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An Analysis of the Sustainability of Basin Water Resources using Vensim Model

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Abstract

Given the high dynamics of water resources management systems, system dynamics approach and vensim model has been used to model the water resources system in the study area. After verification of the model, the sustainability indicators were assessed under simulated scenarios and different policy packages. At the end, the policy packages related to each scenario were ranked based on analytical hierarchy process. According to the results, increased irrigation efficiency and reduced non-revenue water coefficient were the most important objectives in the short and medium terms. Moreover, reducing net crop water demand was necessary. In long term, reducing net crop water demand was the most important objective. Also, increased irrigation efficiency and reduced non-revenue water coefficient had less importance especially in the scenarios of current economic and population growth rate.

Keywords: *system dynamics, Vensim model, sustainability indicators, scenarios and policy packages, analytical hierarchy process*

1. Introduction

Iran is among the dry and semi-dried regions in the world (Naseri *et al.*, 2009) and given the fact that the quality of human life is directly influenced by the planning and management of water resources (Kyessi, 2005), water is one of the critical problems facing basins. Furthermore, the authorities in charge of water resources face a plethora of challenges with respect to intra-stream flows and providing more water for the growing populations, industries and agriculture (Xu *et al.*, 2002). Thus, assessing the sustainability of water resources and the factor affecting the capacity of these resources in providing the needs in various sections is among the crucial issues in water basins and helps us predict the future of water resources and sustainable development planning. Thus, effective strategies and policies are essential for sustainable city development in the region (UN-Water, 2009). Given the increasing economic development in downstream of Karkheh Dam in Khuzestan province (the study area), the basin management faces numerous challenges.

In Iranian hydrological division, Karkheh basin is a part of the Persian Gulf basin. (Mahab Qods Co., 2010). The annual rainfall varies from 205 mm in the southern low areas to 1000 mm in highlands to the extent that the mean annual rainfall of this basin is approximately 477 mm (Behan Sad Consulting Engineers Co., 2010). Karkheh basin covers an area of 51604 square kilometers and 8800 km, or 17% of Karkheh basin, is located in Khuzestan province. Fig. 1 shows the site of the Khuzestan province in the Karkheh Basin (Mahab Qods Co., 2010).

This paper is organized as follows. The relations between the key variables in economic development and the existing variables in the water resources system are first identified and modeled using a system dynamics model. The sustainable indicators of future water management are then assessed. Next, the premier policies which provide more secure water conditions and economic development are proposed. Finally, the paper is followed by summary and conclusion.

2. System Dynamics

An event-oriented view of the world or linear thinking cannot address complex issues (Forrester, 1961; 1969; Sterman, 2000a; Richmond, 1993). Thus, in this study, the System Dynamics modeling (SD), which is based on the non-linear causal thinking, has been used for expanding the dynamic simulated model. This approach, which was originated by Forrester in 1961, is a simulating method for object-oriented feedback with a long history. He proposed this approach to understand strategic principles of the complex dynamic systems which enables the user to acquire a better understanding of the dynamic behavior of the systems over time (Jalali and OstadRahimi, 2006). It should be noted that this ability is specific to the modeling by the detection system dynamics and drawing feedback processes (Sterman, 2000b).

In recent years, growing attention has been paid to this approach

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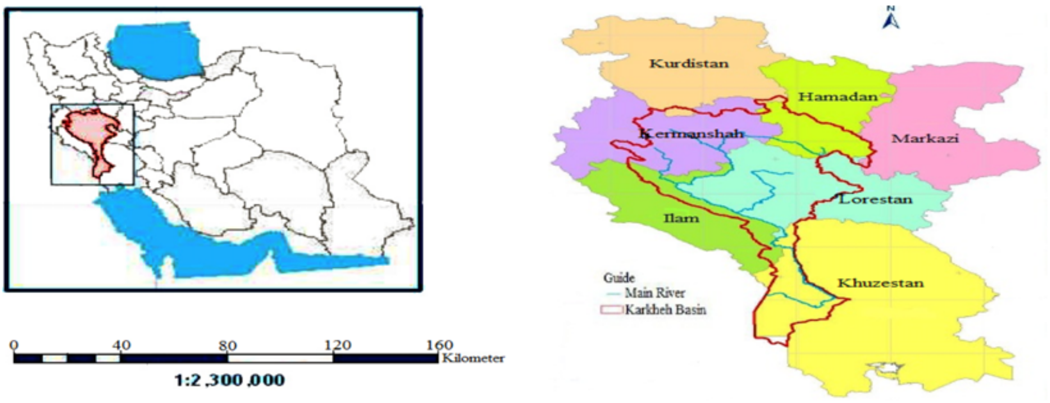


