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Water Resources Carrying Capacity Analysis of YarLung Tsangpo River Basin (I)

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Abstract: Water resources carrying capacity (WRCC) analysis is critically important in providing guidance to the sustainable development strategies of the YarLung Tsangpo River Basin (YTRB) due to the conflicts among the ample water resources, low development level of society, and the fragile ecological environment. This study evaluated the scheduled developing mode of YTRB in the planning years from 2016 to 2030 with a WRCC system containing three components: a hydrological informatics modeling system (HIMS), water resources carrying capacity (WRCC) model, and an index evaluation system. The averaged WRCC index is 4.29, 1.19, and 0.06 for the planning years, and 2.61, 0.98, 0.05 for the baseline years for the three sub-basins. The water deficiency problem becomes more severe in the upper sub-basin and appears in the middle sub-basin with the WRCC index greater than 1, while the water resources are not fully utilized in the lower sub-basin in the planning years, with the WRCC index far less than 1. The GDP of the three sub-basins is greater in the planning years, with 2.25×10^8 , 54.60×10^8 , and 3.94×10^8 dollars year⁻¹ than those in the baseline years with 1.97×10^8 , 47.71×10^8 , 3.43×10^8 dollars year⁻¹. However, GDP per capita/cubic meter keeps decreasing due to the great population growth rate and non-enhanced water use efficiency. The sustainability index is 0.04, 0.23, and 0.47 in the planning years, which is lower than the 0.04, 0.31, and 0.50 in the baseline years. Therefore, the scheduled growth rates of the population, urbanization, and GDP are a developing mode with low sustainability and are not appropriate to be continued in the planning years. Further work is needed to identify a sustainable developing mode with a decreased population growth rate, enhanced water use efficiency in the economic system, and the optimized allocation of water resources distribution in the three sub-basins with hydraulic facilities.

Keywords: YarLung Tsangpo River basin; WRCC; HIMS model; an index evaluation system; sustainability index

1. Introduction

Water resources are the fundamental resource supporting regional economic development and maintaining the balance of the ecological system [1]. Coordinating water resources allocation can help to solve the problem of water deficiency in arid areas and the problem of water quality degradation in humid areas, and maintain the development sustainability of the water resources system, ecological system, and economic system [2–5]. Therefore, studying the water resources carrying capacity (WRCC) is necessary to obtain scientific guidance on water resources allocation and alleviate the conflict between the demand of the society–economy system and water resources supply.

The concept of carrying capacity was initially introduced regarding the population growth rate under the constriction of food and wars [6], rooted in demography and biology, and applied in ecology [7]. WRCC is an extension of carrying capacity in the natural resource field and has been given various definitions from different perspectives [3,8–10]. It is the capacity of water resources

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to sustain a society at a defined good standard of living; defined by Dou et al. [5] as the maximum sustainable socioeconomic scale based on the available water resources and maintenance of good, assigned environmental conditions; and defined by Song et al. [3] as the maximum bearing capacity of water resources for human activity in a certain period of socio-economic development or a certain living standard in a favorable ecological system. Few theoretical breakthroughs have been achieved regarding the WRCC concept internationally, but brief connection has been done with the sustainable development [5,11]. In this study, WRCC is defined as the maximum scale of society that water resources can support under conditions of sustainable development [10,12]. The maximum scale of society is presented as the maximum population growth rate and GDP, while the sustainable development condition means the water demand of human beings can be met and the ecological environment can be preserved [10,12].

WRCC is generally quantified as the ratio between the water demand of social development and water supply under specific conditions. It is commonly calculated using two methods: the modeling method and the index evaluation system method [3,4,13–16]. Liao et al. [4] conducted a WRCC analysis of Shandong Province using the evaluation model to predict the water supply and demand status from 2015 to 2029 based on the historical dataset from 2000 to 2014, and found that the population growth rate was greater than the water consumption rate that the system could afford and the population growth rate needed to be controlled to avoid conditions of insufficient water. Dou et al. [5] studied the WRCC status of Henan Province from 2011 to 2031 with the WRCC quantification model to estimate the maximum GDP under the Henan developmental schedules with the predicted water supply and demand and found that there were 33 sub-regions overloaded with water resources based on the recorded GDP and population in 2010. The planned growth rates of the GDP and population should be reduced to match the carrying capacity of the water resources [5]. Wang et al. [10] analyzed the WRCC status of Haihe River Basin from 1998 to 2007 with the eco-environmental carrying capacity model through estimating the maximum population of 108 million and GDP of 2.7 trillion RMB based on the precondition that the integrated sustainability index of the economy, water resources, and environment were greater than 0.7.

