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Calculation of the water resources dynamic carrying capacity of Tarim River Basin under climate change

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ABSTRACT

Currently, climate change is regarded as one of the most important global environmental problems in the world. Future climate change may further exacerbate the contradiction between supply and demand of water resources in China, and affect water resources carrying capacity. This paper, based on the summary of the water resources carrying capacity researches, systematically expounds the concept and connotation of water resources dynamic carrying capacity, and puts forward its calculation theoretical frames and PSO-COIM method (namely the Prediction-Simulation-Optimization-Based Control Object Inversion Model). By constructing the ARIMAX dynamic regression forecasting model of the meteorological factors such as temperature, precipitation and runoff, the paper, taking Tarim River Basin, which is the largest continental river in China, as a typical example, analyses and calculates its water resources dynamic carrying capacity in future different level years under the three kinds of climate situation: RCP8.5, RCP4.5 and RCP2.6. The results of the calculation can clearly reflect the carrying scale of water resources under different climate situations, also determine its carrying levels in the future predicted economic and social development situation, as well as provide the basis for the sustainable development of Tarim River Basin.

Keywords: Water resource carrying capacity; Climate change; Dynamic carrying capacity; PSO-COIM method; ARIMAX

1. Introduction

Currently, climate change is regarded as one of the most important global environmental problems at home and abroad, and it will have a significant impact on ecological environment, water resources and economic society in the world. Therefore, research on the water resource problems under the climate change is of great practical significance. At present, the impact of climate change on hydrology and water resources mainly concentrated on the process response to hydrological cycle and the change of water volume. Due to its complexity of climate change involving meteorology, hydrology, ecology and social economy, there are relatively few quantitative researches on river ecology, water quality and water resources carrying capacity [1,2]. Although there are a lot of research results of water resources evolution trends and adaptation strategies under the climate change, the study of water resources dynamic carrying capacity under climate change, on the whole, is still less.

Research on water resources carrying capacity boasts of an extensive literature [3–5]. At present, the calculation of water resources carrying capacity is generally based on the hydrological and meteorological data under historical long time series and the volume of available water resources with different guarantee rate in the future planning year. The latter is computed in accordance with historical precipitation

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data using the probability and statistic method, thus not objectively showing the volume of available water resources in the future years. Especially, it does not take the climate change into account, thereby not calculating the volume of water resources carrying capacity under the climate change. It hinders the looking for water resources adaption strategies under the climate change, thus it is particularly urgent to do the calculation of water resources carrying capacity, the analysis of evolution trends and countermeasure studies under the climate change. It is of great significance to the positive response to global climate change, scientifically working out development and utilization program of river basin and regional water resources, safeguarding sustainable use of water resources and sustainable development of the national economy. This paper, based on the summary of existing research achievements, puts forward the concept of water resources dynamic carrying capacity, and expounds the calculation methods and application examples of water resources dynamic carrying capacity under the climate change, making up the drawbacks in concept and calculation of traditional water resources carrying capacity.

1.1. Concept of water resources dynamic carrying capacity

The term carrying capacity was originally a physical conception, meaning the maximum load that an object can withstand without producing any damage. Water resources carrying capacity is the extension of carrying capacity concept in the field of water resources. With the increasing seriousness of water issue, water resources carrying capacity, part of the carrying capacity of natural resources, was put forward by Chinese scholars in the late 1980s. In recent years, many experts and scholars at home and abroad have conducted in-depth studies on the concept, connotation and evaluation methods of water resources carrying capacity. Despite the different understanding of water resources carrying capacity, there are no essential differences in the concepts and definitions that all lay emphasis on “water resources development scale” or “water resources supporting capacity”.

The water resources dynamic carrying capacity is put forward on the basis of drawbacks in calculation of traditional water resources carrying capacity which is based on the volume of available water resources with different guarantee rate in the future planning year, thus not objectively showing the change of water resources in the future years due to climate change and other natural factors. The premise of calculation of water resources dynamic carrying capacity is to obtain the volume of available water resources when the climate or human activity changes in the coming years with the help of the climate model and hydrology model. Therefore, water resources dynamic carrying capacity can be summarized as the maximization of the social and economic development water resources system in some basin or region under the climate change and the impact of human activities, when maintaining the virtuous circle of ecological system, can achieve in the foreseeable period of time.

1.2. Connotation of water resources dynamic carrying capacity

Adopting the probability statistic method, the traditional evaluation of water resources carrying capacity makes a study on water resources in the normal process, failing to fully consider water resources dynamic carrying capacity in face of change in external factors. Based on previous researches on traditional water resources carrying capacity, the definition of water resources dynamic carrying capacity contains the following information:

