Regional Sustainability

Volume 2 | Issue 1 Article 7

1-1-2021

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Recommended Citation

Yang, Shuhong and Yang, Tao (2021) "Exploration of the dynamic water resource carrying capacity of the Keriya River Basin on the southern margin of the Taklimakan Desert, China," *Regional Sustainability*: Vol. 2 : Iss. 1 , Article 7.
DOI: 10.1016/j.regsus.2021.01.005
Available at: https://egijournals.researchcommons.org/regional-sustainability/vol2/iss1/7

Regional Sustainability 2 (2021) 73–82

Contents lists available at ScienceDirect

Regional Sustainability

journal homepage: www.keaipublishing.com/en/journals/regional-sustainability

Full Length Article

Exploration of the dynamic water resource carrying capacity of the Keriya River Basin on the southern margin of the Taklimakan Desert, China

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ARTICLE INFO

Keywords:
Climate change
Economic development
Technological advancement
Water resource carrying capacity
Keriya River Basin

ABSTRACT

The water resource carrying capacity (WRCC) in river basin changes dynamically under climate change, economic development, and technological advancement. Climate change affects hydrological processes and spatial/temporal distribution of water resources; while economic development and technological advancement can also affect the balance of water resources systems. Under climate change, economic development, and technological advancement, it is of great significance to explore the dynamic behavior of WRCC in river basins. This will help to alleviate water resources security issues and build a sustainable water resources system. This study was carried out to evaluate the dynamic WRCC using the "climate, economics, and technology-control objective inversion model", which used total water consumption, water-use efficiency, and restrained total pollutant control in the water functional area as boundary conditions. This study was conducted on the Keriya River Basin, a sub-catchment located in southern margin of the Taklimakan Desert. The WRCC in the Keriya River Basin in 2015 was calculated, and the trends in the short term (2020), middle term (2030), and long term (2050) were predicted. The results revealed that climate change factors have a positive effect on WRCC in the Keriya River Basin, which leads to an increase in total water resources. Economic and technological development exhibits an overall positive effect, while increasing in water consumption and sewage discharge exhibit a negative effect.

1. Introduction

Water is essential for human survival and social development (Yang et al., 2019). Water resource carrying capacity (WRCC) has been changing dynamically due to climate change, economic development, and technological advancement (Jonathan, 1999; Song et al., 2011; Wang et al., 2014). The IPCC report indicated that the global average temperature increased as much as 0.74 °C from 1906 to 2005, and the rate of temperature increment in the past 50 years was around twice that of 100 years ago (IPCC, 2007). The trend of temperature change in China over the past century is consistent with that of global temperature change. The statistics showed that the

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https://doi.org/10.1016/j.regsus.2021.01.005
Received 9 June 2020; Received in revised form 13 December 2020; Accepted 29 January 2021
Available online 12 February 2021

Table 1
Partitioning of water resource region in the Keriya River Basin.

Sub-region	Distribution	Area ($\times$ 10^4 hm^2)	Description
IV–1	Middle and upper reaches of the Keriya River Basin	83.82	Areas above the Nunumaimaitilangan Hydrological Station
IV–2	Irrigation area in the lower reach of the Keriya River Basin	4.85	Areas below the Nunumaimaitilangan Hydrological Station
IV–3	Oasis area in the lower reach of the Keriya River Basin	277.23	Areas downstream of the Keriya River Basin entering deserts
IV–4	River areas in the east of the Keriya River Basin	17.71	Aqiang River, Pishge River, and Tamiya River
Total		383.61	

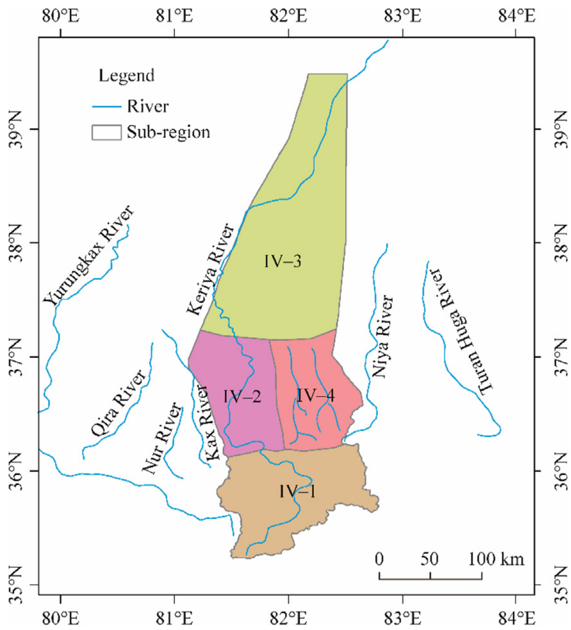

Fig. 1. Location of the study area and distribution of water resource sub-region in the Keriya River Basin. IV–1, middle and upper reaches of the Keriya River Basin; IV–2, irrigation area in the lower reach of the Keriya River Basin; IV–3, oasis area in the lower reach of the Keriya River Basin; and IV–4, river areas in the east of the Keriya River Basin.