The WRCC can also be calculated using the index evaluation system based on the targeted optimizing method or principles to clarify the maximum society scales for the WRCC [14–17]. Cao and Zhang [18] evaluated the WRCC status of Gansu Province from 2006 to 2015 with the indices selected and weights assigned using the principal component method and identified the spatial differences of WRCC in Gansu Province. Kang and Xu [15] evaluated the WRCC of a planned industrial park with an index assessment combined with a dynamic system, and found that the WRCC showed a declining trend on the basis of the planned growth rate of the population and GDP and the declining rate accelerated with the development of the industrial park. Water cycling and water saving technologies needed to be applied to curb the declining rate and investment in the management of environmental protection that is necessary to process the polluted water. Meng et al. [19] analyzed the WRCC of Tarim River Basin, China, in 2002 using the fuzzy comprehensive evaluation method to determine the weight of seven evaluating indices and the index evaluation system to calculate the evaluating scores for the five sub-basins within the Tarim River Basin. It was found that the current water resources exploitation and utilization reached a relatively high degree, and the integrated management of the water resources in the basin should be strengthened in order to utilize water resources scientifically and sustainably.

The YTRB has the amplest water resource in China besides the Yangtze River basin and Pearl River basin [20], however, it suffers from a low level of economic development and a fragile ecological environment [20,21]. This study evaluated the scheduled developing mode through scoring the development sustainability with the WRCC system in the baseline and planning years, and provided specific development suggestions on the basis of the WRCC analysis for the three sub-basins. The WRCC system predicted the streamflow with the HIMS model, calculated the key parameters

in the economic, ecological, and water resources systems using the WRCC model, and evaluated the sustainability of the developing mode with the index evaluation system.

2. Materials and Methods

2.1. Study Domain

YarLung Tsangpo River is an international river with an average elevation of 4621.3 m. The Chinese part is about 2057 km, with the river basin of 242,000 km² located on the Qinghai–Tibetan Plateau (Figure 1). The YTRB is divided into three sub-basins, with the upstream sub-basin from river source to Lhatse County, the midstream sub-basin from Lhatse County to Pi County, the lower sub-basin from Pi County to the rest of the stream basin. A total of 80% of the precipitation is focused from June to September over the entire basin and it is unevenly distributed over the three sub-basins. From the western to the eastern YTRB, the elevation decreases, while the precipitation quantity and air temperature increase. The YTRB goes through three climate zones in the three sub-basins: arid area, semi-arid area, and humid area.

The upper sub-basin is in the western YTRB with an area of 2.6×10^4 km², and is located in the arid area with an annual precipitation less than 300 mm and an air temperature around -0.3 °C. The landform is wide plateau gullies, and the major land cover is alpine steppe, alpine meadow, and alpine bushes. The population is around 15.34×10^8 (Table 1). The middle sub-basin has an area of 16.6×10^4 km² and is located in the semi-arid area with annual precipitation ranging from 300 to 600 mm and an air temperature of around 5.2 °C. The major land cover is semi-arid herbs and broad leaf shrubs, and the topography is characterized by the wide and narrow gullies. The population is around 129.73×10^4 . The middle sub-basin is the center of politics, economy, and culture in the Tibet Autonomous Region [22]. The lower sub-basin is in the eastern part of YTRB with area of 5.0×10^4 km², and is located in the humid area with annual precipitation greater than 4000 mm and an air temperature of around 7.0 °C. It has the amplest water resources, with a population of 8.60×10^4 . The major land cover is alpine forest, and the YarLung Tsangpo Grand Canyon located in this area, which is the largest and deepest canyon in the world. The GDP of the entire YTRB mainly comes from the agriculture, industry, and service industries, indicated by the Tibetan Statistical Year Book from 1995 to 2010.



