Adaptive optimal sustainability framework in urban water supply system under different runoff scenarios

Mahdi Moudi (✉ moudi@cuit.edu.cn)

Chengdu University of Information Technology

Research

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Adaptive optimal sustainability framework in urban water supply system under different runoff scenarios

Moudi Mahdi *

College of Management, Chengdu University of Information Technology, Chengdu 610103, China.

Abstract

Recent droughts have caused a crisis in the water supply procedure, because as available water resources become more limited, the imbalance between the growing water demand and water supply in different sectors leads to unsustainability in the system. Thus, this study proposes a dynamic model to optimize water supply system under different scenarios aimed at improving sustainability of system. In fact, due to the negative impacts of the water crisis, the sustainability of the dynamic water supply system is evaluated and optimized according to the performance indicators of the system. Also, to investigate the proposed model, a real case study of the Sistan basin in Iran over ten years period is conducted. Based on the model, different management insights along with the scenario analysis are considered in order to assess the sustainability of system in more detail. According to the final output, the highest level of sustainability is related to the domestic sector because it has higher reliability and less vulnerability than other sectors.

Keyword: Sustainability of system, Water supply, System performance, Shortage

1. Introduction

Due to rapid population growth and climate change, meeting water demand in a regional water supply system has become a major challenge for decision makers (Xiong et al. 2020; Brown et al. 2015). However, the lack of available water resources, along with the lack of proper water supply management, increasingly threatens the sustainability of the urban water supply system, and the environment (Rathnayaka et al. 2016). Indeed, the sustainability of the water supply system depends on improving efficiency of adaptation measures on both supply and demand sides, so that on the demand side, demand management to delay the need for new resources, and on the supply side, rising the efficiency of optimal use of water resources should be considered (Waite 2010). By definition, sustainability of water supply system is formulated as the geometric mean of performance indices: reliability, resilience, and vulnerability; and it reflects the integrated behavior of the system by considering the possible consequences of the imbalance between water demand and water supply (Sandoval-Solis et al. 2011; Srdjevic and Srdjevic 2017). Indeed, the mentioned indices are considered as the main indicators for analyzing the performance of water supply system in the long-run (Gu et al. 2017; Hashimoto et al. 1982), which in sustainable management of large-scale water

* Corresponding author. *E-mail address:* moudi@cuit.edu.cn

resources planning, in comparison with other cases, they operate as the criteria for the success of sustainable development strategies of system in different hydrological conditions (Srdjevic and Srdjevic 2017). However, the focus of scientific research on the sustainability of the water supply system has recently increased due to runoff uncertainty and the effects of human activities in the basins. For instance, Ryu et al. (2009) developed a multi-criteria decision mechanism (MCDM) by considering subjective scales to analyze the periodic effects of the water resource allocation process on system sustainability. Butler et al. (2017) developed an integrated reliability, resilience, and sustainable framework for the sustainable management of water resources, and then, by analyzing the threats related to water system on large scale, and their effects on system performance, socio-economic, and environmental consequences, provided solutions for decision makers of system. Abdi-Dehkordi et al. (2021) proposed a spatial distribution framework based on the system dynamics approach to enhance the sustainability of the water system, so that a set of individual indicators to evaluate the behavior of the water system by considering the quantitative and qualitative aspects of the environment was considered. Jun et al. (2011) proposed a new framework for the sustainable management of water resources with regard to the four indicators of potential flood damage (PFDC), potential drought damage (PDDC), potential water quality deterioration (PWQDC), and watershed evaluation index (WEIC). Chen et al. (2018) developed a credit-based hierarchical programming model regarding the security of water resources to manage sustainability of regional water system.

Although research on sustainability of water supply system has been well highlighted in the literature, recently, the sustainability of the water supply system seems to be addressed as one of the major concerns when it comes to multi-sectoral sustainability. To this end, this paper develops a dynamic optimal framework to improve sustainability of water supply system considering various performance indicators including resilience, reliability, and vulnerability. However, given that the process of water supply to the sub-areas causing shrinkage of water resources in the basin area, thus, in order to have a long-term vision of the water supply process and to verify that the system is sustainable, in practice, it is vital to propose an optimal framework to improve the sustainability of system. In general, the sustainability measure evaluates water management policies according to the system performance indices intending to investigate the integrated behavior of the system, taking into account possible adverse consequences such as imbalance between supply and demand (Loucks 1997; Sandoval-Solis et al. 2011). However, according to the above descriptions, the main contributions of this study are listed below:

- 1) A dynamic optimization framework has been proposed to cope with drought in the long-term water supply process and to evaluate the system sustainability measure in different sectors.
- 2) Due to the uncertainty in the supply process, different scenarios of water demand and water supply are applied as a management perspective for reviewing and analyzing periodic decisions.