(1) The change of water resources system under the climate change and human activities should be highlighted; that is, it should define the changes of water resources carrying capacity resulting from water resources system change for internal and external causes and take into account the coupling of natural water cycle and social water cycle.
(2) Carrying objects and targets of water resources should be determined. Different from the general concept of water resources carrying capacity, it should highlight the dynamics of its objects and targets, namely the maximization of the social and economic development that water resources system can achieve during different periods, with the dynamic changes of water volume and economic and social development taken into consideration.
(3) Two basic criteria of water resources carrying capacity should be put forward: to maintain the realistic demand for the local social and economic sustainable development; to maintain the stability and virtuous cycle of watershed ecosystem. Thus the harmony between man and nature, between human and water can be achieved.
(4) The spatial scale and spatial range of evaluating water resources carrying capacity should be defined in a certain river basin or region as the basic unit. It should consider the physical mechanism and process of land-surface natural water cycle and the “supply-utilization-consumption-drainage” relation in economic and social water cycle, to realize the coupling between natural water cycle and social water cycle.
(5) The time scale and time range of evaluating water resources carrying capacity should be defined in the predictable period or in the definite period, and it should reflect the dynamic and relative limit nature of water resources carrying capacity. Furthermore, it should reflect that water resources carrying capacity changes with time.

2. Research data and the method

2.1. Calculation framework of water resources dynamic carrying capacity under climate change

Calculation of water resources carrying capacity is a hot issue in the field of water resources research [3]. Currently, there are many calculation methods of water resources carrying capacity, and in summary, they can be divided into three categories: empirical formula method, comprehensive evaluation method and systematic analysis method. The empirical formula method mainly includes background analysis method, conventional trend method and simple quota method. This type of method is relatively simple, but has less study of the correlation among resources, environment and economic society. The comprehensive evaluation method mainly includes comprehensive index method, fuzzy comprehensive evaluation method, principal component analysis method, projection pursuit method and matter element extension model. This type of method can be compared with evaluation criteria by use of some evaluation method to obtain the water resources carrying capacity, and has further application of mathematical methods, but ignores the systematicness of water resources in problems research. The systematic analysis method mainly includes system dynamics method, multi-objective analysis method and optimization model method. This type of method regards the subjects and objects of water resources carrying capacity as a whole and studies the water resources carrying capacity on regional economy and population under different social development modes and different water resources development and utilization. During the study, complexity and systematicness of water resources problems are taken into account, but there is still less simulation of water resource systems. All these methods can be improved in the study of interaction between factors of water resources carrying capacity and in the circulation and transformation rule of water resources in nature and society.

To solve the above problems, Professor Zuo Qiting proposed a simulation- and optimization-based control object inversion model [4,5] (referred to as the COIM method) to make up for the drawbacks of the above three methods. COIM method not only reflects the complexity of water resource systems, social economic systems and ecosystems and their mutual constraints, but also manifests the flexibility of calculation of water resources carrying capacity which can be obtained either through the optimization model solution or through the control object inversion model.

Through analysis of the concept and connotation of water resources carrying capacity and consideration of double effects of climate change and human activities on water resource systems, the calculation framework of water resources dynamic carrying capacity under climate change is put forward in reference to the said COIM method, as shown in Fig. 1.

Basic ideas of this calculation framework are: taking the output module of climate model as the input module of land-surface system, constructing an input–output relationship sub-model between meteorological factors (such as temperature and precipitation) and land-surface water resource systems (river runoff) based on many years of observation data, building the quantitative relations between the “climate change” factor of atmospheric system and “water resource systems”; calculating and forecasting the future development of land-surface water resource systems based on the climate model output results, taking “water resource systems, social economic systems, ecosystems, mutual constraints (stimulation) model” as base models, “maintaining a healthy ecological system” as control constraints, “supporting the largest socio-economic scale” as optimization goal, and establishing the optimization model. “The maximum socio-economic scale” which is achieved through optimizing models solution (or control object inversion model) is water resources dynamic carrying capacity. Following the naming of COIM method, this Prediction-Simulation-Optimization-Based