Figure 1. The outline of YTRB and the spatial distribution of the meteorological and hydrological stations within the basin.

YTRB	Area (10 ⁴ km ²)	Precipitation (mm)	Temperature (°C)	River Length (km)	Population (10 ⁴)	GDP (10 ⁸ Dollars Year ⁻¹)
Upper sub-basin	2.6	<300	-0.3	268	15.3	1.97
Middle sub-basin	16.6	300-600	5.2	1293	129.7	47.7
Lower sub-basin	5.0	>4000	7.0	500	8.2	3.4

Table 1. The basic information of the three sub-basins of the YTRB.

2.2. Structure of the WRCC System

The WRCC system is composed of three parts, as Figure 2 shows. The HIMS model is applied to provide the annual streamflow to the WRCC model by simulating the hydrological processes of the three sub-basins. The WRCC model is used to calculate the key parameters of three systems, including the WRCC index, available water resources, and water resource per capita/ha in the water resource system; the GDP, population, GDP per capita/ha in the economic system; and the concentration of the chemical oxygen demand (CODCr) and the areas of forest and grass in the ecological system. An index evaluation system is utilized to evaluate the three systems' status and calculate the integrated sustainability index based on the status scores of the three systems for each sub-basin. The following three sections introduce the three parts in details.



Figure 2. The structure of the WRCC system.

2.2.1. HIMS Application in the YTRB

HIMS was applied to predict the streamflow in the planning years from 2016 to 2030. The model details can be found in Liu et al. [23]. The HIMS model is a distributed hydrological model for estimating the streamflow based on the law of water balance and energy conservation. The YTRB is divided into three sub-basins with 91 grid cells of $0.5 \times 0.5^{\circ}$ latitude by longitude. The climate dataset came from 10 meteorological stations within the basin with a daily time step from 1985 to 2010 and includes precipitation, maximum, and minimum air temperature. The datasets of DEM, land cover, and soil were from Data Center of Environmental Sciences of the Chinese Academy, with a resolution of $90 \times 90 \text{ m}^2$, $1 \times 1 \text{ km}^2$, and $1 \times 1 \text{ km}^2$, respectively. The observed streamflow came from the four hydrological stations within the study domain from 1980 to 2006 with a daily time step.

The future climate dataset was downloaded from the dataset of CMIP5 under the scenario of RCP4.5 and includes the precipitation and minimum and maximum air temperature from 2010 to 2030. The climate dataset was obtained with evenly weighted general circulation models (GCMs),

as recommended by Huang [24], due to the spatial error produced by the GDMs in the Tibetan area. The resolution of the future climate dataset was $0.5 \times 0.5^{\circ}$ latitude by longitude with a daily time step. HIMS is calibrated and validated with datasets from 1980 to 1995 and from 1996 to 2006 from the four hydrological stations. The simulating results were evaluated with the Nash–Sutcliffe efficiency (NSE) presented by Equation (1) and water error (WE) presented by Equation (2).

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2}$$
(1)

$$WE = \frac{\sum_{i=1}^{n} Y_{i}^{obs} - \sum_{i=1}^{n} Y_{i}^{sim}}{\sum_{i=1}^{n} Y_{i}^{obs}} \times 100\%$$
(2)

where Y_i^{obs} is the *ith* observation, Y_i^{sim} is the *ith* simulated value, Y^{mean} is the mean of the observed data, *n* is the number of datasets. If the NSE is very close to 1, the simulating accuracy is high; if the NSE is close to 0, the simulation performance is not good. If the absolute WE value is close to 0, then simulation accuracy is high. Generally, if the WE is within the range of ±25%, the simulating results are regarded to be satisfactory.

2.2.2. Water Resources Carrying Capacity Model

The WRCC model is composed of three systems: water resource system, economic system, and ecological system, details of which can be found in Wang et al. [10]. This model was used to calculate the key parameters of the three systems.

