
< 10	No crisis

Source: Babran and Honarbakhsh, 2008

Measuring water productivity

Three indicators of Crop Per Drop (CPD), Benefit Per Drop (BPD), and Net Benefit Per Drop (NBPD) are used to calculate water productivity in agriculture. The CPD indicator is the ratio of the product (yield) to the volume of water used per hectare. In other words:

$$CPD = TP/TW_C \quad (1)$$

where TP is the amount of product or yield (kg/ha), and TW_C is the volume of water used (cubic meters) per hectare regardless of rainfall (Ehsani and Khaledy, 2003).

The BPD indicator is the ratio of the gross profit (income) per hectare per unit volume of water (cubic meters per hectare).

$$BPD = TR/TW_C \quad (2)$$

where TR is the value of total product sales per hectare (Bayat and Babazadeh, 2014).
Another indicator for calculating agricultural water productivity is NBPD, which measures the net profit per unit volume of water used.

$$NBPD = NB/TW_C \quad (3)$$

where NB is the net profit (Rials) per hectare (Bayat and Babazadeh, 2014; Karimi and Jolaini, 2017).

Knowledge assessment methodology

Various models are used to assess the knowledge-based economy penetration in countries. The United Nations Development Program's Technology and Science Index (DeVol et al., 2011), the Composite Indicators for Educational Quality Management (Kanpinit, 2008), Quality Assessment of Composite Indicators in University Rankings (Benito and Romera, 2011; Murias et al., 2008), Composite Indicator for Knowledge Transfer (Finne et al., 2011) are among the most well-known indices of the knowledge economy.

One of the most important frameworks used to calculate the composite index of the knowledge-based economy is the knowledge assessment methodology, which was introduced by the World Bank Institute. The components used in the World Bank methodology are as follows:

1)Economic and institutional regime including:[1]
a)Tariff and non-tariff barriers,
b)Rule of law, and
c)Regularity quality.
2)Information and communication infrastructure including:[2]
a)Individuals using the Internet (% of population),
b)Computer subscriptions (per million people), and
c)Fixed telephone subscriptions (per 100 people).
3)Education and skills including:[3]
a)Literacy rate, adult total (% of people ages 15 and above),
b)School enrollment, secondary (% gross), and
c)School enrollment, tertiary (% gross).
4)Innovation system including:[4]
a)Patent applications, residents,
b)Scientific and technical journal papers, and
c)Researchers in R&D (per million people).

The stages of the knowledge assessment methodology are as follows:

1. Extracting raw data from the World Bank.
2. The 0-10 scale describes the performance of each country in each variable relative to the performance of the rest of the studied countries. A score of 10 is the highest, and a score of zero is the lowest.

3.The scoring method in conducted such that all variables are ranked between zero and ten, so the higher the score, the higher the level of knowledge. The following formula is used to normalize the scores for each country relative to the studied countries.

$$\text{Normalized}(\text{u}) = 10 \times (1 - (\frac{\text{NW}}{\text{NC}})) \quad (4)$$

where NC is the total number of countries studied, and NW is the number of countries below or equal to the target index (with poorer performance in that index).

4. The knowledge-based economy index is a composite index that is based on the mean of normalized performance scores for each country in the four components of the knowledge-based economy (Azizi and Moradi, 2018; Gorji and Alipourian, 2011; Afzal and Lawrey, 2012).

Bayesian network

The objective of the Bayesian network is to understand the causal and independent relationships between effective factors and the uncertainty associated with these factors (Arnaldo Valdés, 2018). The Bayesian network provides a framework for representing the uncertainty of variables in the network and consists of three parts: nodes, links, and conditional probability tables. The nodes are variables, and links represent causal relationships between nodes (Mamitimin et al., 2015).

