The Effects of Water Resource Restrictions on Sustainable Development in Semi-Arid Regions: A Case Study of Tongliao City, Inner Mongolia

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Abstract: Water resource is a constraining factor in the sustainable development of semi-arid areas (SAAs). In order to study the constraining effects of scarce water resources on the sustainable development of SAAs more accurately, this paper selects the typical representative of SAAs, Tongliao City, as the case study area, and water resource System Dynamics (SD) model was established for the City that described the constraints and the resultant restrictions on sustainable development. The operation of the SD model showed that under the traditional development path, Tongliao City maintained rapid economic growth even though restriction of its water resources had a significant constraining effect. The simulation showed that in 2018, the first water shortage occurred in Tongliao City and the situation of water shortage was getting worse. By 2030 the water shortage will reach 28.9%. Industrial production and urban living will utilize all of the available ecological water and, in consequence, the natural environment will seriously deteriorate. Analysis of the simulation results has shown that, under the existing development path, the structure of water consumption in Tongliao City is irrational. Continuation of the established development model will result in a drastic shortage of water resources, and will curtail significantly the sustainable development of the city. The results of the present study have demonstrated conclusively that shortage of water resources has become the key factor that will restrict the sustainable development of SAAs. Thus, in the future, development methods should be changed to improve the
utilization efficiency of water resources in order to achieve sustainable development in SAAs.

1. Introduction
SAAs typically are characterized by ecological vulnerability [1]. In China, SAAs are distributed mainly along the southern edge of the Inner Mongolia Plateau and the Great Wall. These areas range in annual precipitation from 200 to 400 mm and dryness from 1 to 2 [2]. Longer-term, large-scale agricultural activities in these locations have disturbed the balance of regional aquatic ecosystems and caused the ecological environment to deteriorate, as indicated by the water scarcity, grassland degradation, desertification, etc [3].

The constraining effects of poor water resources on the sustainable development of semi-arid regions are mainly reflected in three issues: (1) the unbalanced distribution of water resources in time and space and the massive exploitation of irrigation water [4]; (2) the shortage of water resources and the serious waste of water resources in the area [5]; (3) the massive exploitation of ecological water resources causes serious degradation of the ecological environment [6] [7]. In order to better solve the contradiction between human requirements and water availability in SAAs, much research has been conducted on the rational use of regional water resources. Peng established a multi-objective model for ecologically optimal allocation of water resources in drought-irrigated areas in Xinjiang and used Matlab to calculate reasonable proportions of surface water, groundwater, and other water using in irrigation areas, which has provided a valuable reference case for the allocation of water resources in the interlaced areas of agriculture and animal husbandry [8]. Li studied the utilization of water resources in the Inner Mongolia Autonomous Region from the perspective of virtual water and considered that the current virtual water content per unit product in the Inner Mongolia Autonomous Region was too high, mainly because of the excessive proportion of corn seed products in the region. In the future, it will be necessary to reduce the virtual water content in the unit product and use more water resources to make up for the ecological water deficit, and thereby avoid the occurrence of ecological problems [9]. Zheng calculated the ecological water consumption of various indicators in the Guyuan County SAAs, using the Sunswirt equation, and indicated that ecological water consumption in the county was extremely tight, and it was necessary to adopt planning methods to return some cropland to grassland and thereby improve gradually the availability of ecology water [10]. Xu established a SD simulation model for the "zero growth" development of water resources in the SAAs of Tongliao City from the perspective of reasonable allocation of water resources. By running the SD model, the possible time points of "zero growth" of water resources in Tongliao City's "Modernize primary industry", "Secondary industry dominance", and "Tertiary industry leadership" development models were given [11]. These studies provided useful theoretical references for the rational use of limited water resources in the SAAs.

2. Overview of the study area
The SAAs of China involve 11 provinces and regions, including Inner Mongolia, Hebei and Shanxi, with a wide range of differences [12]. In order to carry out targeted research, Tongliao City, in Inner Mongolia, was selected as being a suitable research object [13]. The water resources of Tongliao City and the conditions of social, economic, and ecological environment development are representative of SAAs in general, as it has characteristics that are typical of semi-arid conditions (Table 1). Tongliao city is located in the eastern part of Inner Mongolia 43°22'~43°58’N 121°42’~123°02’E. The average rainfall is 350-400 mm and evaporation is about five times the rainfall. In recent years, the Liaoh River, Xinkai River, and Jiaolai River in Tongliao have been dry throughout the year, due to the arid climate and human development; more than 70 small water reservoirs also have dried, and local underground water level has declined, resulting in a lack of water.
Table 1. Comparison table of social and economic development between Tongliao and semi-arid region.