The remainder of this paper is organized as follows. Section 2 develops the framework of this study and case study. Section 3 expands dynamic optimization model. Section 4 proposes study area and data collection. Section 5 includes results and analysis. Section 6 gives concluding remarks.

2. Framework of indices impacting on sustainability of system during water supply process

In general, the sustainability of a water supply system is a reflection of an adaptive operational approach in which the decision maker adjusts system performance based on the amount of available water resources in a given period (Ajami et al. 2008). Indeed, the optimal performance of system in the long run, regarding limited resources, reflects the improvement of system sustainability, so that a performing system is also considered as a sustainable system (Fechete and Nedelcu 2019). Thus, the sustainability of the water supply system is the integration of performance indicators (as shown in Fig.1) that are adaptive features of the system for the use of available water resources and, in fact summarizes the alternative performance of the system from the perspective of consumers in a given period (Sandoval-Solis et al. 2011).

Fig.1. Framework of water supply system in terms of optimal sustainable development

To this end, the definition provided for the sustainability measure of the water supply system is as follow (Karamouz et al. 2017; Loucks 1997):

$$S_t^j = \eta_t^j * \lambda_t^j * (1 - \beta_t^j) \quad (1)$$

Where, S_t^j is defined as value of the sustainability, η_t^j is reliability index, λ_t^j refers to resilience indicator, and β_t^j is vulnerability index related to sector j in period t . Indeed, reliability, resilience, and vulnerability are considered as performance indices of water supply system (Gu et al. 2017; Hashimoto et al. 1982), which are calculated as follows:

2.1 Reliability

By definition, reliability of system is the probability that satisfactory state of system will remain unchanged for a certain time. Thus, water supply system reliability is measured by whether the system meets a predetermined demand criterion and if not, what rate of the demand is met during the simulated period (Hashimoto et al. 1982; Ajami et al. 2008; Maestro et al. 2014):

$$\eta_t^j = \frac{1}{T} \sum_{t=1}^T (1 - \mu_t^j) \quad t = 1, \dots, T \text{ and } j = 1, \dots, m \quad (2)$$

Where, μ_t^j treats as a binary variable (0 and 1), so that if the requested demand is supplied in period t , then the system is satisfied, so $\mu_t^j = 0$, and vice versa, if there is water shortage $\mu_t^j = 1$. However, the high value of the η_t^j index indicates the high reliability of water supply system.

2.2 Resilience

Resilience refers to the probability that a system will improve from a failure state to an UN failure state. Therefore, the resilience of the water supply system for sector j is referred to as the probability that the system will not experience water shortage during the simulated period (Asefa et al. 2014; Hashimoto et al. 1982):

$$\lambda_t^j = \frac{\sum_{t=1}^T \rho_t^j}{T - \sum_{t=1}^T \mu_t^j} \quad (3)$$

Where ρ_t^j is defined as the transition between failure and UN failure modes in the given period whose value is 1 or 0:

$$\rho_t^j = \begin{cases} 1 & \text{if } y_{t-1}^j \in \text{failure and } y_t^j \in \text{UN failure} \\ 0 & \text{Others} \end{cases} \quad (4)$$

It needs to mention that y_t^j is referred to a given time series of a parameter of interest.

2.3 Vulnerability

The vulnerability of a system is referred to probability value of failures in the simulated period (Sandoval-Solis et al. 2011). By definition, the vulnerability of the water supply system indicates the average of maximum shortages at all failure times (Goharian et al. 2017; Hashimoto et al. 1982; Gu et al. 2017):

$$\beta_t^j = \frac{1}{T_V^j} \sum_{t=1}^T \frac{z_t^j * R_t^j}{D_t^j} \quad (5)$$

119 Where, D_t^j and R_t^j indices represent the water demand and water shortage rates in sector j , respectively,
 120 and T_v^k is referred to as the total number of shortage periods.

$$121 \quad T_v^j = \sum_{t=1}^T \sum_{j=1}^m z_t^j \quad (6)$$

122 In addition, the definition of water shortage in period t is as follows:

$$123 \quad R_t = \begin{cases} \sum_{j=1}^m D_t^j - \sum_{j=1}^m x_t^j, & \sum_{j=1}^m D_t^j > \sum_{j=1}^m x_t^j \\ 0 & , \quad \sum_{j=1}^m D_t^j < \sum_{j=1}^m x_t^j \end{cases} \quad (7)$$

124 However, the rate of water shortage in sector j depends on the gap between the amount of water demand
 125 D_t^j and water supply x_t^j in period t .