average surface temperature rose 1.38 °C in China during 1951–2009, with an average of 0.23 °C in every 10 years (Editing Commission of the Third National Report on Climate Change of China, 2011), which is consistent with the fifth IPCC report (IPCC, 2014). Temperature plays an important role in the water cycle (Nogueira, 2019), which affects spatial and temporal distribution of water resources (Men et al., 2019; Tukimat and Harun, 2019), resulting in the changing of WRCC. Moreover, with the development of economy and technology, especially the increment in water consumption and sewage discharge, the changes in water balance and the dynamic WRCC become more intensive (Wang et al., 2017). Therefore, it is of practical significance to study the dynamic behavior of WRCC under the changing climate, economic, and technological development.

There have been a number of researches to study the methods for calculating WRCC. Among these, the empirical formula is the most straightforward method, and the operation is easy (Hariyanto, 2017; Li and Liu, 2019). A disadvantage of this approach is the lack of interaction among economy factors, society factors, and environment factors. Moreover, there is a lack of quantitative evaluation of specific technical support factor, such as regulation schemes of river basin. Therefore, the empirical method is insufficient to evaluate WRCC under dynamic change conditions. The second method is a comprehensive evaluation approach, which builds a catastrophe progression method and correlation analysis for WRCC assessment (Song et al., 2018; Wu and Hu, 2020). A disadvantage of this technique is that systematic aspects are not fully considered during the calculation, and corresponding indicators and standards are difficult to select; therefore, the results are prone to be subjective and sensitive to expert experience. The third method comprehensively considers economy factors, society factors, and ecology factors to evaluate the complexity of water resources system (Wang et al., 2018; Yang et al., 2019). The disadvantage of the system analysis method is that the calculation is not straightforward and complex. Therefore, the system analysis method is not easy to apply into real application; moreover, the model is not unique (Zuo, 2017; Yi et al., 2018).

Water resource is the most important natural resources in the Keriya River Basin, which is located in the Taklimakan Desert, Xinjiang Uygur Autonomous Region of China. According to Hotan District Water Resources Bulletin (Ministry of Water Resource of Xinjiang, 2016), the total water consumption of the Keriya River Basin was 5.9139 $\times$ 10^8 m^3 in 2015, and the planned water consumption in the near term (2020), middle term (2030), and long term (2050) planning is 6.0280×10^8, 6.3055×10^8, and 6.8605×10^8 m^3, respectively. To achieve sustainable utilization of water resources, it is of practical importance to evaluate the dynamic WRCC in the Keriya River Basin under the changes of climate, economy, and technology (Cheng et al., 2019; Wang et al., 2019; Wei et al., 2019; Peng and Deng, 2020). Therefore, this study adopted the "climate, economics, and technology-control objective inversion model" (CET-COIM model) to evaluate the dynamic WRCC in the Keriya River Basin under the impacts of climate change and human activities, which provides a useful tool for supporting regional water security and social economy development (Kang et al., 2019).

2. Materials and methods

2.1. Study area

Taklimakan Desert is located in arid region of China, which has a large diurnal temperature variation. The area of Taklimakan Desert has extended about 100 km to the south in the past 1000 years, which affects the regional economic and social development (Yu et al., 2015, 2017). The Keriya River Basin is located between 35°14′–39°29′N and 81°09′–82°51′E with the Kunlun Mountains to the south and the Tarim Basin to the north, covering an area of 3.84×10^6 hm^2. The Keriya River Basin includes Keriya River, Tamiya River, Pishge River, Aqiang River, Suketaya River, and others. All of these rivers are originated from the northern slopes of the Kunlun Mountains and flow from south to north into the Taklimakan Desert. The Keriya River Basin is characterized as an arid and semi-arid region, with average annual precipitation of 85.8 mm and average annual evaporation of 2379.0 mm. It had a total population of 2.82×10^5, GDP of 2.37×10^9 CNY, cultivated land of 2.04×10^4 hm^2, and total water resources of 10.40×10^8 m^3 in 2015. Agriculture is the leading industry in the Keriya River Basin, which also accounts for a large proportion of the overall water consumption.