The water resource system of the WRCC model calculates the available water quantity in the water resources system using equations SE1, SE2, and SE3 listed in the Supplementary Section The available water resource is the streamflow, except the part lost to floods and the part remaining in channels to maintain the ecological balance. The economic system of the WRCC model is used to calculate the water demands of the economic system based on the growth rates of the population and the GDP, using equations SE4 to SE6, from three perspectives including industry, agriculture, and domestic life. The ecological system of the WRCC model is used to calculate the water demand of the ecological dilution of the polluted water using SE7. To ensure the ecological safety, the CODCr was no more than 20 mg/L in this study after the treatment of sewage plants and ecological dilution using equations SE8 to SE11. In the WRCC system, the water resources utilized in the economic system are regarded as the polluted water that will be discharged into rivers after treatment in sewage plants. Therefore, the water demand of the ecological dilution. However, the water resource system provides the upper limit of available water resources for the water demands of the two systems.

Finally, the WRCC index is calculated as the ratio between the water demand of economic and ecological systems and the available water quantity of the water resource system. If the ratio is greater than 1, the pressure of the water demand exceeds the water resources carrying capacity with a greater water demand than the available water resources, then the pressure increases with the elevation of this ratio. If the ratio is between 0 and 1, it means the pressure of the water demand is smaller than the water resources carrying capacity.

$$I = W_{demand} / Q_{ava} \tag{3}$$

where *I* is the WRCC index; W_{demand} is the total water demand of ecological system and economic system (m³ year⁻¹); and Q_{ava} is the available water quantity provided by the water resource system (m³ year⁻¹).

2.2.3. The Index Evaluation System

The index evaluation system evaluates the status of the three systems: the water resource system, the economic system, and the ecological system. The indices for each system are selected because they are quantifiable, independent of each other, and representative. The indices together with the five levels are listed in Table 2 on the basis of the Tibetan Statistical Year Book from 1995 to 2015. The score and weight of each index in the system are assigned to one sub-basin with the association analysis approach based on the similarity degree between the level criteria of each index and the value of the sub-basin [25–28]. The level of one system depends on the evaluation scores of all indices in one system [29].

The sustainability index is an integrated measurement to evaluate the developing sustainability of the economic, water resource, and ecological systems. It is obtained based on the score of each system in one sub-basin. It is calculated using Equation (4), as follows:

$$DD(T) = S(T)^{\beta_1} \cdot W(T)^{\beta_2} \cdot E(T)^{\beta_3}$$
(4)

where DD(T) is the sustainability index; S(T) is the score of the economic system; E(T) is the score of the ecological system; W(T) is the score of the water resource system; β_1 , β_2 , β_3 are the weighted exponents for the three factors and assigned to 1/3 as the three factors are equally important for the sustainability measurement.

T represents the annual time step. The range of S(T), E(T), and W(T) is from 0 to 1. The closer DD(T) is to 1, the greater the developing quality is of the study region. The DD(T) format of the time series is presented with Max(SUI) to evaluate the sustainability of regional development with regard to the economic, water resource, and ecological systems. The Max(SUI) is calculated using Equation (3) as follows:

$$Max(SUI) = Max(\sum_{T=1}^{N} DD(T)/N)$$
(5)

where *N* is the number of years.

Table 2. The evaluation system of the combined systems of the water resources, economic, and ecological environment.

System	Factor	Unit	I—E *	II—G *	III—A *	VI—B *	V—EB *
	Water resource per capita	m ³	10^{5}	5000	1700	1000	500
Water resources	Water resource per ha *	10 ⁴ m ³ /ha	7.42	5.88	4.48	3.08	2.52
	WRCC index		0.01	0.1	0.3	0.5	0.8
	GDP per capita	dollars	5303	3181	1060	606	151
Economy	GDP per cubic meter of water	dollars/m ³	2.71	2.26	1.36	0.90	0.23
	Urbanization rate	(%)	60	50	40	30	15
	DOCCr	mg/L	10	15	20	30	40
Ecology	Forestland percentage	(%)	80	60	40	20	10
	Grassland percentage	(%)	80	60	40	20	10

* Note: (1) E denotes excellent; G denotes Good; A denotes Acceptable; B denotes bad; EB denotes extremely bad.