126 **3. Dynamic optimization model**

127 Based on the applied long-term evaluation framework, a dynamic model is proposed to optimize the
 128 sustainability of the water supply system in a given period.

$$129 \quad \max F = \eta_t^j * \lambda_t^j * (1 - \beta_t^j) \quad (8)$$

130 *Constraints are listed as below:*

131 The volume of water in the reservoir based on the volume of water availability related to the prior period
 132 and the rate of runoff is defined as below:

$$133 \quad l_t = \min \left[l_{t-1} - \sum_{j=1}^m x_t^j + I_t, \bar{l} \right] \quad (9)$$

134 Where, l_{t-1} is the volume of available water in the reservoir in period $t - 1$, I_t is the rate of runoff during
 135 the period t , and $\bar{l}$ is referred to the maximum capacity of the reservoir.

136 Besides, the amount of water allocated to different sectors must be less than the amount of water in the
 137 reservoir:

$$138 \quad 0 \leq \sum_{j=1}^m x_t^j \leq l_t \quad (10)$$

139 In addition, the volume of water transferred to sub-areas must be less than the amount of available water in
 140 the reservoirs:

$$141 \quad l_t^{\min} \leq l_t \leq \bar{l} \quad (11)$$

142 However, the global dynamic model of this study to reduce the impacts of drought on the water supply
 143 system and maximizing the level of sustainability in the optimal system is as follow:

$$\max F = \eta_t^j * \lambda_t^j * (1 - \beta_t^j)$$

$$144 \quad \left\{ \begin{array}{l} \eta_t^j = \frac{1}{T} \sum_{t=1}^T (1 - \mu_t^j) \quad t = 1, \dots, T \text{ and } j = 1, \dots, m \\ \lambda_t^j = \frac{\sum_{t=1}^T \rho_t^j}{T - \sum_{t=1}^T \mu_t^j} \\ \beta_t^j = \frac{1}{T_v^j} \sum_{t=1}^T \frac{z_t^j * R_t^j}{D_t^j} \\ T_v^j = \sum_{t=1}^T \sum_{j=1}^m z_t^j \\ R_t^j = \begin{cases} \sum_{j=1}^m D_t^j - \sum_{j=1}^m x_t^j, & \sum_{j=1}^m D_t^j > \sum_{j=1}^m x_t^j \\ 0, & \sum_{j=1}^m D_t^j < \sum_{j=1}^m x_t^j \end{cases} \\ l_t = \min \left[l_{t-1} - \sum_{j=1}^m x_t^j + I_t, \bar{l} \right] \\ 0 \leq \sum_{j=1}^m x_t^j \leq l_t \\ l_t^{\min} \leq l_t \leq \bar{l} \\ \rho_t^j = \begin{cases} 1 & \text{if } y_{t-1}^j \in \text{failure and } y_t^j \in UN \text{ failure} \\ 0 & \text{Others} \end{cases} \\ w_\eta + w_\lambda + w_\beta = 1 \end{array} \right.$$

145 **4. Case study and data collection**

146 The Sistan Basin (30°–31.5° N to 61°–66° E), also known as Hamoon watershed, is located in Sistan and
 147 Baluchestan province of Iran near the border of Iran-Afghanistan. In recent years, due to the arid climatic
 148 conditions of the region and the reduction of the average annual rainfall (60 mm, which occurs mainly in

winter) on the one hand, and operating of successive dams on the Helmand River as the main source of water supply in this basin, on the other hand, the drought situation has become extremely acute (He et al. 2021; Najafi, and Vatanfada 2011). For mentioned reasons, the decision-makers to manage the water demand of the two sub-areas of Zabol and Zahedan, diverted the runoff flowing to Helmand river to the Chahnimeh reservoirs (Yao et al. 2019). But recently, with the intensification of drought and shrinking of water resources, decision makers have been unable to maintain the deviation between water demand and water supply different sectors, so this study considered the Sistan basin as a the study area (Fig.2).