2.2. Partitioning of water resource region

The Keriya River Basin includes an ecological sensitive sub-region of the Taklimakan Desert and an ecological protection region (Zuo, 2017). We divided the Keriya River Basin into four sub-regions (IV–1, IV–2, IV–3, and IV–4) according to the natural geographic conditions, water resources distribution, human activities, and economic and technological levels (Table 1; Fig. 1). IV–1 is dominated by mountain ecosystem, which has few human activities and low economic development; IV–2 is dominated by artificial oasis ecosystem, which is a water-consuming area with high-level human activities and economic development; IV–3 is dominated by desert ecosystem, which is the drainage and dissipation areas of water resource with fragile ecosystem; IV–4 is dominated by natural oasis ecosystem, where the consumption and dissipation of water resource occur.

The main characteristics of each calculation unit (sub-region) are as follows: sub-region IV–1 is the runoff yield area with abundant precipitation and water resources stored in the forms of glaciers and snow. Sub-regions IV–2 and IV–4 are the watershed flow concentration and spring overflow areas, as well as human habitation areas. In these areas, the surface water and groundwater reserves are sufficient, and the consumption of water resource is large. Sub-region IV–3 is a water scarcity area located at the downstream of the Keriya River. The water resources in the upper and middle reaches of the Keriya River are generally depleted by evaporation and infiltration, where the surface water can only reach sub-region IV–3 during the flood season.

2.3. Selection of the computing model

In this study, we introduced climate change, economic development, and technological advancement scenarios factors to the "control objective inversion model" initially developed by Zuo (2005), and proposed the "climate, economics, and technology-control objective inversion model", referred to as the CET-COIM model hereafter. The aim is to maximize the objective function constructed with economic and social scale supported by the basin. Thresholds of planned water consumption in the near term, middle term, and long term were introduced as the external constraints to maintain the sustainability of ecosystem. Once the objective function is solved, the current WRCC and its prediction values in the short term, medium term, and long term can be predicted.

The population, cultivated land area, and industrial added value were used in CET-COIM model to solve the objective function, and other related indicators were classified into these three groups. We constructed a sub-model to measure the relationship among meteorological, economic, and technological impact factors, and established the land surface water resources system by taking climate models, economic models, and technological models as external inputs to the land surface water resources system. The constraints of CET-COIM model included water resources cycle transformation equation, pollutant cycle transformation equation, economic and social system constraint equation, WRCC constraint equation, ecological and environmental control objective constraint equation, and the thresholds of planned water consumption. Here, climate models and economic and technological models were used as the input modules for CET-COIM model. The objective function and constraints for CET-COIM model are as follows:

(1) Objective function (maximum scale of economic society):

$$Max(P,\ A,\ S,\ \ldots), \tag{1}$$

where P is population size, represented by total population; A is industrial added value (CNY); and S is cultivated land area (hm^2).

(2) Constraints:

$$\left.\begin{array}{c} Sub\ Mod(RCP) \\ Sub\ Mod(RCP-Q) \\ Sub\ Mod(RETP) \\ Sub\ Mod(RETP-Q) \\ Equations(P_{\mathrm{rec}}, E, Q, W, V) \\ Equations(Q, W, C) \\ Sub\ Mod(P, T, A) \\ In\ equations(W_{\mathrm{s}}, C_{\mathrm{s}}) \end{array}\right\}, \tag{2}$$

where Sub Mod(*RCP*): *RCP* stands for regional climate model prediction. The dataset of climate change prediction produced and published by the National Climate Center of China Meteorological Administration (https://www.ncc-cma.net/) was taken as the constraints to CET-COIM model and the input of land-water resources system. Sub Mod(*RCP-Q*): meteorological factors at different temporal and spatial scales were taken as driving indicators of land-water resources system changes. Sub Mod(*RETP*): *RETP* stands for regional economic and technical model prediction. The annual economic and technical data were taken as the input module to land-water resources system to represent dynamic conditions of water resources under economic and technological changes. Sub Mod(-*RETP-Q*): economic and technological factors at different temporal scales were selected as the driving input indicators to land-water resources system changes. Equations(P_{rec}, E, Q, W, V): the equations were used to express the relationships among the elements in water resources system, where P_{rec} denotes precipitation, E denotes evaporation, Q denotes flow discharge, W denotes waste discharge, and V denotes variation. Equations(Q, W, C): pollutant cycle transformation relationship equation, which quantitatively reflects the transformation relationship of natural water quality and the process of pollutant production and transportation, where C denotes concentration. Sub Mod(P, T, A): the internal constraint equation of the economic and social system, which reflects the constraints among the various indicators in the social economic system, where T denotes water resources carrying capacity threshold and A denotes industrial added value. In equations(W_s, C_s): eco-environmental control index equation, which represents the condition of ecosystem, where C_s denotes sewage pollutant concentration and W_s is total water storage (m^3).