(a) (b)

Fig. 1. (a) Location of Karkheh Basin in Iran, (b) Site of Khuzestan Province in Karkheh Basin

in the analysis and modeling of water resource systems. Xu *et al.* (2002) conducted an analysis of the sustainability of water resource in Yellow River by means of system dynamics approach. Jalali and Afshar (2005) used system dynamics techniques for flood routing in multi-reservoir systems in the Karun River in Iran. Kojiri *et al.* (2008) carried out a global modeling of the continental water resources using system dynamics. Feng *et al.* (2008) used the system dynamics to analyze the carrying capacity of water resources in Yiwu City in China. Qi and Chang (2011) modeled the system dynamics to estimate the urban water need in a metropolitan area under the effects of the economic uncertainties. Rehan *et al.* (2011) applied the system dynamics to manage water and sewage network in Canada. Ryu *et al.* (2012) developed a system dynamics model of the Eastern Snake Plain Aquifer to study how the aquifer might respond under various water management scenarios involving water conservation, managed recharge, demand reduction and weather modification. Hoekema and Ryu (2013) evaluated economic impacts of water conservation and hydrological forecasts in the Salmon Tract, Southern Idaho.

3. Model Structure

In this section, based on the system dynamics approach, the existing mechanisms in downstream water resources system of Karkheh are modeled. To model the discussed system, the Vensim model, which is able to depict, simulate, analyze and optimize the system dynamics models (Mohammadi *et al.*, 2010) is used. The system dynamics model consists of six parts: population, service economy, industrial economy, agricultural economy, water demand of three economic subsystems and available water resources of the basin for consuming in economic subsystems. These parts and their relationships have been clearly shown in Fig. 2 which is a simple representation of the mechanisms affecting the regional water system (Tavakoli Nabari, 2010). The period between 1994 and 2006 is considered for the model verification and the period between 2006 and 2031 is considered for the future simulation.

3.1 Population Subsystem

Service water demand is a subset of water demand. Thus, it is necessary to estimate the population of the study area in order to estimate water demand of this subsystem. Demographic fluctuations are due to natural growth rate of the population and the effect of economic growth on the study area's population. Increasing rate of economic growth and the GDP (Gross Domestic Product) in this region and consequently, increased job opportunities along with the inclination of the neighboring basin residents to migrate to the study area for the purpose of inhabitation, work and education are among the reasons for the population growth in this area. Here, job utility function, which compares the job opportunities per capita in this region with the normal job opportunities per capita in the country, is an effective factor for modification or enhancement of the population growth rate (Tavakoli Nabari, 2010).

3.2 Subsystems of the Economic Activities

As the economic development of any society depends on its water resources, the analysis of the economic activities subsystems is required to estimate the water demand in these sections. These subsystems include service, industrial and agricultural economy subsystems.

3.3 Water Demand Subsystem

The ultimate goal of modeling the subsystems of economic activities is to estimate the average water demand in the three sections. Demand is the most important variable in water resources management in each region, which can help managers and decision makers in the future planning.

3.4 Water Resources Subsystem

The subsystem of the water resources in downstream of Karkheh Dam includes surface and ground water. Water demand is primarily met by surface water resources. The subsystem modeling of water resources is to model the balance between surface and ground water resources in this research. Considering the insignificant evaporation of underground aquifers and the lack

