The study on supply and demand of water resources in Alar city based on the system dynamics model

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Abstract. According to the status of water resources shortage in Alar, this paper establishes a system dynamics (SD) model for the water resources carrying capacity (WRCC) and analyzes the balance between water resources supply and demand. Three cases are designed to simulate the level of WRCC from 2010 to 2030. The total water demand and secondary product output value are chosen as the evaluation indices to study the WRCC in Alar. The results show that the carrying capacity of water resources in Alar cannot meet the demand of social economic development in recent years, and case 3 could effectively alleviate water scarcity. Based on the results, in order to guarantee sustainable utilization of water resources and social economy development, it is necessary to increase water saving policies and increase the introduction amount of surface water in the future.

1. Introduction

With the development of the social economy and the growth of the population, the problem of water waste and pollution presents a serious situation, water shortages will severely constrain economic and social development in the 21st century and may lead to conflicts between countries [1]. According to statistics, the global urban domestic water consumption in 2050 will be equivalent to the current global water consumption, 55% of the world’s population will face a water crisis. At present, there are more than 400 water-scarce cities in 668 establishing cities in China, among them there are more than 130 cities facing with serious water shortage [2]. The contradiction between supply and demand of water resources has become one of the main reasons restricting the healthy and stable development of China’s economy.

The sustainable development of city is the current hot topic, and many scholars have researched the relationship between the WRCC and sustainable development [3-6]. D P Xu et al [3] studied the sustainable development of water resources in Tongliao city using SD method and Analytical Hierarchy Process. Changhai Wang et al [4] established a SD model for Beijing wetland water resources and evaluated its WRCC. Juntao Zhang et al [5] showed that water resources are the key factor affecting regional sustainable development. Jiuyu Zheng et al [6] constructed the matching calculation model and analyzed the matching degree on agricultural water and land resources in Hetao irrigation area.

In order to study mutual relationships between social sustainable development and water resources, the WRCC was put forward, which plays a crucial role in the comprehensive development of a country or region, as well as its development scale [7]. The WRCC is a primary factor in restricting sustainable development [8-14]. The primary WRCC evaluation method is system dynamics, which is able to observe the internal dynamic features of WRCC globally and analyzes effects of policy
changes on the WRCC development trend. Comparing with other methods, the system dynamics method has time-varying, nonlinear and multiple feedback characteristics, such as analytic hierarchy process [14], information entropy [15] and principle component analysis [16]. The system dynamics method has its own advantage when dealing with the problem of complex and ecological sustainable development [17].

This paper is based on theories from many research results. The research concentrates on the water resources in Alar, with a target to achieve sustainable development. The authors establish a SD model to scientifically evaluate the WRCC in Alar firstly. Then authors simulate and analyze the change of WRCC under different circumstances. Lastly the optimization strategy is sought to provide technical guidance for further exploitation and optimal allocation of Alar water resources.

Compared with other papers which also deal with the WRCC, the results to be given in this paper have the following three points:
1) Establish a SD model for water resources supply and demand in Alar city;
2) Design three schemes and analyze the simulation results;
3) Provide optimization strategy for water resources sustainable development in Alar city in the future.

2. Study area
Alar City, in Aksu region of Xinjiang Province, is located in the south of Tianshan Mountains and in the north of Taklamakan Desert. Four major river systems run through Alar: the Aksu River, Yerqianghe River, Hetian River, and Tarim River.

The average temperature is $8.10^\circ \text{C}$, average annual rainfall is 47.92 mm, and average annual evaporation is 1,368.73 mm. The climate is dry for many years, precipitation is scarce, sunshine time is strong, and evaporation is strong, it belongs to the extreme continental arid desert climate in the warm temperate zone. Alar has less precipitation, large evaporation, and no effective runoff from local surface water resources; Precipitation has almost no recharge of groundwater, which is mainly supplied by lateral recharge and irrigation water. So the available water resources in Alar mainly contain the entry water and a small amount of groundwater.