A common way to overcome the uncertainty of variables in the network is to measure the confidence level of the variable on the condition of its parent value. The process of measuring confidence level is the same as determining the prior probability of a variable given the value of the parent in the network. The Bayesian network consists of two qualitative and quantitative stages. At the qualitative stage, the graphical structure of the network is designed, which includes directional and non-rotational connections that express the dependent relationships between the variables. Directional connectors are arrows pointing in a certain direction, and the non-rotational connections are meant to be a way to start from one point and cross the set of directional connections with no return to the starting point. Then, at the quantitative stage, the dependent relationships between the variables are expressed as the conditional probability distribution. The most important issue in the map is to determine the probability distribution (Mitchell, 1997). "Conditional probability” relies on Bayesian theorem, for which the mathematical equation can be written as:

$$P(i|j) = \frac{P(i)P(j|i)}{P(j)} \quad (5)$$

where "i" and "j" are the two random events, "$P(i)$" represents the probability of event i, and "$P(j)$" represents the probability of event j. "$P(j|i)$" is the conditional probability of event *i* under the condition that event *j* occurs" (Mamitimin et al., 2015; Pearl, 1988; Koski and Noble, 2011; Blitzstein and Hwang, 2014). In the present study, the Netica software package was employed for modeling the Bayesian network.

Results and Discussion

Water crisis measurement

In the present study, the U.N. indicator was used to assess the water crisis. Given that 70% of renewable water resources are used in Iran, the country is in a state of severe water crisis.

Water productivity measurement

BPD indicator was used to calculate water productivity in the agriculture sector. Figure 2 shows the trend of this indicator over the years 2001-2016. The indicator has been decreasing and increasing over the years 2001-2008, but the increase element is more pronounced. In 2008, this indicator declined dramatically but increased over the years 2008-2015. The value of this indicator was almost constant during 2015-2016.

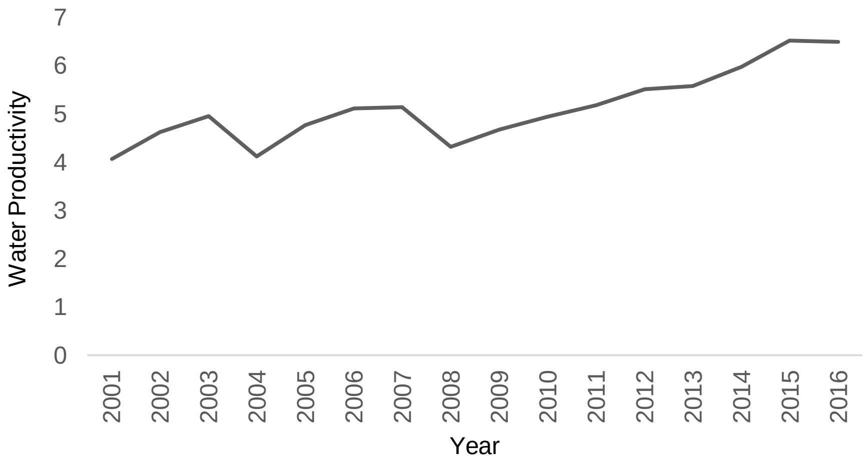

Figure 2. The trend of changes in water productivity in Iran's agriculture sector

The data and the knowledge assessment methodology

Considering the World Bank Knowledge Assessment Methodology and socio-economic and cultural conditions of Iran, the variables considered for each of the components of the knowledge-based economy index in this study are as follows:

1)Economic and institutional regime including:

a)Ratio of trade (export + import) to GDP (constant 2010 US$),

b) Rule of law, and

c) Regularity quality.

2)Information and communication infrastructure including:

a)Individuals using the Internet (% of population), and

b) Fixed telephone subscriptions (per 100 people).

3) Education and skills including:

a) School enrollment, secondary (% gross), and

b) School enrollment, tertiary (% gross).

4) Innovation system including:

a) Patent applications, residents, and

b) Research and development expenditure (% of GDP).

Spain, South Korea, France, Ukraine, the Netherlands, Germany, Italy, the Czech Republic, Bulgaria, Romania, and India were included in calculating the knowledge-based economy index and comparing Iran's position based on this index. According to FAO statistics (AQUASTAT, 2015), in terms of internal renewable water resources per capita (cubic meters), these countries rank close to Iran, and their knowledge-based index statistics are available. The ranking results of the selected countries, according to the knowledge-based economy index, are presented in Figure 3. It is clear that Iran has the poorest performance among the selected countries and occupies the last place; therefore, appropriate planning and policymaking should be taken for Iran to advance its knowledge.

Bayesian network

As mentioned earlier, there are two stages for building a Bayesian network as follows.