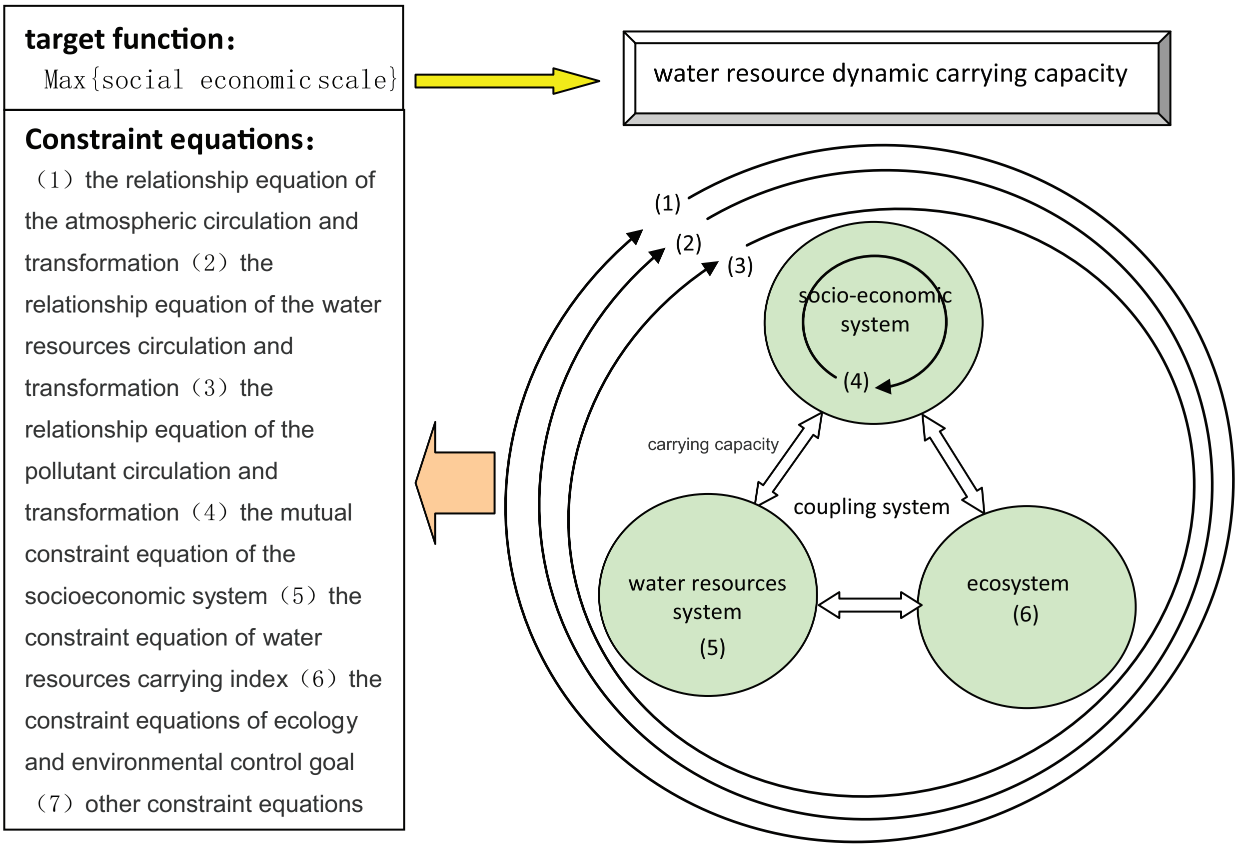

Fig. 1. Calculation frame of dynamic carrying capacity of water resources under the changing climate.

Control Object Inversion Model can be referred to as PSO-COIM method [6].

The PSO-COIM method is established, with the maximum socio-economic scale (here refer to the water resources dynamic carrying capacity) as the objective function, the output module of climate model as the external input of land-surface water resource systems, the input–output relationship between meteorological factors and land-surface water resource systems as the sub-model. Due to the extreme complexity of climate change itself, this model is less likely to have in-depth study of reason and mechanism of climate change; therefore, this model adopts climate model output as input of water resource systems, making it possible to consider different scenarios of climate change, which reflects its practicability and flexibility. That is, PSO-COIM model takes into account change trend of water resources carrying capacity under different climate models and reflects the features of water resources dynamic carrying capacity.

2.2. Several key problems and feasible computing methods

Experts and scholars at home and abroad have made a lot of researches on the impact of climate change on hydrology and water resources at different basins or regions and achieved fruitful results [7–9]. Researches on the response of water resources at different basins or regions to climate change generally follow the model of “future climate scenario setting-hydrological simulation-impact study”. Among them, what kind of climate change scenarios are selected, what kind of hydrological models are used, and how the coupling of atmosphere–land model is achieved are of paramount importance in the case study. In this paper, a simple but practical method is used in the case study, which uses the existing climate models to analyze the climate scenarios and obtain the meteorological factors data as the input of water resource system changes; adopting the system identification method based on historical data, the input–output relationship sub-model between meteorological factors and land-surface water resource systems is established, and it can calculate the output results of water resources system factors by input of different meteorological factors in real time; based on the above data, the “adaptive system identification unit model” method [10] is applied to calculate the characteristic value of water resources at each key node and at different partitions. Here is the brief introduction of the said three aspects:

2.2.1. Climate scenario analysis

The climate change scenario is based on a series of scientific assumptions and provides a continuous and consistent description of the future world climate. The IPCC (Intergovernmental Panel on Climate Change) has developed two greenhouse gas and aerosol emission scenarios, namely IS92 (1992) and SRES (2000) emission scenarios, which were applied to the third and fourth IPCC Assessment Report, respectively [11,12]. In 2011, Climatic Change published a special issue, detailing the new generation of greenhouse gas emission scenarios, including RCP8.5, RCP6.0, RCP4.5 and RCP2.6 [13]. In 2012, the China Meteorological Administration National Climate Center downscaled the simulation results of 21 CMIP5 global climate models to the same resolution via interpolation, then used the simple average method for multi-model ensemble, and finally developed a set of monthly average data including historical emission scenarios during 1901–2005 and RCP2.6, RCP4.5 and RCP8.5 emission scenarios from 2006 to 2100, which were provided to researchers for reference in research of climate change impacts. Climate scenario analysis aims to provide background data for the calculation of water resources dynamic carrying capacity, the data that include the analysis of the past and current climate and the forecasting of future scenarios.