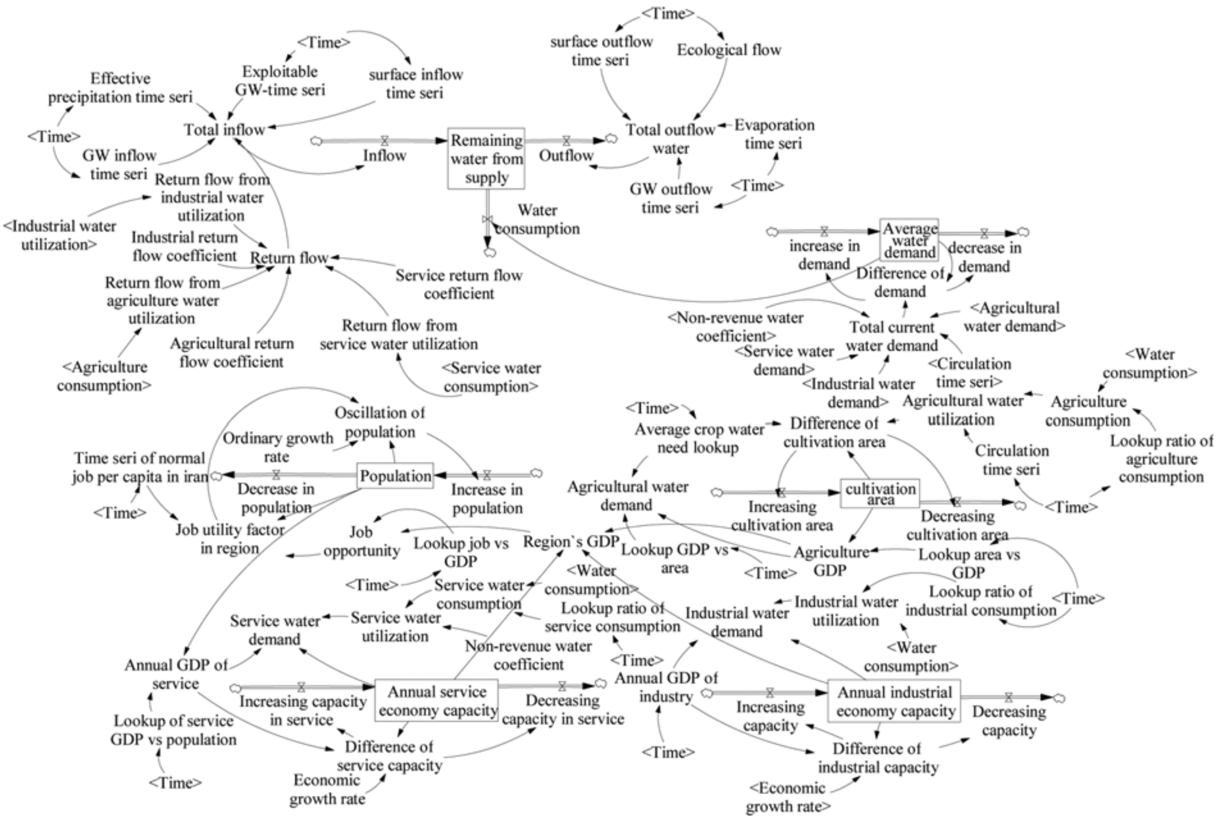


Fig. 2. Schematic of System Dynamics for Water Management in Karkheh Basin

of accurate statistics on the volume of irresponsible exploitation of the basin, evaporation of underground aquifers and the volume of irresponsible exploitation of the basin have not been included in the model.

4. Simulation and Ranking of the Policy Packages under Different Scenarios

4.1 Scenarios and Policies

After the verification of the model and proving its ability to evaluate the state of the issue, the policies are carried out under different scenarios. Thus, in the period between 2006 and 2031, the model should be able to analyze the impact of policies and the results obtained from their simulation based on the existing scenarios. Therefore, in this study, assuming the changes in climatic, economic and social conditions, six scenarios are designed.

Normal, wet and drought climatic conditions of rainfall and the output of Karkheh dam are used in scenarios construction. In order to incorporate the economic changes in the scenarios, the current economic growth rate of the basin (8%) and the target economic growth rate (10%) are used. In addition, in order to incorporate the social change in the scenarios, the current population growth rate (1.71%) and the predicted population growth rate (1.32%) are used.

After the presentation of the scenarios, the formulation of the policy packages based on the applied scenarios is pursued. policy packages are created based on some exogenous parameters of the model that can be changed by decision maker or policy maker. And this is the difference among the scenarios and policies. To create such policy packages, exogenous parameters such as net crop water demand of the basin, the ratio of different economic subsystems from water resources, irrigation efficiency and the non-revenue water coefficient are used at two levels.

As to the net crop water demand, the level of 5314 m^3 per ten thousand square meters is based on the long-term average of this parameter and the level of 4340 m^3 per ten thousand square meters is based on the water need for wheat cropping pattern. Wheat crop, due to the low water need of this product compared to other products and the focus of government policies on the guaranteed purchase of this product and self-sufficiency in its production, is considered as the second level (Hoseini, 2010; Tavakoli Nabari, 2010).