| Region      | Urbanization (%) | Capita GDP (10^4 yuan/p) | Industry structure (%) | Proportion of agriculture water-use efficiency (%) | Agriculture water-use efficiency (yuan/m^3) | Total water-use efficiency (yuan/m^3) | Proportion of ecological water-use efficiency (%) |
|-------------|------------------|--------------------------|------------------------|---------------------------------------------------|------------------------------------------|-------------------------------------|--------------------------------------------------|
| SAAs        | 38               | 5.7                      | 14:58:28               | 85                                                | 10.8                                     | 63.4                                | 36                                               |
| Tongliao    | 39               | 2.54                     | 13:59:28               | 76                                                | 9.8                                      | 67.5                                | 32                                               |

Through an on-the-spot investigation of Tongliao City, it was found that unbalanced water use, low water utilization efficiency, and deterioration of the water environment were important factors that have limited the sustainable development of Tongliao City. The total amount of water available in this city is about 3.1 billion cubic meters, which is 992 cubic meters per capita and only 47% of the national level. Water resources are extremely scarce; statistics show that the industrial structure was 14:51:35 in 2015, which indicates that Tongliao City was still underdeveloped in the industrial economy. Additionally, the proportion of water used for production in the primary industry, which is dominated by agriculture and animal husbandry, accounted for about 85%. Thus, the water utilization structure is very unbalanced; The integrated water use efficiency of Tongliao is 63.6 yuan/m^3, of which the industrial and agricultural water utilization efficiency is 410 yuan/m^3 and 11 yuan/m^3, respectively; far below the national average level of 113 yuan/m^3 [14]. The water resources of Tongliao City mainly are groundwater. And the observational data have shown that, at present, some parts of Tongliao City exhibit a trend of over-exploitation of groundwater and, to varying degrees, the water ecological environment has been destroyed.

A comprehensive analysis has shown that the development of water resources in Tongliao City is approaching the limit of those resources. If the current rate of development were to be maintained, the regional water resources soon will be depleted but socio-economic development will not be improved. By using the SD method, this paper aims to simulate the development status of the socio-economic system in Tongliao City and evaluate how current development trends will need to be modified to improve the sustainability of the region.

3. Data sources and methods

3.1. Data sources
This research mainly used statistical data, primarily including the Statistical Yearbook of Tongliao (2000-2017), statistics about the banners and counties in Tongliao (2000-2017), Tongliao Water Resources Bulletin (2000-2017), and Tongliao Water Conservance Bulletin (2000-2017).

3.2. Methods
This paper uses SD methods to conduct research. The SD method has characteristics of time-varying, nonlinear and multiple feedback. Compared with other methods, such as the analytic hierarchy process information entropy [15] and principal component analysis [16], it has specific advantages in dealing with the "complex and dynamic social-economic-ecological sustainable development" problem [17]. This study takes water resource as an important prerequisite that would constrain Tongliao City’s sustainable development.

Based on the current social and economic development status of Tongliao City, a SD simulation model was established to simulate the development status of the city under constrained water resources during the next 15 years. The aim was to find efficient methods to alleviate regional water shortages and
provide useful theoretical explorations that might deliver future sustainable development in semi-arid regions.

3.2.1. Constructing model. ‘Vensim’ is a visual model tool that can conceptualize, simulate, analyze, and optimize system dynamic models. Vensim provides model methods that are based on causality chains, state variables, and flow graphs, and allows the behavior of models to be studied from a global perspective. It is a relatively simple and practical system simulation tool, which is widely used in various scientific research fields.

This investigation used Vensim software as a simulation platform to establish the interaction between the three major subsystems of the Tongliao production environment: the living environment and ecological environment and the water resources support system. It could also be used to determine the representative indicators of the three environment subsystems in order to build the system dynamic model. The research indices of the living environment subsystem included the urban living water requirement, the rural living water requirement, the standard sheep water requirement, the rural population, the urban population, and the number of standard sheep. The production environment subsystems mainly included the primary indicators of agricultural water demand, secondary production water demand, tertiary production water demand, the total output value of a product, cultivated land area, the total output value of secondary products, and the total output value of tertiary industries. The ecosystem mainly included an indicator of ecological water use, indicating the relative abundance (or scarcity) of available water in the ecosystem. At the same time, using years of statistical data to determine the water quotas of users in each of the two major subsystems, such as living and production, as a model from which to establish the basis of correlations between the various subsystems and the total amount of water resources. The degree of water shortage in each calendar year was calculated by simulation to indicate the extent to which the water resources system is able to support socio-economic development under the current development trend. Each subsystem environment impacts the production and life subsystem according to the degree of water shortage in each calendar year and, by the application of long-term sequence simulation, the future economic, social, and ecological development of the region can be obtained. The annual precipitation rate in a certain area is somewhat unpredictable. A comprehensive analysis of data from Tongliao City Water Resources Yearbook 2010-2017 showed that 75% of the nominal precipitation rate is relatively common in Tongliao City. Therefore, the present study used 75% of nominal precipitation rate as the basis of the model. The system dynamic model diagram is shown in Figure 1.