2.2.2. Input–output relationship between meteorological factors and land-surface water resource systems

Meteorological conditions are the main factors affecting the total water resources in the river basin, and the changes of temperature and precipitation are easy to cause environmental changes such as snow cover, freezing and thawing, evaporation, runoff and so on, further leading to changes of time–frequency of hydrological events and of water resources volume. Thus, the input–output relationship between them can be constructed according to this mechanism. There are many ways to construct a system input–output relationship model, among which the system identification method is the most frequently used. While this paper only describes ARIMAX model used in the case study.

Multivariate stationary time series (ARIMAX) model is established for constructing the quantitative regression relationship between the input series and the output series. It is widely used to describe the variation of multivariate time series in complex systems [14–16], and it also demonstrates unique advantages in water resources systems. In addition to following its change rules, land-surface water resource systems are also affected by other time series, such as temperature, precipitation and human activities. In this case, a single time series model or an ARIMAX model with an input time series cannot better express the change rule of multivariate time series in water resource systems; therefore, it is necessary to establish an ARIMAX model with multiple input variables.

The ARIMAX model is constructed by assuming that the response sequence y_t and the input variable sequence (i.e., independent variable sequence) $x_t^{(i)}$ are both stationary and first constructing regression models of the response sequence and the input variable sequence:

$$y_t = \sum_{j=0}^{\infty} v_j^{(1)} B^j x_t^{(1)} + \sum_{j=0}^{\infty} v_j^{(2)} B^j x_t^{(2)} + \cdots + \sum_{j=0}^{\infty} v_j^{(k)} B^j x_t^{(k)} + \frac{\theta(B)}{\varphi(B)} a_t \tag{1}$$

where, $\theta(B) = 1 - \theta_1 B - \cdots - \theta_q B^q$, $\varphi(B) = 1 - \varphi_1 B - \cdots - \varphi_p B^p$ is transfer function model, $x_t^{(j)}$ is input factor (intervention factor) and y_t is output factor.

For reducing the number of parameters, it can be simplified to:

$$y_t - \mu = \frac{\theta_1(B) B^{b_1}}{\varphi_1(B)} x_t^{(1)} + \cdots + \frac{\theta_k(B) B^{b_k}}{\varphi_k(B)} x_t^{(k)} + \frac{\theta(B)}{\varphi(B)} a_t \tag{2}$$

where, $\theta_i(B) = \theta_0^{(i)} - \theta_1^{(i)}B - \cdots - \theta_{q_i}^{(i)}B^{q_i}, \varphi_i(B) = \varphi_0^{(i)} - \varphi_1^{(i)}B - \cdots - \varphi_{p_i}^{(i)}B^{p_i}$, $(i = 1, \ldots\ldots, k)$.

The above model is ARIMAX model [14–16], also called ARIMA model with intervention sequence or dynamic regression model. This model can be used to express the hydrological response sequence under climate change as a combination of past values of random fluctuated hydrological sequences and past values of temperature and precipitation sequences (called input sequences). The hydrological response sequence represents the dependent sequence or output sequence, and the input sequences such as temperature and precipitation sequences represent the independent sequence or predictive factor sequence.

2.2.3. Simulation of water resources system changes

Considering the complexity of land-surface water resource systems, it is not easy to establish a model to simulate changes of water resources, especially in a large and complex river basin. In this paper, an adaptive system identification unit (ASIU) model is proposed. To facilitate the simulation of water resource changes in a complex basin, Professor Zuo Qiting proposed the ASIU model in his paper [10] based on the idea of unit model, the theory of water balance, and hydro-system identification method and applied and tested it in the Tarim River Basin. The model incorporates the advantages of the unit model, the water balance model and the hydro-system identification method, and can simulate the real-time and adaptive characteristics of water resources system changes in complex basins. In short, it is “adaptive” and “suitable for complex river basin” [10].

The overall construction process of ASIU model includes: (1) dividing the study area into different calculation units by using watershed zoning and zone classification method, to ensure there are water flow and related matter exchange between unit and unit; (2) according to the water balance principle, adopting hydrological system identification method and establishing a water quantity model in each unit based on the actual data, to reflect the “supply-utilization-consumption-drainage” water cycle; (3) following the model integration method and certain computing order and criteria, calculating the coupling of all units with system dynamics method, and further integrating the coupled unit models to a water resource system model of the whole basin. Detailed calculation procedures and applications can be found in a paper by Zuo and Zhang [10].

2.3. PSO-COIM model solution

The complexity of constraints, especially the insertion of input–output relationship sub-model between climate model output module, meteorological factors and land-surface water resource systems, makes the PSO-COIM model established under normal circumstances more complex, adding our difficulty to accurately find its optimal solution. In this case, we can learn from the commonly used methods [4,5], and use computer simulation technology for step-by-step “numerical iterative” computation, to find a non-inferior solution as the final result. Detailed calculation procedures can be found in related literature, such as a paper by Zuo [5].