(3) Transformation equation:

Total water volume equilibrium equation:

$$P + Q_{\mathrm{Tran}} + Q_{\mathrm{In}} = E + W_{\mathrm{Cons}} + \Delta W_{\mathrm{Grou}} + \Delta V_{\mathrm{Sur}} + Q_{\mathrm{Out}}, \tag{3}$$

where Q_{Tran} denotes transferred water volume (m^3); Q_{In} and Q_{Out} denote water inflow and outflow (m^3), respectively; E denotes total evaporation (m^3); W_{Cons} denotes total water consumption (m^3); and ΔW_{Grou} and ΔV_{Sur} denote variations in groundwater storage and surface water storage (m^3), respectively.

Available water resources equation:

$$Q_{\mathrm{Can}} = Q_{\mathrm{Self}} + Q_{\mathrm{In}} + Q_{\mathrm{Again}}, \tag{4}$$

where Q_{Can} is available water volume (m^3); Q_{Self} is self-used water volume (m^3); Q_{In} is water inflow (m^3); and Q_{Again} refers water that can be reusable (m^3).

Available water resources distribution equation:

$$Q_{\mathrm{Can}} = W_{\mathrm{Indu}} + W_{\mathrm{Age}} + W_{\mathrm{Life}} + W_{\mathrm{Other}} + \Delta W, \tag{5}$$

where W_{Indu} is industrial water use (m^3); W_{Age} is agricultural water use (m^3); W_{Life} is water for living (m^3); W_{Other} is other industries used water (m^3); and ΔW is surplus available water resource (m^3).

Water resource utilization-water meter consumption conversion equation:

$$W_{\mathrm{Indu}} + W_{\mathrm{Age}} + W_{\mathrm{Life}} + W_{\mathrm{Other}} = W_{\mathrm{Cons}} + W_{\mathrm{Ret}}, \tag{6}$$

where W_{Cons} is total water consumption (m^3) and W_{Ret} is total returned water volume (m^3).

Water resource consumption equation:

$$W_{\mathrm{Cons}} = E_{\mathrm{I}} + E_{\mathrm{A}} + E_{\mathrm{L}}, \tag{7}$$

where E_I is industrial water consumption (m^3); E_A is agricultural water consumption (m^3); and E_L is domestic water consumption (m^3).

Calculation equation of returned water resource utilization:

$$W_{\mathrm{Ret}} = C_{\mathrm{Ret}} + Q_{\mathrm{Ret}}, \tag{8}$$

where W_{Ret} is total returned water volume (m^3); C_{Ret} is returned concentration water (m^3); and Q_{Ret} is returned discharge (m^3).

Total pollutant discharge into the river course equation:

$$W_{\mathrm{WD}} = \sum_{i=1}^{n} [Q_{\mathrm{W}i} C_{\mathrm{D}i} + Q_{\mathrm{W}i}(1 - u_{\mathrm{i}}) C_{\mathrm{W}i}], \tag{9}$$

where W_{WD} is total pollution discharge (m^3); $Q_{\mathrm{W}i}$ is sewage discharge of ith calculation unit (m^3); $C_{\mathrm{D}i}$ and $C_{\mathrm{W}i}$ denote concentration and comprehensive concentration of pollution in the ith calculation unit after sewage treatment, respectively; and u_i is sewage water fraction.

Water quality simulation equation:

$$Q_m C_m = Q_I C_I + W_{WD} - \beta(Q_I C_I + W_{\mathrm{WD}}), \tag{10}$$

where Q_m denotes the flow at control section (m^3); C_m denotes the concentration at control section; Q_I denotes the flow at upstream section (m^3); C_I denotes the concentration at upstream section; and β denotes comprehensive reduction rate of pollution.

Internal constraint equations of economic and social systems:

$$\begin{cases} Y_{I1} \le \dfrac{Y_{\mathrm{Indu}}}{P} \le Y_{I2} \\ Y_{A1} \le \dfrac{Y_{\mathrm{Arg}}}{P} \le Y_{A2} \end{cases}, \tag{11}$$

where Y_{I1} and Y_{I2} denote lower and upper limits of industrial product per capita (CNY), respectively; Y_{A1} and Y_{A2} denote lower and upper limits of agricultural product per capita (CNY), respectively; Y_{Indu} denotes industrial product (CNY); and Y_{Arg} denotes agricultural product (CNY).