The other exogenous parameter is the ratio of various economic subsystems from water resources. This parameter is either oriented toward the continuation of the current situation or the shift of the water resources to the industry sector. Currently, the ratio of water consumption in agricultural, service and industrial subsystems are respectively 98.6%, 1.2% and 0.2%. To incorporate the second level, the ratio of water consumption in different subsystems of the country is compared to the neighboring countries. According to the proposed water package and the Fifth Economic Development Plan and despite the limited water resources, our country has allocated a larger ratio of its water consumption to agricultural sector which requires a fundamental reconsideration. Thus, at the second level, the water ratio of the agriculture, service and industry sectors, in accordance with the proportion of water consumption in Uzbekistan, are assumed 94%, 2% and 4% respectively.

The irrigation efficiency and non-revenue water coefficient parameters are defined at two levels. The first level is the continuation of the current state with the irrigation efficiency of 31% and non-revenue water coefficient of 30%. The second level addresses the improved status of these two parameters. At this level, the irrigation efficiency will increase to 40% according to the fifth economic development plan and the non-revenue water coefficient will drop to 26.5% in accordance with the fourth economic development plan.

4.2 Sustainability Indicators

The monitoring of a system requires a set of processing indicators that can describe the system dynamic (Hoseini, 2010). One the other hand, the performance indicators measure the status of a system and are able to measure the efficiency of the sustainable development processes at a particular time like a snapshot (Bagheri and Hjorth, 2005). In this study, four process and performance indicators including the resource stress, the resource economic productivity, job utility and average demand are analyzed under various scenarios and policy packages.

To explain the strategy of "economic growth and development with limited water resources approach" in the region, to know how it works and to evaluate its performance over time, an appropriate index is needed. The "resource stress" is such an index, which is calculated according to Eq. (1):

$$\text{Resource stress} = \frac{\text{water demand}}{\text{supplied water}} \tag{1}$$

The threshold limit of this process index is equivalent to 1 where all supplied water is allocated to the demand in the basin. The value greater than 1 indicates that the volume of water demand in the region is greater than the supplied water.

The second sustainability index is the resource economic productivity which is used to explain the strategy of "water resources allocation with added value approach". The unit of this process index is *IRR* (Iranian currency) per cubic meter, which is calculated according to Eq. (2):

$$\text{Resource economic productivity} = \frac{\text{added productive value}}{\text{water consumption}} \tag{2}$$

Job utility is the third index, which is used to explain the "economic development with social development approach" strategy. It is calculated according to Eq. (3):

$$\text{Job utility} = \frac{\text{Job opportunities per capita in the region}}{\text{Job opportunities per capita in the country}} \tag{3}$$

A process index like the other two indicators, this index is dimensionless and its value can be slightly greater or lower than 1.The last sustainability indicator is the average demand index, which is a performance index and is estimated directly by the model.

4.3 Ranking Policy Packages

After simulating the various policy packages and evaluating the sustainable development indicators, the ranking of the policy packages and adopting the best policies seem essential. The analytical hierarchy algorithm is a managerial algorithm that is suitable when a manager faces different indicators with different weights during ranking and selection. As it was said before, there are four sustainability indicators with different weights and priority. So, this algorithm is used for ranking policy packages.

With respect to the weight and priority of the indicators and having the values of indicators in various policy packages, the analytical hierarchy process sets out to rank the policy packages in short term (8 years), medium term (15 years) and long term (25 years).

5. Discussions

The period between 1994 and 2006 was used to verify the model. It should be noted that the reliability of the model is based on the attitude of the model designer toward the dynamic model and the intended objectives of the model (Sterman, 2000b). Moreover, the period between 2006 and 2031 was used to simulate the future. Also, analytical hierarchy algorithm was used to rank policy packages. We will present and discuss the results in what follows.