Qualitative stage

At the qualitative stage, the pilot causal network of the Bayesian was designed and presented. After determining all possible dependencies between the variables, the revised causal network generated a finalized network. After providing the final network, the causal relationships that were general and obvious were eliminated, and the deductive relationships were maintained. The direct and indirect relationships and rotational relationships were also identified and modified according to the principles stated for plotting the causal network. For the development of the BN model, information and data from sources, such as expert interviews, scientific literature, and official statistics, were collected. The related variables and key indicators were identified. In the next step, interactions among all relevant factors were defined via one-on-one discussions with experts in the fields of the knowledge-based economy, water crisis, agricultural growth, and water management.

The nodes used for plotting the causal network include those cited in Table 3.

Table 3. Variables and variables states in the Bayesian network

Nodes	States	Function
gGDP	Two breakpoints and three states	$\mathrm{gGDP} = \mathrm{F}(\mathrm{IF}, \mathrm{gM_2}, \mathrm{WC}, \mathrm{gGDP_a}, \mathrm{gGDP_i}, \mathrm{WC_a}, \mathrm{WC_i}, \mathrm{KEI}, \mathrm{WP_a}, \mathrm{SPI})$ The factors affecting Iran's economic growth rate were considered according to expert interviews and various studies, including Roson and Damania (2016) Bakhshi Dastjerdi and Khaki Najafabadi (2011), Asadzadeh *et al*. (2017), Mohammadzadeh Asl *et al*. (2017) and Haji-Rahimi and Torkamani (2003), as well as economic growth theory.
IF	Two breakpoints and three states	$\mathrm{IF} = \mathrm{F}(\mathrm{gM_2}, \mathrm{WC}, \mathrm{gGDP}, \mathrm{gGDP_a}, \mathrm{gGDP_i}, \mathrm{SPI})$ The factors affecting inflation were considered according to expert interviews and studies of Ghobadi and Komaijani (2010) and Haji-Rahimi and Torkamani (2003), and Iranian economic conditions
WC	Four states: $\mathrm{WC} < 10$ $10 < \mathrm{WC} < 20$ $20 < \mathrm{WC} < 40$ $\mathrm{WC} > 40$	$\mathrm{WC} = \mathrm{F}(\mathrm{gGDP}, \mathrm{gGDP_a}, \mathrm{gGDP_i}, \mathrm{SPI}, \mathrm{WC_a}, \mathrm{WC_i}, \mathrm{KEI}, \mathrm{LAI}, \mathrm{WP_a})$ The factors affecting the water crisis were considered according to expert interviews and studies of Jalalinasab *et al*. (2014), Kharazmi *et al*. (2011), and Abbasi *et al*. (2017), and Iranian economic conditions.
$\mathrm{gGDP_a}, \mathrm{gGD}$	Two breakpoints and three states	$\mathrm{gGDP_a} = \mathrm{F}(\mathrm{IF}, \mathrm{gM_2}, \mathrm{WC}, \mathrm{WC_a}, \mathrm{WP_a}, \mathrm{SPI})$ $\mathrm{gGDP_i} = \mathrm{F}(\mathrm{IF}, \mathrm{gM_2}, \mathrm{WC}, \mathrm{WC_i}, \mathrm{WP_a}, \mathrm{SPI})$ The factors affecting the growth rate of industry and agriculture sectors were considered according to expert interviews and studies of Bakhshi Dastjerdi and Khaki Najafabadi (2011), Asadzadeh *et al*. (2017), and Mohammadzadeh Asl *et al*. (2017), and Iranian economic conditions.
$\mathrm{WP_a}$	One breakpoint and two states	$\mathrm{WP_a} = \mathrm{F}(\mathrm{gGDP_a}, \mathrm{WC_a}, \mathrm{KEI}, \mathrm{LAI})$ The factors affecting water productivity in the agriculture sector were considered according to expert interviews and the studies by Keshavarz and Dehghanisanije (2012) and Abbasi *et al*. (2017), and Iranian economic conditions.
SPI	One breakpoint and two states	$\mathrm{SPI} = \mathrm{F}(\mathrm{gGDP}, \mathrm{gGDP_a}, \mathrm{gGDP_i}, \mathrm{WC}, \mathrm{KEI})$ The factors affecting drought were considered according to expert interviews and studies of Kavakebi *et al.* (2015) and Kariminazar *et al.* (2010), and Iranian economic conditions.
LAI	One breakpoint and two states	$\mathrm{LAI} = \mathrm{F}(\mathrm{IF}, \mathrm{KEI})$ The factors affecting land area under pressure irrigation were considered based on various studies, including Gholi Khani Farahani *et al*. (2013) and Aghapour *et al.* (2014), as well as according to expert interviews, and in accordance with Iranian economic conditions.