Fig.2. Sistan Basin location, Iran

Therefore, the data related to the capacity of reservoirs and the amount of runoff are derived from the Bulletin of Regional Water Department of the Sistan and some citations (Thomas and Varzi 2015; Yao et al. 2019; He et al. 2021). Besides, data on water demand for the three sectors of agricultural, industrial, and domestic are extracted from statistical Bulletin registered with the Sistan and Baluchestan Regional Water Authority Department.

Table 1

Parameter of water demand in sub-areas

j		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Zabol (10^6m^3)	AGR	49.17	52.65	50.82	52.00	55.62	53.31	53.92	50.47	57.05	56.43
	IND	11.58	10.86	12.09	13.29	13.01	16.93	14.78	13.41	15.23	16.11
	DOM	5.16	6.17	6.64	7.14	6.48	7.86	7.32	8.44	9.27	9.84
Zahedan (10^6m^3)	AGR	24.38	23.79	21.85	24.07	25.21	27.69	28.41	28.17	29.57	31.71
	IND	33.14	35.16	43.79	37.19	41.56	42.27	41.96	44.40	43.16	45.78
	DOM	19.43	21.14	22.68	23.36	24.08	23.76	27.50	32.33	25.64	28.53
Streamflow (m^3s^{-1})		6.23	5.96	5.38	6.87	6.16	5.75	4.89	6.03	5.46	5.74

• AGR= Agricultural sector, IND= Industrial sector, DOM= Domestic sector

Table 2

Reservoirs Parameters in the basin (10^6m^3)

Reservoirs	Chahnimeh 1	Chahnimeh 2	Chahnimeh 3	Chahnimeh 4	Zabol	Zahedan
Dead storage	51.22	36.29	39.65	89.58	16.23	23.16
Active storage	139.28	107.67	128.73	337.86	43.35	51.47
Total storage	220.00	220.00	220.00	820.00	155.00	155.00

5. Model results and analysis

5.1 Adopted optimal water supply to sub-sectors

Table 3 are listed the optimal outputs related to water allocation between sectors of the two sub-areas.

According to the output, the amount of water allocated to the agricultural sector in Zabol is more than other sectors since the demand for water in this sector has been higher. For the city of Zahedan, the largest volume of water has been allocated to the industrial sector, so that between 2015 and 2017, the volume of water allocated to this sector was higher than $40.00 * 10^6\text{m}^3$. Also, the volume of water allocated to the domestic sector of Zahedan in the whole period is almost four times that of Zabol city, so that the most water allocated to this sector is related to the year 2015 with a value equal to $30.19 * 10^6\text{m}^3$.

By analysis of system sustainability (as shown in Table 4), the domestic sector has acquired the highest value for both sub-areas (0.491, 0.389) since the status of this sector in all three factors of reliability, resilience (resilience factor has not changed because the status of the system did not alter from failure to UN failure), and vulnerability is better than other two sectors.

Table. 3

Optimal water allocated to sectors (10^6m^3)

x_t^j		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Zabol	AGR	47.36	48.17	49.74	50.53	52.09	51.87	50.34	49.49	56.59	54.12
	IND	10.13	09.72	10.67	11.58	12.28	14.38	13.58	12.17	14.37	15.27
	DOM	4.79	5.36	5.14	6.28	5.87	6.41	6.18	7.17	8.59	7.79
Zahedan	AGR	19.76	21.08	19.39	22.53	23.78	26.02	25.94	27.49	26.76	28.34
	IND	32.35	33.64	40.73	36.01	39.00	40.92	39.81	42.14	42.68	44.46
	DOM	18.19	20.04	21.36	22.14	23.36	22.61	25.71	30.19	24.28	27.09

Table 4

Analysis of sustainability measure

	Reliability			Resilience			Vulnerability			Sustainability		
	AGR	IND	DOM	AGR	IND	DOM	AGR	IND	DOM	AGR	IND	DOM
Zabol	0.2	0.4	0.4	1	1	1	0.036	0.028	0.019	0.192	0.388	0.491
	DOM=IND>AGR			DOM=IND=AGR			AGR>IND>DOM			DOM>IND>AGR		
Zahedan	0.3	0.2	0.4	1	1	1	0.029	0.030	0.026	0.194	0.194	0.389
	DOM>AGR>IND			DOM=IND=AGR			IND>AGR>DOM			DOM>IND=AGR		