3. Results and analysis

3.1. Overview of study area

Tarim River is the longest inland river in China. Its basin is located in the south of Xinjiang Uygur Autonomous Region and covers an area of 1.02 × 10^6 km^2, 71°39′–93°45′ east longitude and 34°20′–43°39′ north latitude. Tarim River lies in the heartland of Eurasia and flows through the south Xinjiang of central Tarim Basin. Currently, there are only three water systems having natural hydraulic connection, especially surface water connection with the mainstream of Tarim River: namely Akesu River, Yarkant River and Hotian River, known as three origins at the upper reaches of Tarim River. Kaikong River feeds water to the lower reaches of Tarim River via Kuta Main Canal. All these are jointly called “4 origins and 1 mainstream”, as shown in Fig. 2. The Tarim River is located in the northwest inland arid area, and its basin represents the typical mountain basin and consists of the mountain ecosystem, oasis ecosystem and desert ecosystem from top to bottom. Rich in land resources, light-heat resources, oil and natural gas resources, Tarim River Basin is China’s important cotton production base, petrochemical base and energy base. In this basin, the water shortage and ecological environment deterioration are becoming worse and worse, and the future climate change will certainly lead to the change of its water resources system. Therefore, it is of great significance to carry out the research on water resources dynamic carrying capacity in this basin under the climate change.

This research selects the representative hydrological stations of “4 origins and 1 mainstream” of Tarim River, including: Dashankou on Kaidu River, Shaliguilanke and Xiehela on Akesu River, Kaqun and Yuzimenleke on Yarkant River, Wuluwati and Tongguziluoke on Hotian River, and Alaer, Xinquman and Qiala on mainstream. The surface runoff data derive from the surface water resource database of Xinjiang Hydrographic and Water Resources Survey Bureau, in which the observational data from 1961 to 2010 are used; the meteorological data derive from the observational data of nationwide meteorological stations of China Meteorological Administration from 1961 to 2010; the global climate model and climate change prediction data used are from the “China Climate Change Prediction Data Set” (Version3.0); the social economy data are derived from Xinjiang Statistical Yearbook and Statistical Yearbook of Xinjiang Production and Construction Corps.

3.2. Calculation process and results

3.2.1. Analysis of water resource regime

The catchment areas controlled by Shaliguilanke hydrological station and Xiehela hydrological station on Akesu River are 19,166 and 12,816 km^2 respectively, their mean annual runoffs are 28.66 × 10^8 and 48.58 × 10^8 m^3, respectively, and their yearly runoff deviation coefficient are 0.24 and 0.22, respectively. The catchment areas controlled by Kaqun hydrological station and Yuzimenleke hydrological station on Yarkant River are 50,248 and 5,389 km^2, their mean annual runoffs are 65.99 × 10^8 and 8.47 × 10^8 m^3, respectively, and their yearly runoff deviation coefficient are 0.19 and 0.20, respectively. The catchment areas controlled by Wuluwati