Constraint equation of WRCC:

$$T = \frac{V_{\mathrm{use}}}{Q_{\mathrm{can}}} \le 1, \tag{12}$$

where V_{use} is the actual WRCC (m^3).

Eco-environmental control indicator equation:

$$\begin{cases} Q_m \cdot C_m \le W_s \\ C_m \le C_s \\ \Delta W_{\mathrm{Eco}} = \Delta W + Q_{\mathrm{Ret}} - W_{\mathrm{s}} \end{cases}, \tag{13}$$

where ΔW_{Eco} is surplus available ecological water (m^3) and ΔW is variation of water storage (m^3).

2.4. Iteration method

CET-COIM model is a complex nonlinear model, and its optimal parameter setting is very difficult to solve directly. Therefore, a numerical iteration method was used to find the approximate optimal solution in this study. The key steps of the numerical iteration method (Zhang and Zuo, 2012) are listed as follows:

Assign parameters to CET-COIM model. Parameters are initially estimated with historical data, and then updated during iterations.

P_0 is the initial value, which is the population of the current year (2015), ΔP is the increment step, thus the updated population is expressed as: $P_1 = P_0 + \Delta P$. We determined the initial value P_0 and the increment step ΔP according to the specific situation of the study area.

Substitute P_0 and P_1 into P to determine whether P_0 and P_1 satisfy constraint equation. If P_1 satisfies the equation, let $P_2 = P_1$ and $P_3 = P_1 + \Delta P$; if P_0 satisfies the equation while P_1 does not, dichotomy algorithm is used for the next iteration, i.e., $P_2 = (P_1 + P_0)/2$ and $P_3 = P_1$; and if neither P_0 nor P_1 satisfies the equation, backward step is applied to the next iteration, i.e., $P_2 = P_0 - \Delta P$ and $P_3 = P_0$.

P_2 and P_3 are substituted into P to determine whether P_2 and P_3 satisfy the constraint equation. The iteration is repeated until $|P_{i+1} - P_i| < \varepsilon$.

When the algorithm terminates, we evaluated the values of E, Q, W, and V.

2.5. Estimation of carrying capacity ratio

The ratio between the calculated value or predicted value and the maximal theoretical value can reflect utilization potential of water resource in this basin, which is estimated with the equation as follows:

$$I = \frac{P_S}{P_C}, \tag{14}$$

where I is the carrying capacity ratio; Ps denotes the actual or predicted value; and Pc denotes the maximum theoretical value.

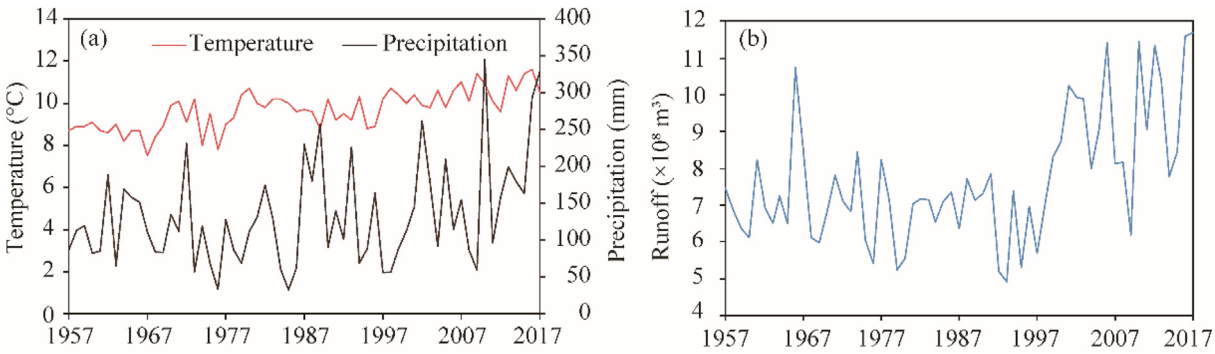

Fig. 2. Changes of the temperature and precipitation (a) and runoff (b) in the Keriya River Basin during 1957–2017.