In addition, Figure 3 shows an analysis maintaining the deviation between the total volume of water supplied to each sub-areas and total water demand. Based on the final output, the maximum gap between water demand and water supply for Zahedan city was experienced in 2008 and 2010 with water supply rate of $70.30 * 10^6m^3$ and $81.48 * 10^6m^3$ and water demand equal to $76.95 * 10^6m^3$ and $88.32 * 10^6m^3$, respectively, while this rate for Zabol city is related to 2009 and 2013 with a value equal to $63.25 * 10^6m^3$ and $72.66 * 10^6m^3$ for the supply side and $69.98 * 10^6m^3$ and $78.10 * 10^6m^3$ for the demand side. Although the optimal process of water supply has reduced the deviation between water demand and water supply, due to increasing demand for water regarding population growth and also reducing runoff rates in the Sistan basin, the unsustainability of the water supply system is still prominent.

Fig.3. Maintaining the deviation between water demand and water supply

5.2 Scenario analysis of sustainability measure in water supply procedure

Given that water supply measures in the upcoming years are influenced by uncertainty in the volume of runoff, therefore, scenario analysis method proposed by Xu et al. (2019) is considered to analyze the sustainability of water supply system. Indeed, according to historical runoff data, the two new scenarios, streamflow rate 90% and 70% of current runoff rate, are considered to provide an optimal solution and to assess sustainability measure.

Table 5

Scenario analysis of water supply

j	I_t	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Zabol	AGR	46.19	46.96	47.41	45.5	49.33	49.56	46.59	49.93	54.62	54.24	46.19
	IND	9.00	9.36	8.52	10.84	12.07	10.6	10.71	12.47	13.99	13.26	9.00
	DOM	3.82	5.37	5.03	5.46	3.69	6.88	5.5	5.79	7.37	6.92	3.82
Zahedan	AGR	18.79	19.45	17.86	21.39	23.87	25.42	25.23	26.63	23.5	24.57	18.79
	IND	31.96	33.11	38.85	36.1	41.73	41.31	42.09	42.89	41.71	43.99	31.96
	DOM	20.19	22.44	22.98	23.46	24.77	20.52	26.68	28.17	25.99	26.61	20.19
Zabol	AGR	46.53	46.96	45.02	45.63	47.58	49.13	45.68	49.69	55.78	52.86	46.53
	IND	8.41	10.36	7.57	9.73	10.87	9.39	9.15	12.81	12.27	11.96	8.41

	-30%	DOM	4.29	4.93	4.62	4.38	3.69	5.66	5.82	5.13	7.5	6.51	4.29
Zahedan		AGR	17.76	18.39	17.02	21.61	23.12	24.33	22.97	26.53	22.42	23.97	17.76
		IND	32.21	33.67	37.25	34.94	40.56	42.1	40.98	41.64	41.71	42.28	32.21
		DOM	18.81	20.65	21.43	22.58	23.61	20.32	25.29	26.92	26.64	26.03	18.81

By comparing the outputs listed in Table 5 with Table 3, the deviation between water demand and water supply for the domestic sector under the following scenarios is slightly different, while this value for the other two sectors, as the largest water recipient sectors, has further deviated.

In addition, according to the analysis of sustainability measure indicated in Figure 5, in the first scenario (reduced runoff by -10%), the minimum rate of sustainability in Zabol and Zahedan is related to the agricultural sector with values (0.1932, 0.1946) respectively, while for the second scenario (reduced runoff by -30%), the minimum sustainability is related to the industrial sector with values equal to (0.1954 and 0.0972) for the two cities of Zabol and Zahedan, which means these two sectors are the most sensitive sectors in terms of sustainable development. Also, the domestic sector, which had less water demand than the other two sectors, had maximum sustainability in both scenarios.