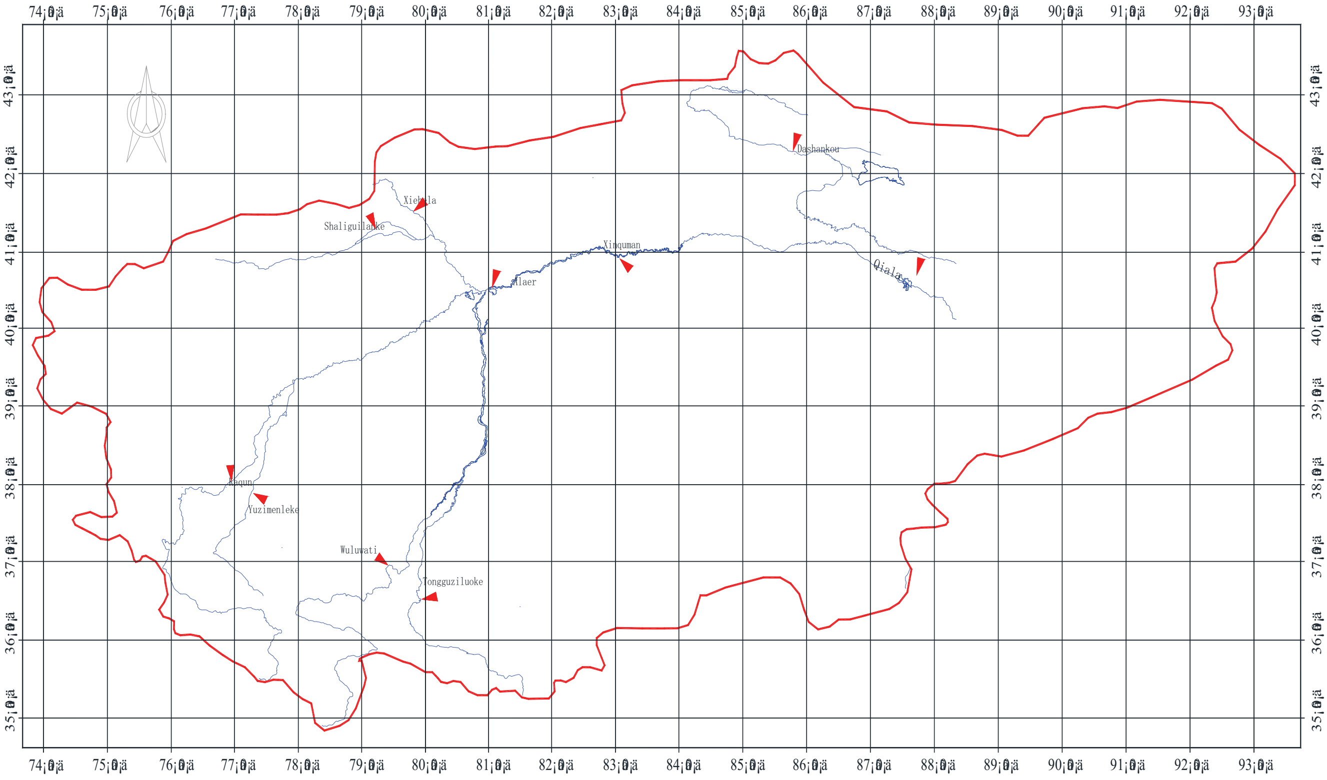

Fig. 2. Distribution sketch map of water system of Tarim River Basin.

hydrological station and Tongguziluoke hydrological station on Hotian River are 19,983 and 14,575 km^2, respectively, their mean annual runoffs are 20.73 × 10^8 and 22.30 × 10^8 m^3, respectively, and their yearly runoff deviation coefficient are 0.25 and 0.23, respectively. The catchment area controlled by Dashankou hydrological station on Kaikong River is 19,022 km^2, its mean annual runoff is 35.15 × 10^8 m^3, and its yearly runoff deviation coefficient is 0.17. The mean annual runoffs of Alaer hydrological station, Xinquman hydrological station and Qiala hydrological station on mainstream of Tarim River are 43.38 × 10^8, 35.43 × 10^8 and 5.49 × 10^8 m^3, respectively, and their yearly runoff deviation coefficient are 0.27, 0.29 and 0.80 (Table 1). The overall water resource regime in Tarim River Basin reflects that mountainous runoff of origin area is relatively stable, and the interannual variation is relatively small; in mainstream area, the water intake and use are larger due to the impact of human activities, and the interannual variation of river runoff is larger.

3.2.2. Dynamic prediction of basin water resources quantities under climate change

Due to special geographical location and basin structure of Tarim River Basin, the river runoff is mainly supplied by melt water of glacier snow which is affected by temperature, precipitation and other meteorological factors, and applies to the ARIMAX model which contains multiple input variables. In addition to following its own change rules, basin water resources system is also affected by other time series, such as temperature, precipitation and human activities. In this case, an ARIMA model with a single time series or an ARIMAX model with an input time series cannot better express the change rule of multivariate time series in water resources system; therefore, for the integrity of econometric model, it is necessary to establish an ARIMAX model with multiple input variables. The ARIMAX models of Hotian River, Yarkant River, Akesu River and Kaikong River are established respectively, and the modeling data include the long-term historical climate simulation and future climate change prediction data under RCP8.5, RCP4.5 and RCP2.6 scenarios, as well as the runoff observational data of the hydrological stations in origin area from 1961 to 2010. Due to too large differences in air temperature, precipitation and runoff, the sequence diagrams for these three factors are drawn respectively. From the results of unit root stationary test, the three sequences for these four origins are all stable, but some factors present non-white noise sequence, so relative optimum order determination shall be made respectively. Establish the ARIMAX model of each origin mountainous runoff according to the relative optimum order determination, and finalize the dynamic prediction model formulas of mountainous runoff for Hotian River, Yarkant River, Akesu River and Kaikong River through AIC and SBC statistics comparative analysis. Based on such formulas, the water resources dynamic prediction volumes of "4 origins and 1 mainstream" in Tarim River Basin in different level years under RCP8.5, RCP4.5 and RCP2.6 scenarios can be obtained (Table 2). The overall situations of water resources of Tarim River Basin in 2020 and 2030 under RCP8.5, RCP4.5 and RCP2.6 scenarios are relatively stable, of which, the water resource volumes of Akesu River and Kaikong River show an increasing trend, while the water resource volumes of Hotian River and Yarkant River show a decreasing trend.

Table 1
Hydrological stations characteristic values in the “4 origins and 1 mainstream” of Tarim River Basin

Name of rivers		Hydrological station	Catchment area (km^2)	Mean annual runoff		Time order(a)
				C_V	(10^{8}m^3)	
Akesu River	Toxkan River	Shaliguilanke	19,166 (10,206)	0.24	28.66	50
	Kumarik River	Xiehela	12,816 (2,306)	0.22	48.58	50
Yarkant River	Yarkant River	Kaqun	50,248 (47,378)	0.19	65.99	50
	Tizinafu River	Yuzimenleke	5,389	0.20	8.47	50
Hotian River	Kara kashgar River	Wuluwati	19,983	0.25	20.73	50
	Yurungqash River	Tongguziluoke	14,575	0.23	22.30	50
Kaikong River	Kaidu River	Dashankou	19,022	0.17	35.15	50
Tarim River	Main stream	Alaer		0.27	43.38	50
Tarim River	Main stream	Xinquman		0.29	35.43	50
Tarim River	Main stream	Qiala		0.80	5.49	50

Note: Numbers in the brackets are catchment area in China.