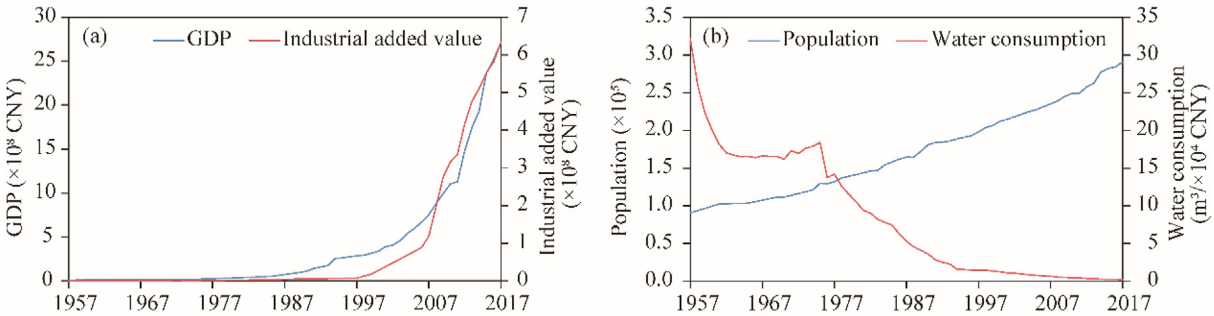

Fig. 3. Changes of economic indicators (a) and technical indicators (b) in the Keriya River Basin during 1957–2017.

2.6. Scenario selection

General circulation models (GCMs) are widely used to study the impact of climate change on water resources. Four typical Representative Concentration Pathway (RCP) scenarios, including RCP8.5, RCP6.0, RCP4.5, and RCP2.6, were applied in the fifth IPCC report (IPCC, 2014). China's National Climate Center provided users with simulated and predicted data from Coupled Model Intercomparison Project Phase 5 (CMIP5) with global climate model and regional climate model. Therefore, the third edition of the "Data Set of Climate Change Prediction in China" was used in this study, and three RCP scenarios, including RCP2.6, RCP4.5, and RCP8.5, were used. The precipitation and temperature in periods 1901–2015 (historical period) and 2016–2050 (future period) were used (Gao et al., 2008; Song et al., 2008; Shi et al., 2009, 2010).

In terms of economic and technology scenario, the industrial added value and other related data were chosen in this study (IPCC, 2014). The simulation period was selected as 1901–2015, and the future period was 2016–2050.

2.7. Data sources

In this paper, we extracted some indicators reflecting economic and technological changes from Hotan District Water Resources Bulletin (Ministry of Water Resource of Xinjiang, 2016), including GDP, industrial added value, population, and water consumption.

3. Results and discussion

3.1. Characteristics of climate indicators

Temperature, precipitation, and runoff are the main indicators used to reflect climate change in the study area. Fig. 2 presents the observed hydro-meteorological data during 1957–2017 at the Nuermaimaitilangan Hydrological Station in the Keriya River Basin, which indicated that the trends in temperature, precipitation, and annual runoff are consistent. The temperature exhibited an upward trend from the 1980s in general, which is consistent with the trend of world's climate change (Nogueira, 2019). It is clear in Fig. 2 that the precipitation and runoff in the Keriya River Basin showed an increment trend. The runoff in the Keriya River Basin is mainly recharged by the glacier and snow melting, and partially from precipitation. The increment in temperature accelerates the melting of

Table 2
Calculation results of the dynamic water resource carrying capacity in the current year (2015), the short term (2020), the middle term (2030), and the long term (2050).

Year	Scenario	Population ($\times 10^5$)		Cultivated land area ($\times 10^4$ hm^2)		Industrial added value ($\times 10^8$ CNY)		Carrying capacity
		Actual/Predicted	Bearable	Actual/Predicted	Bearable	Actual/Predicted	Bearable	
2015	RCP2.6	2.82	3.32	3.36	3.99	5.52	6.52	0.85
	RCP4.5	2.82	3.32	3.36	3.97	5.52	6.41	0.85
	RCP8.5	2.82	3.35	3.36	4.00	5.52	6.73	0.83
2020	RCP2.6	3.09	3.61	3.69	4.41	8.66	10.67	0.83
	RCP4.5	3.09	3.69	3.69	4.42	8.66	10.48	0.83
	RCP8.5	3.09	3.65	3.69	4.42	8.66	10.39	0.84
2030	RCP2.6	3.80	5.12	4.54	6.19	30.19	42.13	0.73
	RCP4.5	3.80	5.19	4.54	6.20	30.19	42.66	0.72
	RCP8.5	3.80	5.14	4.54	6.18	30.19	41.94	0.73
2050	RCP2.6	4.64	7.38	5.54	8.49	72.82	111.05	0.64
	RCP4.5	4.64	7.43	5.54	8.56	72.82	112.78	0.64
	RCP8.5	4.64	7.40	5.54	8.47	72.82	111.29	0.64

glaciers, which will inevitably lead to an increment in runoff in a short period such like several years or decades; therefore, the total amount of WRCC increases.