Figure 1. Regional Development SD Simulation Model under Water Resources Constraints in Tongliao City
3.2.2. Model verification. The results of simulation of SD models generally are somewhat inaccurate in comparison with the reality. If the degree of error can be controlled within a reasonable range, it is generally considered that the economic and social development trends reflected by the simulation results of a system dynamic model are reasonably objective. This study used 2014 as the starting point for the model’s operation, and the 2015 and 2016 years' operating data comprised the model test data.

The main economic and technical indicators were selected as the inspection objects. These indicators mainly included the total water demand, the primary industry water demand, the secondary industry water demand, the total output value of the primary industry production, the total output value of the tertiary industries, the per capita GDP, and the total urban population. The indicators covered a wide range of aspects, covering water, production, and social development, and reflected the error range of the model simulation results quite accurately (Table 2). The error rate between the calculated values and the actual values in 2015 and 2016 were within approximately 5%, and the error direction was essentially the same. This showed that the SD model established in this study was more reliable than conventional predictive methodologies and could be used to simulate the development of social and economic development according to the traditional agricultural development plan for Tongliao City.

| Indicators                        | 2014 Actual value | 2014 Analog value | Error rate | 2015 Actual value | 2015 Analog value | Error rate |
|-----------------------------------|-------------------|-------------------|-----------|-------------------|-------------------|-----------|
| Total demand water (10^8m^3)      | 27.38             | 27.58             | 0.73%     | 28.92             | 30.02             | 3.80%     |
| Primary industry water demand (10^8 m^3) | 21.84             | 21.93             | 0.41%     | 21.89             | 21.66             | -1.05%    |
| Second industry water demand (10^8 m^3) | 2.47              | 2.59              | 4.86%     | 3.13              | 3.25              | 3.83%     |
| Total output value of the primary industry (10^8yuan) | 267.61            | 280.79            | 4.93%     | 269.68            | 281.45            | 4.36%     |
| Total output value of the tertiary industry (10^8yuan) | 609.35            | 596.36            | 2.13%     | 658.89            | 683.08            | 3.67%     |
| Per capita GDP (yuan)             | 57727             | 59360             | 2.83%     | 60123             | 62115             | 3.31%     |
| Total urban population (10^4people) | 141.71            | 142.35            | 0.45%     | 144.64            | 147.8             | 2.18%     |

4. SD simulation results
The model was run to get the SD simulation results, as shown in Table 3. The simulation results showed that, under the traditional industry development path, Tongliao City would continue the current development speed and status of the three industries, and its social and economic development and water resources utilization would undergo significant change. Then, during the first “what if” investigation, the industrial structure of Tongliao City was adjusted from 16:47:37 in the industry in 2020 to 9:37:53 in 2030. The dynamic simulation model indicated that the industrial structure would undergo a qualitative change from the beginning of industrialization preparation to the acceleration of industrialization. During the second “what if” investigation, the water use structure of the tertiary industry in Tongliao City was observed to undergo a tremendous change from 66:30:4 in 2020 to 46:45:9 in 2030. The water demand for agriculture was reduced slightly, but the total water requirement in China's share dropped sharply, to only 43%. The industrial water demand surged, and the share also soared to 41%. The share of the third production water requirement has also changed to a certain extent, reaching 8%, and the share of domestic water demand would remain essentially unchanged. However, by 2030, the model showed that ecological water consumption would be completely utilized by production water and domestic water requirements, and the remainder would not meet ecological water needs. While maintaining rapid economic development, the degree of water shortage in Tongliao City also would change. The simulation showed that in 2018, the phenomenon of water shortage first...
appeared and, subsequently, the water shortage situation became progressively more and more serious. By 2030, there will be no remaining provision for ecological water, and the water shortage would reach 28.9%.