Table 2
Dynamic prediction of water resource volume in Tarim River Basin (10,000 m^3)

Partition	Water resource volume in 2020 under different scenarios			Water resource volume in 2030 under different scenarios		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Hotian River	463242	462749	468906	461403	462750	454587
Yarkant River	722798	719962	720004	705851	704811	698280
Akesu River	796123	793728	813991	846141	869591	861298
Kaikong River	363181	385238	388575	393206	373832	384039
Total	2345344	2361677	2391476	2406601	2410984	2398204

3.2.3. Calculation of basin water resources dynamic carrying capacity

3.2.3.1. Calculation of basin water resources dynamic carrying capacity in historical development stages. In May 2000, Tarim River Basin started to implement downstream ecological water compensation program; based on the early, middle and later periods of the implementation of this control scheme, this paper selected three different typical years, that is, 1998, 2005 and 2010, established calculation models of water resources dynamic carrying capacity according to the above-mentioned methods, and calculated the total carrying populations in 1998, 2005 and 2010 through numerical iteration method. See the detailed calculation results in Table 3, which reflect the changing trend of water resources carrying capacity in this basin in the past periods in a relatively scientific manner.

The research results indicated that: in these three typical years (1998, 2005 and 2010), the water resources carrying capacity of Tarim River Basin shows a dynamic change trend, the water resources carrying degree of Hotian River Basin shows a good changing trend, and the economic and social development scales are always within the scope of water resources carrying capacity; the water resources carrying degree of Yarkant River Basin changes significantly, and the economic and social development scales gradually exceed the water resources carrying capacity; the water resources carrying degree of Akesu River Basin also changes significantly, seemingly the economic and social development scales in this basin are still within the water resources carrying capacity, but the water volume of mainstream required to be discharged is large, Akesu River Basin bears larger pressure in the future; the water resources carrying degree of Kaikong River Basin shows a bad changing trend, and the economic and social development scales always exceed the water resources carrying capacity, causing larger carrying pressure.

3.2.3.2. Calculation of water resources dynamic carrying capacity in the future under different climate scenarios The calculation model of water resources dynamic carrying capacity under climate change scenario was established according to the method introduced in this paper, and the total carrying populations under three different climate model scenarios in 2020 and 2030 were calculated through numerical iteration method, as shown in Table 4. “Water resources carrying degree *D*” is used for expressing to what extent the water resources bear the pressure of social and economic development, *D* equals to the ratio of actual or predicted total population and the water resources carrying total population. See Table 5 for the calculation results.

The results showed that the water resources carrying capacity of Tarim River Basin under RCP8.5, RCP4.5 and RCP2.6 climate scenarios in 2020 and 2030 shows a dynamic change trend. The water resources carrying degree of Hotian River Basin changes slightly, the economic and social

Table 3
Calculation results of water resources dynamic carrying capacity in Tarim River Basin

Partition	1998			2005			2010		
	Actual population	Supportable population	I	Actual population	Supportable population	I	Actual population	Supportable population	I
Hotian River	101	118	0.85	112	155	0.72	135.3	208	0.65
Yarkant River	179	187	0.95	202	260	0.78	212.16	195	1.09
Akesu River	112	179	0.62	120	186	0.64	133.18	157	0.85
Kaikong River	77	77	1.00	84	78	1.08	120.5	94	1.28
Mainstream of Tarim River	12	0		13	0		14.42	0	
Total	469	562	0.83	518	678	0.76	601	654	0.92

Note: Unit of population (10,000 persons), carrying degree *I*.

Table 4
Calculation results of dynamic carrying capacity of water resources (the number of people) in Tarim River Basin

Partition	Number of people carried in 2020 under different scenarios			Number of people carried in 2030 under different scenarios		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Hotian River	161.7	161.5	163.7	195.2	195.8	192.3
Yarkant River	263.0	262.0	262.0	319.5	319.1	316.1
Akesu River	136.9	136.5	140.0	170.2	175.0	173.3
Kaikong River	181.5	192.5	194.2	258.1	245.4	252.1
Total	743.1	752.5	759.8	943.1	935.2	933.8

Note: Unit of population: 10,000 persons.

Table 5
Calculation results of carrying degree *D* of water resources in Tarim River Basin

Partition	Carrying degree D of water resources in 2020 under different scenarios			Carrying degree D of water resources in 2030 under different scenarios		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Hotian River	1.01	1.01	1.00	1.01	1.01	1.02
Yarkant River	0.92	0.93	0.93	0.89	0.89	0.90
Akesu River	1.16	1.16	1.13	1.09	1.06	1.07
Kaikong River	0.92	0.86	0.86	0.83	0.87	0.85
Total	0.98	0.97	0.96	0.93	0.94	0.94

development scales are always at the critical state of water resources carrying capacity and are at slightly overload state; the changing trend of water resources carrying degree of Yarkant River Basin improves slightly, but the economic and social development scales are always at the critical state of water resources carrying capacity and are at basically carrying state; the water resources carrying degree of Akesu River Basin changes in a relatively significant manner, but the economic and social development scales still exceed the scope of water resources carrying capacity, despite of the relatively abundant water resources in Akesu River Basin, the large water volume required to be discharged in mainstream and the large agricultural water demand in origin area cause great pressure to the water resources carrying capacity; the changing trend of water resources carrying capacity of Kaikong River Basin is good, and the economic and social development scales are gradually being controlled within the scope of water resources carrying capacity. In consideration that the global climate change is attracting more and more attention, greenhouse gas emission may be effectively controlled in the future, so the middle scenario (RCP4.5) is selected as the scenario most likely to occur in the future level year.