Fig.4. Scenario analysis of sustainability measure in water supply procedure

5.3 Adjusted strategies for analysis of sustainability measure under demand shrinkage scenarios

According to recent studies (Najafi and Vatanfada 2011; Moghaddamnia et al. 2009; Yao et al. 2019), the Sistan basin will experience rainfall reduction and temperature rising, which means that the situation of water resources will be more limited. On the other hand, the increase in demand for water due to population growth causes the expansion to deviate between the demand for water and water supply. However, adaptation measures for water supply focus on proposing water distribution policies and strategies between different sectors and neglect the development of water demand management options. To this end, proposing

practical managerial insights compatible with the current situation, such as the development of leverage policies such as tariffs for water, the use of advanced technologies to reduce demand for water, such as the development of drip irrigation systems, treatment and reuse of wastewater, can be alternatively effective for conserving water resources. Thus, this study applies the demand shrinkage scenarios (at 10% and 20% less than the actual demand) proposed by He et al. (2021) to evaluate the sustainability of the water supply system.

According to the output listed in Table 6, the reliability and resilience of all three agricultural, industrial, and domestic sectors show an improvement compared to Table 4, but the value of the vulnerability factor for all three sectors has not changed much. In general, with the improvement of these factors, the sustainability of the system has become more optimal than before.

Table 6

The impact of demand shrinkage scenarios on sustainability measure

j	Demand shrinkage	Reliability			Resilience			Vulnerability			Sustainability		
		AGR	IND	DOM	AGR	IND	DOM	AGR	IND	DOM	AGR	IND	DOM
Zabol	10%	0.3	0.5	0.6	1	1	0.2	0.040	0.035	0.015	0.288	0.482	0.591
Zahedan		0.4	0.6	0.6	1	0.2	1	0.033	0.037	0.028	0.387	0.578	0.583
Zabol	20%	0.7	0.5	0.5	0.2	0.4	0.5	0.041	0.026	0.017	0.671	0.487	0.492
Zahedan		0.5	0.6	0.7	0.2	0.3	0.6	0.032	0.039	0.021	0.484	0.672	0.587

5.4 Discussion

In general, due to climate change, the water crisis problem is becoming more acute, which can be minimized with proper planning. While the multi-sectoral users in sub-areas request different volumes of water by different priorities, the development of new adaptive measures to prioritize water supply between key sectors can increase system sustainability. Besides, in areas such as Sistan, which is highly dependent on the volume of runoff, proposing managerial insights is very effective in reserving available waters. In this regard, the rate of water consumption depends on the rate of population (Of Sciences 1999), so that increasing population and the need for food, would increase consumption of fresh water. Therefore, strategic simulation of population distribution patterns in order to analyze water demand, development of more efficient irrigation systems, and alteration of crop patterns, etc. can help to better manage the limited water resources. However, according to the above description, the superiority of the proposed model is as follows:

- 1) The proposed framework in this study is a practical mechanism to optimize the water supply system at the regional scale and improve sustainability under different scenarios in an uncertain

environment, which provides a long-term perspective to the basin authorities and facilitates the planning of limited water resources in order to maximize the sustainability of system.

- 2) To minimize the impacts of runoff uncertainty on the optimal water supply process, the development of appropriate adaptive measures to maintain the deviation between water supply and water demand is effective. To this end, a sole focus on water resources management does not lead to adaptation, and the development of new policies such as demand shrinkage scenarios can lead to increased long-term system sustainability.

6. Conclusion

Since the sustainability of the water supply system depends on the status of regional water resources, this study proposed an optimal framework for the sustainability of water supply system between three sectors in an uncertain environment. In fact, an assessment index was applied for the sustainable development of the system, to analyze shortage in the regional water supply system based on the performance indicators. Also, a case study from Iran was proposed to examine the developed model. However, this study lists the following recommendations based on the outputs: 1) Based on the degree of drought, decision makers can first distinguish the more sensitive sectors according to the objective function and then allocate water to each of these sectors according to their priority for system sustainability. 2) Sustainable water conservation and mitigation of drought impacts require the development of innovations that are compatible with the severity of the water crisis in the sectors that receive the most water. 3) Given that the uncertainty of climate change has not been proposed in this study, projecting the climate change patterns to examine the scale and amount of runoff and then planning for optimal water allocation in the basin area can lead to the development of strategic management of system sustainability. 4) Finally, the expansion of long-term policies with a focus on increasing system reliability and resilience versus reducing system vulnerability reflects sustainable system development.

Declarations

Availability of data and material

Not applicable.

Competing Interests

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294

295 **Authors' contributions**

296 Not applicable.

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299

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