Where gGDP: GDP growth rate, gGDP_a: agriculture sector GDP growth rate, $\mathrm{gGDP_i}$: industry sector GDP growth rate, WC: water crisis indicator, $\mathrm{gM_2}$: liquidity growth rate, $\mathrm{WC_a}$: water use in agriculture sector, $\mathrm{WC_i}$: water use in industry sector, KEI: knowledge-based economy index, IF: inflation rate, SPI: standard precipitation index (drought), $\mathrm{WP_a}$: water productivity in agriculture sector, and LAI: land area equipped with pressure irrigation.

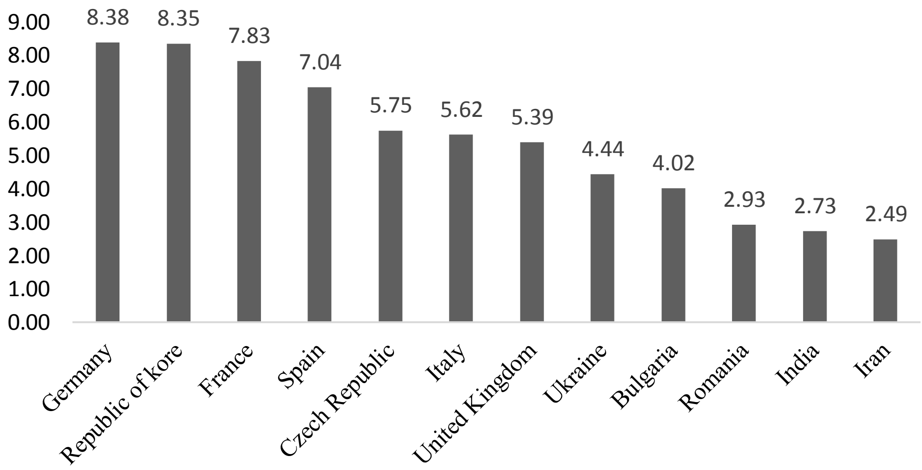

Figure 3. Knowledge-based index of the studied countries

Quantitative stage and determining the status of variables

In order to determine the state of the time series variables in the network, first, the growth rates of the variables were calculated, and next, breakpoints (using breakpoints tests), and states of each variable were determined using software Eviews 7 (Table 3). The finalized network is shown in Figure 4.

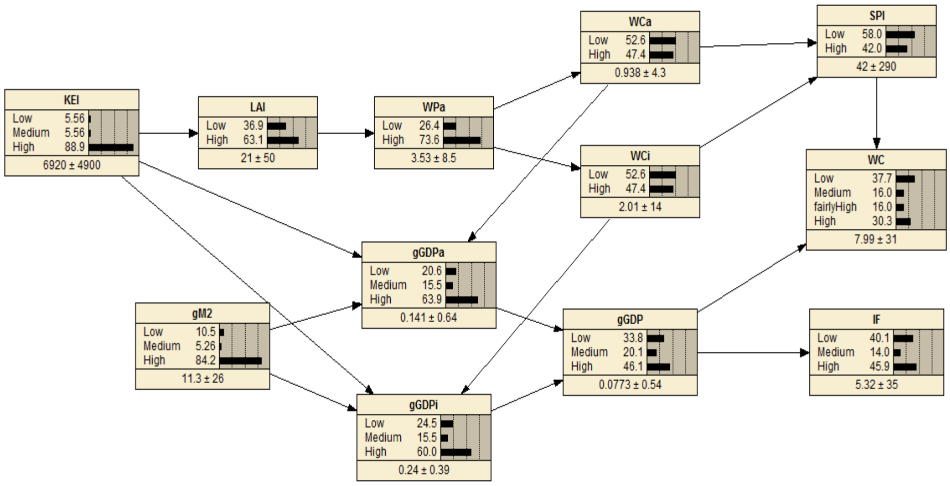

Figure 4. Bayesian causal network with the probability distribution of variables' status

The final network consisted of 12 nodes and 15 links (Figure 4). As shown, the probability that the water crisis indicator is in a severe crisis status is 30.3%, the probability that it is in the mean and balanced status is 16%, and the probability that it will be in no crisis status is 37.7%. The numbers in the lower section of the table for each variable from right to left represent the standard deviation and medium of each variable, respectively.