The actual total water supply of Alar is 21.4 million $m^3$ from the existing water supply facilities in 2016. The total population of Alar is 326800 and total water demand is 33.3 million $m^3$. This status quo indicates that the water supply capacity of the water supply project has not been able to meet the requirements of the national economic development for water demand. Through the analysis of the current situation of supply and demand in the city, it can be seen that with the development of society and economy, the demand for water will continue to increase during a certain period of time, and the contradiction between supply and demand will become more prominent.

3. SD model of water resources sustainable utilization

3.1. Data resources
The main resources of data in this paper are from two parts: the Alar statistical Yearbook (2010-2018), and Tarim River Water Management Office. In addition, some information is also collected from the official website, and the others are calculated by the mathematical formula.

3.2. System dynamics simulation
This paper will use Vensim as a simulation platform to establish a SD model of the water resources supply and demand in Alar city, which include domestic, production, ecological water demand subsystem and water supply subsystem. In fact, the four various subsystems are interrelated with each other. Figure 1 describes SD model of Alar water resources supply and demand system and gives the detailed relationship among the four subsystems.
1. Domestic water demand subsystem. It consists of urban and rural domestic water demand. Urban (rural) domestic water demand is the product of urban (rural) population and urban (rural) domestic water consumption quota.

2. Production water demand subsystem. It is the sum of primary industry water demand, secondary and tertiary industry water demand. The primary industry water demand includes the livestock water demand and agricultural irrigation water demand. The secondary (tertiary) industry water demand is the product of GDP-Gross Domestic Product water consumption and secondary (tertiary) industry output value.

3. Ecological water demand subsystem. It mainly contains ecological environment water demand.

4. Water supply subsystem. The available water resources in Alar include surface water supply, groundwater supply, reservoir storage water, agricultural irrigation saving water, reclaimed water and entry water. The parameters of reclaimed water reusing rate and entry water are table function, which changes with time.

**Figure 1.** SD model of Alar water resources supply and demand system.

The initial value of the main variables in water resources simulation is as Table 1.

**Table 1.** Initial value of the main variables.

| total population/ 10^4 people | urbanization rate/ % | secondary output value/million yuan | tertiary output value/million yuan | large livestock/ 10^4 head | small livestock/ 10^4 head |
|-------------------------------|----------------------|-------------------------------------|-----------------------------------|---------------------------|--------------------------|
| 29.23 | 63.58 | 28.9 | 19.7 | 4.94 | 49.61 |

This research also shows the establishment of major equation.
The equation of level variable \( L \) is as follows:

\[
L(t) = L(t_0) + \int_{t_0}^{t} R(t)dt, \tag{1}
\]

\( L(t) \) is the accumulated variable value at time \( t \); \( R(t) \) is the rate of change in \( L(t) \).

The equation of rate variable \( R \) describes as:

\[
R(t) = g[L(t), A(t), e(t), c], \tag{2}
\]

Where \( L(t), R(t) \) have the same definitions as Formula (1), \( A(t), e(t) \) is the auxiliary variable value and exogenous variable value respectively, \( c \) is a constant.

The equation of auxiliary variable \( A \) takes the following form:

\[
A(t) = f[L(t), A'(t), e(t), c], \tag{3}
\]

\( A'(t) \) is the other auxiliary variable besides which will be determined.

3.3. Boundary conditions of the model

In order to facilitate the study, the all subordinate counties in Alar are used as the spatial scale boundaries in the model. The simulation time is from 2010 to 2030, the simulation base year is 2010, and the simulation time step is one year.

4. Scheme design and simulation results analyze

4.1. Validity test

According to standard modeling procedures, a model should be run before performing a comprehensive error test of its structure and function to ensure the validity and authenticity of the model. The validity test takes the initial beginning data, and then tests the existing historical data against the simulation results for error. This paper only gives the historical data validity test of the total population within 10 years in Table 2. From which we can find that the relative error of the indices in the model is within \( \pm 10\% \), which shows that the simulation results of the model are well matched with the actual situation. Therefore, the parameters of the model can be applied to the prediction stage.