3.2.3.3. Change analysis of water resources carrying capacity in different level years Analyzing the calculation results (Table 6) of water resources carrying degree of Tarim River Basin in different historical development stages and future level years, we can obviously see that the water resources carrying capacity of Tarim River Basin shows a dynamic change trend.

Table 6
Calculation results of water resources carrying degree (index *I*) of Tarim River Basin in different years

Partition	1998	2005	2010	2020	2030
	Carrying degree	Carrying degree	Carrying degree	Carrying degree	Carrying degree
Hotian River	0.85	0.72	0.65	1.01	1.01
Yarkant River	0.95	0.78	1.09	0.93	0.89
Akesu River	0.62	0.64	0.85	1.16	1.06
Kaikong River	1.00	1.08	1.28	0.86	0.87
Total	0.83	0.76	0.92	0.97	0.94

The water resources carrying degree of Hotian River Basin changes significantly, the economic and social development scales in 1998, 2005 and 2010 are always within the carrying scope of water resources, but the carrying states in 2020 and 2030 change from carrying state to slightly overload state; the water resources carrying degree of Yarkant River Basin fluctuates, the economic and social development scales in 2010 exceed the carrying scope of water resources and are at slightly overload state, but in 1998, 2005, 2020 and 2030 are at the critical state of water resources carrying capacity and present basically carrying state; the water resources carrying degree of Akesu River Basin changes obviously, the economic and social development scales in 1998, 2005 and 2010 are always within the carrying scope of water resources, which, however, exceed the scope of water resources carrying capacity in 2020 and 2030, that is, changing from carrying state to slightly overload state, despite of the relatively abundant water resources in Akesu River Basin, the large water volume required to be discharged in mainstream and the large agricultural water demand in origin area cause great pressure to the water resources carrying capacity; the changing trend of water resources carrying capacity of Kaikong River Basin is good, and the economic and social development scales always exceed the carrying scope of water resources and are at slightly overload state in 1998, 2005 and 2010, which, however, are gradually being controlled within the scope of water resources carrying capacity in 2020 and 2030, that is, changing into carrying state, this has certain relation to the obvious increase of water resources volume in Kaikong River Basin. Through multi-analysis, the calculated results reflect in a relatively scientific and reasonable manner the changing conditions of water resources in this basin, economic and social development scales, and the changing trend of water resources carrying capacity in this basin.

As is mentioned above, the table selects the middle scenario (RCP4.5) as the results in the future level years. As the global climate change is attracting more and more attention, greenhouse gas emission will be effectively controlled in the future, so the middle scenario (RCP4.5) is selected as the scenario most likely to occur in the future level years. Certainly, if the climate scenario changes in the future, the results can be output and substituted in the calculation to obtain the corresponding results.

4. Conclusion

This paper analyzes and summarizes the researches of domestic and overseas experts in the field of water resources carrying capacity, puts forward and systematically elaborates the concept and connotation of water resources dynamic carrying capacity under climate change scenarios, and proposes the theoretical framework and main methods for calculation of water resources dynamic carrying capacity under climate change scenarios based on the previous research results. Taking Tarim River Basin (the largest inland river in our country) as the typical example, this paper also analyzes the water resources regime of Tarim River Basin, establishes the ARIMAX dynamic regression prediction models of air temperature, precipitation and runoff, analyzes and calculates the water resources dynamic carrying capacity of Tarim River Basin in different level years in the future under the climate scenarios of RCP8.5, RCP4.5 and RCP2.6.

Through the example application in this paper, we can see that PSO-COIM calculation model preferably reflects the concept and connotation of water resources dynamic carrying capacity under climate change scenarios and fully considers the uncertainties of climate change and human activities, and that the calculation results fully express the dynamic change characteristics. This model can not only express the dynamic evolving process of water resources carrying capacity in the past but also fully reflect the changing process and trend of water resources carrying capacity under different climate model scenarios in the future; it is suitable for the calculation of water resources carrying capacity of complex basin. PSO-COIM method is an important improvement and beneficial complement to COIM method, and this theory is of great significance in evaluating the impact of climate change on water resources carrying capacity and guaranteeing the economic and social sustainable development of our country.

In consideration that the research contents involve meteorology, hydrology, ecology, social economy and many other disciplines, and based on the complexity of problems, this paper uses some simplified calculation methods when establishing the model, for example: using a simple regression analysis method to establish the input–output relationship between meteorological factors and land-surface water resource systems, or using a generalized adaptive system identification unit model to establish the change simulation model of water resource systems. In the future, research in this field can be further expanded to make the calculation results more accurate and more practical.

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