Scenario management

The BN model was applied as a decision analysis tool for the probabilistic impact of scenarios of knowledge-based economy index advance and an increasing growth rate of the agriculture sector over the water crisis.

KEI scenario

The most important scenario in the present study is the impact of advances in the knowledge-based economy index on the water crisis (Figure 5).

According to the scenario Iran's advances in the knowledge-based economy index (high probability, by 100%), it is observed that the state of the growth rate of land area equipped for irrigation under pressure and agriculture sector water productivity is high (64.7 and 74.4, respectively). Due to the impact of the water productivity variable in the agriculture sector on the growth rate of water use in agriculture and industry sectors, the highest probability is low (52. 4%). Also, the highest probability of drought indicator growth rate is low (severe crisis, 57.8%), and the highest probability of water crisis indicator is low (less than 10% of total renewable water resource, 37.7%).

The results of this scenario show that the advances in the knowledge-based economy index can make a significant increase in the growth rate of land area equipped for irrigation under pressure and water productivity in the agriculture sector. They also reduce water use in the agriculture and industry sectors and can help mitigate the problem of the water crisis.

The second impact of advances in the knowledge-based economy is increase in economic growth. Knowledge - based economy increases economic growth through the use of new technologies in various sectors of the economy, commercialization of sectors' products, as well as support for activities that increase the share of knowledge in production. Since the agriculture sector is one of the most important sectors of the Iranian economy and water, as an input, plays an important role in the production of this sector, so increase in water productivity accelerates the growth of the agriculture sector.

The third impact of advances in the knowledge-based economy is the increase in the inflation rate. By increasing economic growth, demand for commodities and inputs increases. As a result, the inflation rate rises.

The results also show that the drought indicator is in an extremely dry state. Despite the advent of the knowledge-based economy, Iran is still in a status of drought due to environmental problems worldwide and nationaly and is affected by the increased greenhouse gases and gradual warming.

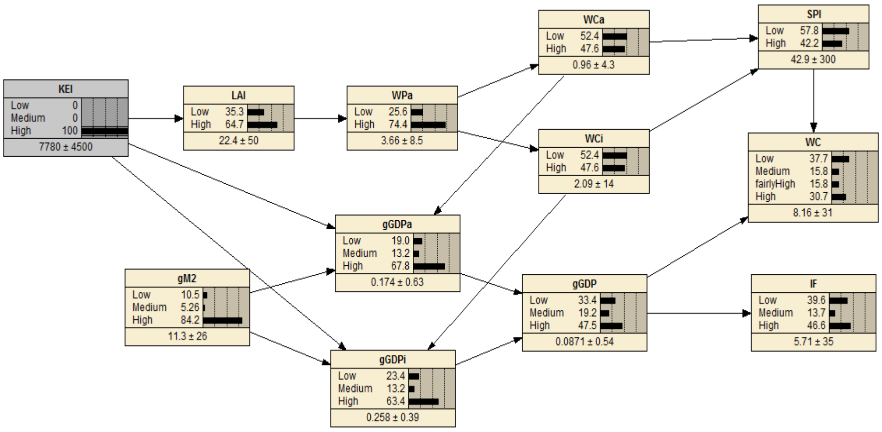

Figure 5. Probability value of advances in knowledge-based economy index

gGDP scenario

With a higher economic growth rate (high probability, by 100%), it is observed that the growth rate of water consumption in the industry sector will be 50.5% and water crisis with the probability of 43.1% is in the high status (Figure 6). Therefore, increasing economic growth could exacerbate the problem of the water crisis in Iran. The industry sector has the largest share of GDP in the country. The higher economic growth rate, which is further facilitated by the growth of this sector, will increase water consumption by this sector thereby exacerbating the state of the water crisis. Therefore, planning for increasing economic growth in Iran should be accompanied by environmental considerations, including the conservation of water resources.