| Year | Total population actual value \( 10^4 \) | Simulated value \( 10^4 \) | Error (%) |
|------|----------------------------------------|-----------------|----------|
| 2010 | 29.23                                  | 29.23           | 0.00     |
| 2011 | 29.69                                  | 29.90           | 0.7      |
| 2012 | 29.81                                  | 30.58           | 2.58     |
| 2013 | 31.00                                  | 31.27           | 0.87     |
| 2014 | 31.01                                  | 31.99           | 3.16     |
| 2015 | 31.80                                  | 32.71           | 2.86     |
| 2016 | 32.68                                  | 33.46           | 2.39     |
| 2017 | 35.79                                  | 34.22           | -4.39    |

4.2. Case design

The primary object of case design for water resources sustainable utilization is to solve the imbalance problem of water supply and demand in future and to eliminate restriction of water resources to socioeconomic development. On the basis of above analysis, three cases are designed and their regulation strategies are as follow:
Case 1: Current situation maintaining scheme--The sensitive parameters maintain at current year level. In 2010, the production sewage discharge rate and domestic sewage discharge rate are 0.138, 0.2. And the GDP consumption water is 11.9 $m^3$ per 10,000 yuan.

Case 2: Economic development scheme--Developing economy is still the top priority of Alar city in the present and future. In this scheme, living standards and quality of life will be improved. So the urbanization rate, production sewage discharge rate and domestic sewage discharge rate will be increased to 65%, 20%, 25%, respectively. And the GDP consumption water increases to 15 $m^3$ per 10,000 yuan. The other decision variables remain the same as in case 1.

Case 3: Sustainable development scheme--In this case, there has been consistent growth in three industries, the water demand of production and domestic have been greatly reduced. While secondary and tertiary production growth rate have been increased. So the production sewage discharge rate, domestic sewage discharge rate and GDP consumption will be reduced to 0.09, 0.15, 7.5 $m^3$ per 10,000 yuan. Furthermore secondary production growth rate, tertiary growth rate, agricultural irritation waving rate will be increased to 31%, 17%, 90%. The other decision variables keep the same as in case 1.

4.3. Simulation results analyze

Based on the simulation results of above three schemes, the research chooses total water demand, secondary product value as main parameters to analyze the WRCC in Alar city, the simulation results are shown in Figure 2. From which, we can choose the best one for water resources sustainable utilization, and the results can provide guidance for further exploitation of Alar water resources.

![Figure 2. Simulation of total water demand and secondary product value in different cases.](image-url)
From Figure 2, we can see that the total water demand growth rate in case 2 is the fastest. That is because the economic development requires a lot of water. As case 3 takes both the economic development and water conservation into consideration, its total water demand growth rate is the smallest. Thus, no matter which scheme is adopted in the future, the total water demand will continue to increase with the economic development. Meanwhile, the secondary industry output value also increases over time. Case 2 mainly considers economic development, so the secondary industry output value growth rate is the fastest. And the growth rate is the smallest under current situation maintaining scheme. Therefore, comparing with other schemes, sustainable development scheme is more conducive to the coordinated development of local production, life and ecology.

According to the above analysis, case 3 is the best choice for the future sustainable developments of Alar, which is the fundamental way to improve water resources using efficiency and the WRCC. Thus the sustainable development scheme, that realizes balance between water supply and demand and ensures water resources sustainable utilization, is the optimal scheme for water resources and economic sustainable developments of Alar.

5. Conclusions
Based on the characteristics and advantages of system dynamics in solving complex large-scale system problems, the paper establishes a SD model of Alar WRCC and analyzes the simulation results, which show that the balance of water resources supply and demand is not realized during simulation years. Meanwhile the imbalance of supply and demand restricts industrial and agricultural development, and becomes the key factor of Alar sustainable development. For the purpose of water resources sustainable utilization, three schemes are designed by targeting water supply and demand balance. The analysis results show that case 3 can essentially meet the needs of future economic development. Based on an analysis of the socioeconomic status and various simulation results, it is suggested that the WRCC of Alar should be improved by controlling the water consumption, increasing the amount of reclaimed water, improving sewage treatment capacity, adjusting industrial structure and increasing the introduction amount of surface water.

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