3.2. Economic and technological conditions

In terms of economic and technological indicators, this study used GDP, industrial added value, population, and water consumption to reflect economic and technological changes. As shown in Fig. 3, GDP, industrial added value, and population showed an increment trend between 1957 and 2017; however, the water consumption in the area showed a decrement trend. The population in the study area exhibited the fastest increment trend. Water consumption decreased rapidly between 1957 and 1999 and tended to be stabilized thereafter. GDP and industrial added value increased rapidly after 2000. The reason for these results is that economic and social development can also improve the utilization efficiency of water resource, such as the water reuse technology. Therefore, economic and social development is benefit for the improvement of WRCC.

3.3. Dynamic water resource carrying capacity (WRCC)

We estimated WRCC using CET-COIM model, under the three climate change scenarios RCP2.6, RCP4.5, and RCP8.5, with one economic indicator and one technical indicator. With WRCC and upper limit of regional load as boundary constraints, the maximum scales of bearable population, cultivated land area, and industrial added value under the three different climate change scenarios in the current year (2015), the short term (2020), the middle term (2030), and the long term (2050) were predicted. The results are listed in Table 2.

CET-COIM model was used to optimize the economy and society scale objective function, and the dynamic WRCC were evaluated. CET-COIM model incorporated external modules, such like climate model, economy model, and technology model, and estimated relationships among climate factors, economy factors, and technology factors. Through numerical iterative method, the dynamic WRCC under variable circumstances, for instance RCP2.6, RCP4.5, and RCP8.5, were evaluated.

As shown in Table 2, the advance in economy and technology acts positively in preservation and utilization of water resources. Through analysis and comparison, we found that the optimal dynamic WRCC is under RCP4.5 in the study area. The result in Table 2 displays WRCC in variation situation and its trend in the study area, which leaves sufficient room for the sustainable development of regional economy and society. The result showed that the indices of population, farmland, and industrial added value adopted in the Keriya River Basin are under the limits of maximal theoretical WRCC. All WRCC values of population, farmland, industrial added value are larger than 0.6, which displays a gradual decreasing trend. Although there is still some limitation by coupling economic and technological scenarios and three climate scenarios RCP2.6, RCP4.5, RCP8.5 with CET-COIM model, the model still provides great scientific research and practical application value for evaluating WRCC under the complex climate change and economic and technological systems.

3.4. Optimum scheme selection

As can be seen from Table 2, RCP4.5, as the intermediate scenario, is recommended as the optimal solution for the model. RCP4.5 pattern is more consistent with the current WRCC, as well as the actual condition of the Keriya River Basin. Under this scenario, the largest economic and social scales that can be borne by the water resources in the current year (2015), the short term (2020), the middle term (2030), and the long term (2050) are as follows: populations of 3.32×10^5, 3.69×10^5, 5.19×10^5, and 7.43×10^5, respectively; cultivated land areas of 3.97×10^4, 4.42×10^4, 6.20×10^4, and 8.56×10^4 hm^2, respectively; and industrial added values of 6.41×10^8,

Table 3
Grades of the water resource carrying capacity (I).

Range of I	$I \leq 0.6$	$0.6 < I \leq 1.0$	$1.0 < I \leq 1.5$	$1.5 < I \leq 2.0$	$2.0 < I$
Grade of carrying capacity	Completely bearable	Bearable	Mildly overloaded	Moderately overloaded	Severely overloaded

10.48×10^8, 42.66×10^8, and 112.78×10^8 CNY, respectively. The results showed that RCP4.5 is the most recommended scenario by