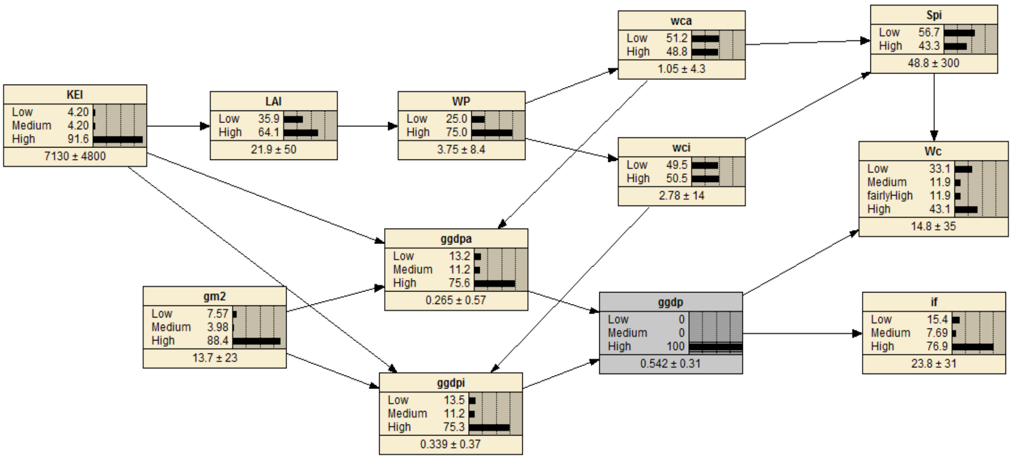

Figure 6. Probability value of increasing economic growth rate

We resorted to experts' opinions and scientific findings from the literature to evaluate and validate the results of the Bayesian network.

Sensitivity analysis

Sensitivity analysis is performed using the Netica software to investigate the variables with the highest impact on the water crisis. As shown in Table 4, the water crisis is the target variable and standard precipitation index (drought), GDP growth rate, inflation rate, water use in industry sector, water use in agriculture sector, industry sector GDP growth rate, water productivity in agriculture sector, agriculture sector GDP growth rate, land area equipped with pressure irrigation, liquidity growth rate, and knowledge-based economy index are the variables that most influence water crisis.

Table 4. Sensitivity analysis of the BN model

Variable	Variance Reduction
SPI	73.94
gGDP	48.9
IF	18.4
WC_i	9.46
WC_a	8.09
$gGDP_i$	5.50
WP_a	3.30
$gGDP_a$	1.84
LAI	1.05
gM_2	0.33
KEI	0.23

Conclusion

In this study, a Bayesian network model was used to investigate the impact of the knowledge-based economy index and economic growth rate on the water crisis in Iran. The results showed that the water crisis in Iran would be reduced by implementing a knowledge-based economy scenario. The knowledge-based economy can alleviate the water crisis in Iran through the components of innovation, knowledge and human resources, information and communication infrastructures, and economic incentives and institutional regimes. In this regard, increasing the level of education and productivity of human resources to manage the water crisis and put Iran in a more appropriate position should be a priority for policymakers. In order to improve the information and communication infrastructure component, infrastructure weaknesses in ICT should be eliminated to help manage the water crisis by increasing water productivity. In the field of innovation, increasing the R&D budget as well as commercializing research and inventions in the field of water technologies can help manage the water crisis. The results also showed that as the economic growth rate increases, the water crisis in Iran becomes more severe. Therefore, planning and policymaking should be consistent with sustainable development to preserve natural and environmental resources such as water parallel with economic growth and progress.

We studied the impact of the knowledge-based economy index on the water crisis in Iran. As the agriculture sector is the largest user of water, it is recommended to study the impact of knowledge economy components in agriculture on water consumption in this section.

Footnotes

1. In fact, it includes incentives that ensure efficient use of existing knowledge in order to flourish entrepreneurship.
2. A modern and accessible system for information and communication infrastructure can facilitate effective communication, dissemination, and information processing.
3. The educated population maintains a high level of knowledge creation, sharing, and use.
4. An efficient innovation system can move companies, universities, consultants, and other organizations into a growing global knowledge system and provide them with local needs as well as technological solutions.

Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript.

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