5.1 Model Calibration/Verification

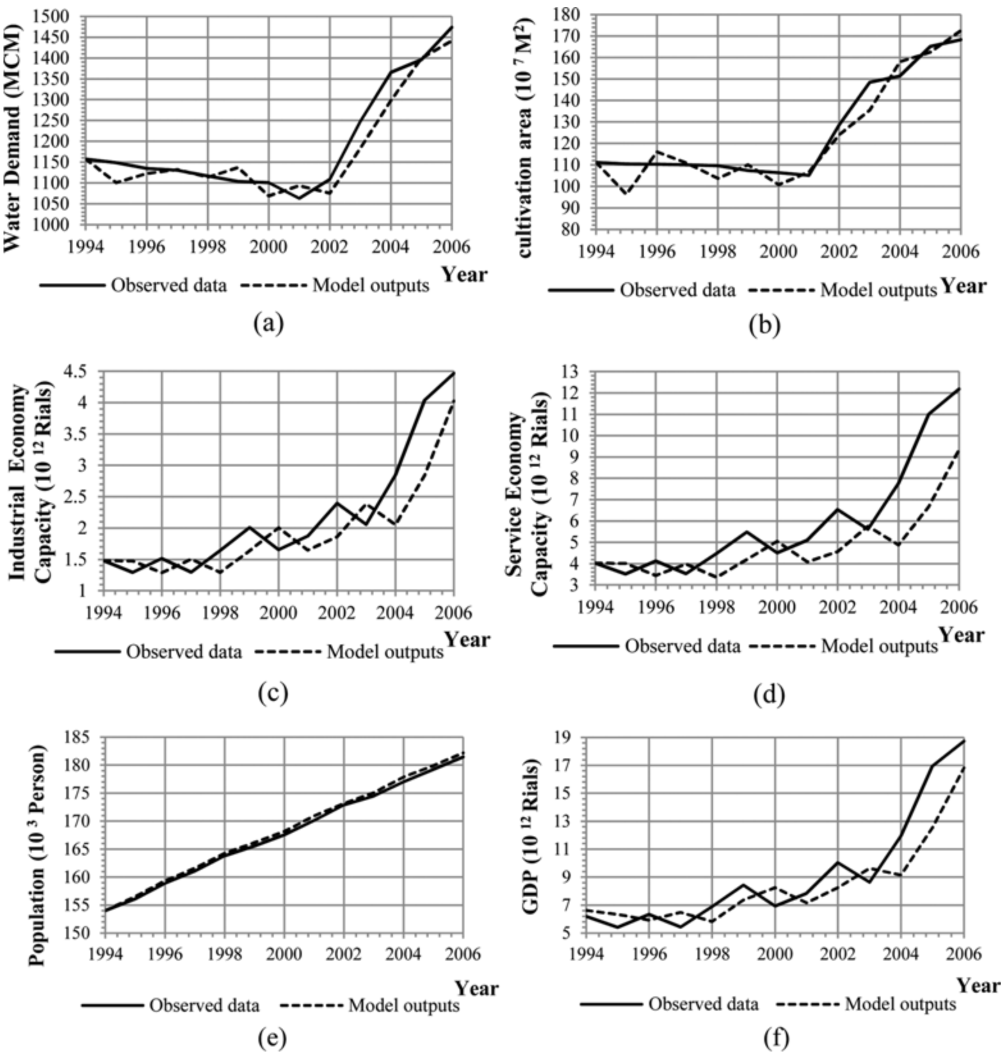
Calibration is one of the tests used for model verification. In calibration, the outputs of the model are compared to the observed data to examine the consistency of the data obtained from the model with the historical. Here, the mere adherence of the model behavior to the observed data is sufficient for the success of the model (Tavakoli Nabari, 2010). Moreover, in this study, the coefficient of determination (R^2) and the relative Root Mean Square Error (RMSE) are used to investigate the significance of the behavior generated from the model with the observed behaviors.

$$R^2 = \frac{\Sigma_{i=1}^{n} x_i y_i}{\sqrt{\Sigma_{i=1}^{n} x_i^2 \Sigma_{i=1}^{n} y_i^2}} \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\left(\Sigma_{i=1}^{n}\left(\frac{x_i - y_i}{x_i}\right)^2\right)} \tag{5}$$

where, X_i is the observed data, y_i is the model outputs and n is the number of data. The results of the calibration tests are presented in Fig. 3 and Table 1. Based on the results, the model is able to reproduce the main variables trends.

Sensitivity analysis is another test. If a system dynamics model can reiterate the initial behavior pattern of the variable under the influence of the reasonable changes in the input parameters with respect to numerical sensitivity, then the model is verified. Here,



(a) (b) (c) (d) (e) (f)

Fig. 3. Model Calibration: (a) Water Demand, (b) Cultivation Area, (c) Industrial Economy Capacity, (d) Service Economy Capacity, (e) Population, (f) GDP

Table 1. Results of Statistical Tests

Variable	R^2	RMSE
Water demand	0.935	0.029
Cultivation area	0.927	0.054
Economic capacity (industrial subsystem)	0.823	0.188
Economic capacity (service subsystem)	0.785	0.22
Population	0.98	0.0034
GDP	0.883	0.16

variables, such as water demand and cultivation area are the most sensitive because the current and future water availability is constrained by economic development in the region. According to the results, the present model is able to reiterate the behavior pattern of the variables, showing the success of the model in the sensitivity analysis test.