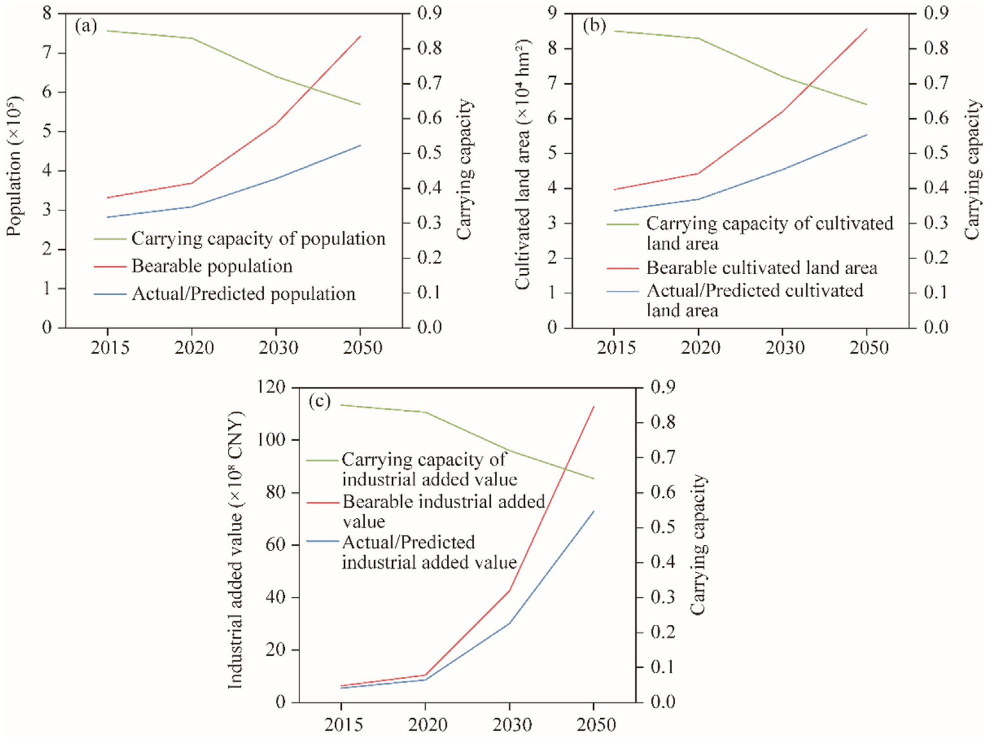

Fig. 4. Changes of WRCC in the population (a), cultivated land area (b), and industrial added value (c) during 2015–2050 (the actual value in 2015 and the predicted values in 2020, 2030, and 2050).

considering population, cultivated land area, and industrial added value. This is mainly because the most parameters in CET-COIM model were calibrated under RCP4.5 scenario, which can truly reflect the dynamic behavior of WRCC in the Keriya River Basin.

3.5. Assessment of WRCC in the Keriya River Basin

The numerical value estimated from CET-COIM model is regarded as the maximum theoretical WRCC in the Keriya River Basin. We divided the thresholds of carrying capacity into five grades, as shown in Table 3.

As can be seen from Fig. 4, the I values all range from 0.6 to 1.0 and exhibit a downward annual trend. The scale of economic and social development in the study area is affordable by the maximum theoretical WRCC in the basin under climate, economic, and technological change scenarios (Fig. 4). In particular, economic and technological development improves water-use efficiency, which affects the increment in WRCC. The results showed that there is a decrement trend in carrying capacity. This is mainly because the economic and technological development in the Keriya River Basin is at relatively low pace in the early stage, where there is limited human activities and water resource utilization activities; therefore, the theoretical WRCC is relatively larger. However, the actual value and calculated prediction value are both smaller than the theoretical value, which leads to the carrying capacity lower than 1.0; on the other hand, the results showed that it is possible to further improve the WRCC in the Keriya River Basin.

4. Conclusions and future works

4.1. Conclusions

The WRCC in river basins plays a key role, and it can be affected by a number of factors. This paper was conducted to evaluate the dynamic WRCC in the Keriya River Basin. The main conclusions are as follow: under the influences of climate change and human activities, WRCC varies dynamically in the Keriya River Basin. The climate factors display a positive effect on WRCC, while economy and technology factors show a bidirectional effect. This study indicates that the most influential part of climate change is the increasing temperature, which shows a positive effect on WRCC. The advance in economy and technology has positive effects on WRCC. With advance in technology and awareness of water resources utilization, the same amount of water resources could support a much larger size of economy and society, which can increase WRCC. However, increment in consumed and pollutant discharge can also result in a decrement in WRCC. The impacts of economic and technological factor are overall positive. This study will fill the research gap on evaluating effects of economy and technology advance on WRCC by CET-COIM model, as well as assessing the dynamic WRCC.

4.2. Future works

Climate system and economy and technology system are both complex systems, the coupling between them is complicated as there are a lot of influencing factors. Therefore, there is still limitation for the current study on the dynamic WRCC. The WRCC has a huge practical significance for constructing security of water resources and water ecology. We need to explore the corresponding research methods and technologies for the small and medium sized catchments with remote location and less economic and social impact. For the study of dynamic WRCC, in addition to climate change and development of economy and technology, there are many other factors need to be analyzed and modeled in future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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