Table 3. Simulation results of social and economic development under the constraints of water resources in Tongliao City

| Index                                          | 2020    | 2025    | 2030    |
|------------------------------------------------|---------|---------|---------|
| Total output value of the primary industry     | 703.1   | 1002.9  | 1274.93 |
| (10^8 yuan)                                    |         |         |         |
| Total output value of the second industry      | 2076    | 3313.1  | 5143.82 |
| (10^8 yuan)                                    |         |         |         |
| Total output value of the tertiary industry    | 1651.1  | 3558.4  | 7364.26 |
| (10^8 yuan)                                    |         |         |         |
| Total GDP                                      | 4430.17 | 7874.5  | 137834  |
| (10^8 yuan)                                    |         |         |         |
| Industrial structure                           | 16:47:37| 13:42:45| 9:37:53 |
| Primary industry water demand (10^8 m^3)      | 20.18   | 19.51   | 18.87   |
| Second industry water demand (10^8 m^3)       | 9.10    | 13.06   | 18.09   |
| Tertiary industry water demand (10^8 m^3)     | 1.12    | 2.09    | 3.67    |
| Water shortage (10 m^3)                        | 1.51    | 6.11    | 12.62   |
| Tertiary industry water demand structures      | 66:30:4 | 56:38:6 | 46:45:9 |
| Ecological water demand (10^8 m^3)            | 10.18   | 5.54    | -1.02   |
| Water shortage degree                          | 4.66%   | 16.21%  | 28.9%   |
| Total water efficiency (yuan/m^3)             | 136.47  | 212.24  | 315.69  |

Note: The water demand structure is the primary industry water demand: the secondary industry water demand: the tertiary industry water demand

5. Discussion

Through the simulation studies, it has been shown that under the traditional agricultural development path, excessive agricultural development will cause social, economic, and ecological systems to show a clearly unsustainable state. The study has shown, without doubt, that following the current state of development, the utilization of water is irrational and the amount of water that is used inefficiently for agriculture is relatively large. Although the use of agricultural water-saving technology, to a certain extent, has alleviated the excessive use of agricultural water, which has reduced the amount of agricultural water use, the absolute amount of reduction is not high, accounting for only 12.88% of agricultural water withdrawal. With the rapid development of the secondary and tertiary industries, the amount of water needed for both developments has grown rapidly. As a result, the total water use during the development of Tongliao City has climbed to 4.366 billion cubic meters and the water supply gap has reached 1.262 billion cubic meters per annum. From the perspective of water utilization efficiency, the efficiency of water use in the secondary and tertiary industries is higher than that of the first production, which is more than ten or more times that of the primary industry. Under such circumstances, if the current state of development can be changed and the demand for water resources in traditional agriculture can be reduced, and the water saved by the primary industry can support the development of secondary and tertiary industries, it will better promote the economic development of Tongliao City.

Secondly, under the current development path, the water requirement for the ecological environment has been completely taken for the development of production and there is still a large demand gap for the available water resources. It shows that the current development path not only lacks sustainability but also will cause serious damage to the ecological environment. Therefore, if the current development trend is continued, the sustainability of Tongliao City will face the bottleneck of water resource
constraint. Changing the current development trend in Tongliao City and alleviating water resource constraints to permit sustainable development are crucially necessary.

Thirdly, if the traditional mode of economic development based on agricultural production can be changed, for example by implementing the strategy of returning farmland to animal husbandry and rebalancing the agricultural economy, substantial savings in water resource utilization could be achieved. The saved water resources could be used to promote the secondary and tertiary industries while improving the ecological environment, which will not only improve the economic efficiency of water resource utilization but also improve the environmental quality of the region.

6. Discussion
The constraint effect of water resources on the sustainable development of SAAs under the traditional agricultural development path is mainly due to the contradiction of production development caused by the lack of water resources and the unreasonable allocation of regional water resources departments caused by excessive development of traditional agriculture, and the deterioration of the ecological environment caused by the development of traditional agriculture.

The unreasonable allocation among water resources departments is manifest mainly in the fact that the agricultural production department, with low production efficiency, consumes a large proportion of the available water resources, which has led to water shortages in the secondary and tertiary industries with higher water resource utilization efficiency, and has also resulted in the evident contradiction in regional sustainable development.

The rapid development of traditional agriculture and the massive increase in water demand has caused serious deterioration in the ecological environment of the SAAs. Under such circumstances, the transformation of the traditional agriculture-based methods and implementing a strategy of returning farmland to pasture and rebalancing of the agricultural economy can greatly promote the sustainable development of such regions.

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