5.2 Evaluation of Policy Packages under Different Scenarios

The six scenarios used in this study include climatic, economic and social changes, and based on these scenarios; the model simulated the various policy packages. The details of scenarios and policies have been shown in Tables 2 and 3.

Estimating the values of sustainable indicators for each policy is necessary to evaluate the policy packages for each scenario in order to achieve sustainable development. In Figs. 4 and 5, the monitoring results of two sustainable indicators have been shown during the period between 1994 and 2006 based on basin's conditions at that time. Also, these results for eight policy packages under scenarios have been shown during the period between 2006 and 2031.

It can be said that the trend of resource economic productivity index is almost similar in all scenarios. In Fig. 4, the trend for two scenarios has been shown. What is interesting here is the dramatic drop in value of the index after reaching the peak. This is why a rise in the GDP will increase the economic growth, and consequently the attraction of the immigrants. Due to the ex-

Table 2. Scenarios

Scenarios	Scenarios details
1	Normal climatic conditions + Current economic growth rate + Current population growth rate
2	Normal climatic conditions + Optimum economic growth rate + Predicted population growth rate
3	Wet climatic conditions + Current economic growth rate + Current population growth rate
4	Wet climatic conditions + Optimum economic growth rate + Predicted population growth rate
5	Drought climatic conditions + Current economic growth rate + Current population growth rate
6	Drought climatic conditions + Optimum economic growth rate + Predicted population growth rate

Table 3. Code and Provisions of the Policy Packages under Six Different Scenarios

Policy package codes	The provision of policy codes
1	Irrigation efficiency (31%), non-revenue water coefficient (30%), net crop water demand (5314), the ratio of water consumption in different sectors (98.6%, 1.2% and 0.2%)
2	Irrigation efficiency (40%), non-revenue water coefficient (26.5%), net crop water demand (4340), the ratio of water consumption in different sectors (94%, 2% and 4%)
3	Irrigation efficiency (31%), non-revenue water coefficient (30%), net crop water demand (4340), the ratio of water consumption in different sectors (94%, 2% and 4%)
4	Irrigation efficiency (31%), non-revenue water coefficient (30%), net crop water demand (4340), the ratio of water consumption in different sectors (98.6%, 1.2% and 0.2%)
5	Irrigation efficiency (31%), non-revenue water coefficient (30%), net crop water demand (5314), the ratio of water consumption in different sectors (94%, 2% and 4%)
6	Irrigation efficiency (40%), non-revenue water coefficient (26.5%), net crop water demand (5314), the ratio of water consumption in different sectors (98.6%, 1.2% and 0.2%)
7	Irrigation efficiency (40%), non-revenue water coefficient (26.5%), net crop water demand (5314), the ratio of water consumption in different sectors (94%, 2% and 4%)
8	Irrigation efficiency (40%), non-revenue water coefficient (26.5%), net crop water demand (4340), the ratio of water consumption in different sectors (98.6%, 1.2% and 0.2%)

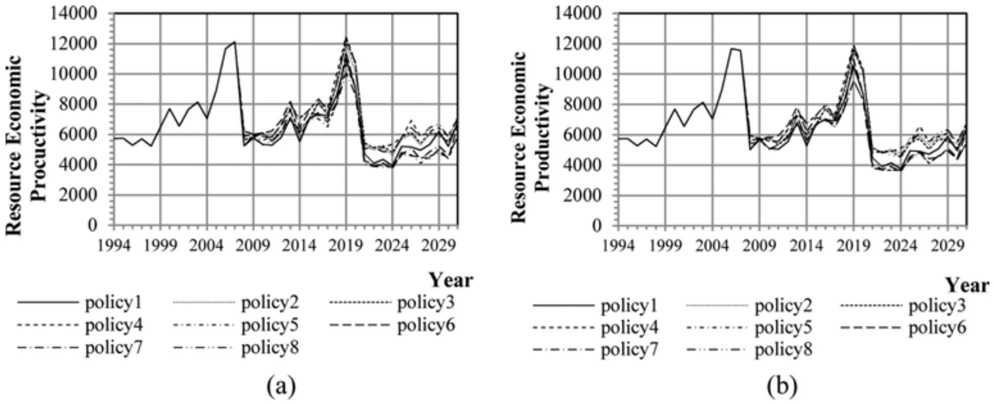


Fig. 4. Behavior of Resource Economic Productivity Index: (a) Scenario 1, (b) Scenario 2

cessive inflow of the immigrant population as well as the incompatibility between the GDP and the population, job opportunities and increased water demands, there has been a drop in the basin. And this issue has repeated during the time. So, this index has a periodic trend in the basin.

The resource stress index in the scenarios with similar climatic conditions follows the same trend. In the scenarios with optimum economic growth rate and the predicted population growth rate, the value of stress is higher than the scenarios with current economic and social status. Also, the value of this index is the highest in the scenarios with drought climatic conditions and is the least in the scenarios with wet climatic conditions. According to the diagrams of all scenarios, the study area will face the water crisis in the future.

Different scenarios and policy packages do not make a significant change in the trend of job utility index.

5.3 Premier Policy Packages

A simple example of analytical hierarchy algorithm is given to increase the readability. A person wants to select a car among three cars. Price, fuel consumption and convenience are three indicators. The importance and weight of these indicators is not

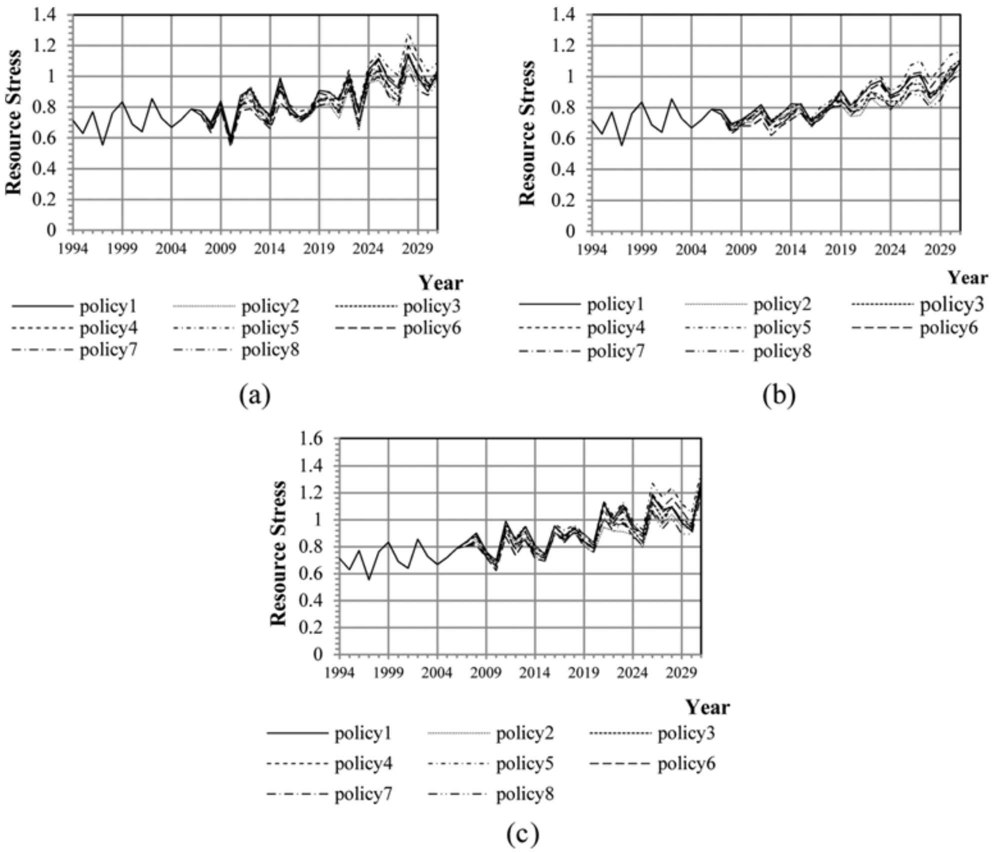


Fig. 5. Behavior of Resource Stress Index: (a) Scenario 1, (b) Scenario 3, (c) Scenario 5

equal for the person. Also the priority and weight of indicators is different from one car to another car. So, the person faces a complex decision. Analytical hierarchy process can be used to rank cars. In this research, the first step of ranking policy packages involves ranking indicators and determining their weights with the aim of ranking the policy packages according to the priorities and the importance of each indicator. Accordingly, we designed a survey form to compare the indicators in paired based on analytical hierarchy algorithm. The form was completed by a number of experts in water resources based on their experience. After preparing numerical pair wise comparison matrix, the weight of each index was determined using arithmetic mean method. Accordingly, the final weight of the resource stress index, the resource economic productivity index, job utility index and average water demand index were respectively 0.4544, 0.2758, 0.2019 and 0.0677. After this step, the policies of each scenario were ranked based on the final weight of the indicators and their values.

According to the results, the premier policy packages in short-term objectives of the scenarios with current economic and population growth rate were the ones in which the irrigation efficiency and the non-revenue water coefficient were in level 2 and the ratio of various economic subsystems from water resources was in level 1.If all the above parameters were in level 1, the inclusion of level 2 in net crop water demand would be crucial to achieving the premier policies. So, The premier policy packages in this status were policy packages 6, 8, 4, 7, 5, 2, 3, 1, respectively. Also, the premier policy packages in short-term objectives of scenarios related to the optimum economic growth and predicted population growth were the ones in which the irrigation efficiency and non-revenue water coefficient were in level 2 and the ratio of various economic subsystems from water resources was in level 1. When all the above parameters were in level 1 or 2, incorporating the parameter of net crop water demand in level 2 was essential to achieving the top ranking policies. So, The premier policy packages in this status were policy packages 6, 8, 4, 2, 5, 7, 3, 1, respectively. It was also true about premier policy packages in the medium-term objectives of the top six scenarios.

The premier policy packages in long-term objectives of the scenarios with current economic and population growth rate were the ones that focused their objectives on actualizing the parameter of level 1 in connection with the ratio of various economic subsystems from water resources and the parameter of level 2 with respect to net crop water demand. So, The premier policy packages in this status were policy packages 8, 4, 2, 3, 6, 7, 1, 5, respectively. Furthermore, the premier policy packages in long-term objectives of optimum economic growth and predicted population growth scenarios were the ones that focused their objectives on actualizing the second level of irrigation efficiency, non-revenue water coefficient and net crop water demand. Among these two, the second level of net crop water demand was preferred. So, The premier policy packages in this status were policy packages 8, 2, 4, 3, 6, 1, 7, 5, respectively.

Based on the above-said points, the ranking of policy packages in scenarios with similar economic and social conditions were almost the same. Moreover, given the variable rank of the policy packages in various scenarios, it could be concluded that with increased time interval, the policy packages in which the net crop water demand is in level 2 had priority. This process was more dramatic in scenarios with optimum economic growth and the predicted population growth rate.

6. Conclusions

In this study, the integrated sustainability of water resources system in the downstream of Karkheh Dam in Khuzestan province was investigated from the perspective of system dynamics under various scenarios and policy packages based on sustainability indicators. First, the current system dynamics model was carried out between 1994 and 2006, and after ensuring the ability of the model in representation of the real system, the future behavior under various scenarios and policy packages in the period between 2006 and 2031 was simulated and the sustainability indicators were monitored. Finally, the policy packages were ranked in short-term, medium-term and long-term periods. According to the analyses, the results are as follows:

1. In order to achieve the sustainable development in the short-term objectives of the six scenarios, special attentions should be paid to increase the irrigation efficiency to 40% through investment in this area. Moreover, the non-revenue water coefficient as well as physical and non-physical water losses in service sector should be reduced to 26.5% through preventing leaks, the breaks of pipe and water supply facilities, the water meter errors and the unauthorized water consumption. Furthermore, particular attention should be paid to changing the cropping pattern to meet the required 4340 cubic meters per ten thousand square meters of net crop water demand in accordance with the water need of the wheat-cropping pattern.
2. In order to achieve sustainable development in the medium-term objectives of the six scenarios, the solutions proposed in paragraph 1 are efficient, the only difference being that in scenarios with optimum economic growth and predicted population growth rates, the solution offered for changing the cropping pattern in line with the 4340 cubic meters per ten thousand square meters of net crop water demand requires more attention.
3. The focus on the solution of changing the cropping pattern in keeping with 4340 cubic meters per ten thousand square meters of net crop water demand is the most important strategy in long-term objectives under the six different scenarios.
4. According to the above-mentioned points, the strategy planners should consider changing the cropping pattern in short-term, medium-term and long-term period, as this solution becomes more and more important over time.
5. Maintaining the current water resources ratio of different economic sectors in the short-term objectives under the six scenarios is of paramount importance. Moreover, retaining the discussed trend in the medium-term objectives of the current economic scenarios and the current population growth rate are essential, while this is not as important in the scenarios related to the optimum economic growth and the predicted population growth rate. Overall, given the ranking of the policy packages in short-term to long-term objectives, the importance of maintaining the current allocated ratio, especially in the scenarios related to the optimum economic growth and the predicted population growth rate, has decreased.

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