3. Results

3.1. HIMS Application to the YarLung Tsangpo River Basin

The streamflow was estimated as the total water resources of the water resource system and used to calculate the available water resources to support the economic system and maintain the ecological system. The streamflow of the four stations within the YTRB was well-simulated by the HIMS model based on the statistical results in both the calibration and validation periods (Table 3). At the Lhatse station, the streamflow comparisons between the simulation and observation are showed in Figure 3a, and the predicted streamflow of the future period is presented in Figure 3b at the daily time step. Though the simulated streamflow of the three stations are not presented due to the length limitation of

this paper, the statistical metrics of the four stations are listed in Table 3. The HIMS model shows better performance at the stations of Nugesha, Yangcun, and Nuxia than at Lhatse station, as Lhatse station is located in the arid area with a small quantity of precipitation and streamflow (Table 3). This finding is close to that obtained by Parajka et al. [30], who found that runoff-hydrograph predictions tend to be more accurate in humid than in arid catchments based on the meta-data analysis of 34 reports of 3874 catchments with over 20 hydrological models, and provided detailed analysis of some individual basins from the 34 reports. The streamflow is high in the wet period from May to September and low in the dry period from October to April (Figure 4a,b).

	Stations		oration	Valie	dation	
		NSE	WE (%)	NSE	WE (%)	
Lha	itse station	0.84	-0.5	0.89	-16	
Nug	esha station	0.95	-4	0.90	-3	
Yang	cun station	0.93	-0.2	0.90	0.4	
Nu	xia station	0.94	-10	0.94	0.7	
(*) 2400 (*)	calibr	ation	┍╶╖┼╖┍┍╵	valida	tion	o o cipitation (mm)
a o 1990 1992	1994 1996 10	998 200	0 2002 20	04 2006	2008 2010	⊥ 150 ਸ਼ ਸ਼
b bb bbb.	pbserved streamf		nulated stream	flow – pred	dicted streamflo	- -

Table 3. HIMS model calibration results at the four hydrological stations within the YTRB.

Figure 3. HIMS model calibration and validation in the baseline years (**a**) and prediction in the planning years (**b**) at the Lhatse station.

3.2. WRCC Index of the YTRB in Baseline Years

The integrated sustainability of the baseline years was evaluated to present the water resources usage status based on the observational datasets from 1990 to 2010, shown in Table 4, with the utilization of the WRCC system. In the economic system, more than 90% of the water demand came from agriculture, followed by industry and domestic life in the three sub-basins. In the ecological system, the water demand was the greatest in the middle sub-basin for ecological dilution, as it has the largest water demand and pollution of the three sub-basins. The total water demand is the sum of the water resource demands of the ecological system and economic system. It was the greatest in the middle sub-basin, followed by the upper and lower sub-basins (Table 4), as the middle sub-basin has the greatest population and largest area (Table 1). In the water resource system, the available water resource is the greatest in the lower sub-basin, followed by the upper sub-basin, followed by the upper sub-basin, followed by the middle and upper sub-basins, as the lower sub-basin is located in the humid area, while the middle and upper sub-basins are located in the semi-arid and arid areas. The rate of available water resource is the ratio between the available water resource and the total water resource, which was 1%, 4%, 1% for the upper, middle,

and lower sub-basins, respectively. The middle sub-basin has the greatest rate due to the four reservoirs constructed in this area [20] and fewer hydraulic facilities in the upper and lower sub-basins.

Systems	Parameters	Upper Sub-Basin	Middle Sub-Basin	Lower Sub-Basin
Water resource	Total water resource ($10^8 \text{ m}^3 \text{ year}^{-1}$)	56.18	481.65	1049.91
evetor	Available water resource (10 ⁸ m ³ year ⁻¹)	5.62	19.24	10.50
system	Available water resource rate (%)	1	4	1
	Total water demand ($10^8 \text{ m}^3 \text{ year}^{-1}$)	1.43	18.03	0.51
Economic system	Agricultural water consumption $(10^8 \text{ m}^3 \text{ year}^{-1})$	1.39	15.78	0.49
	Domestic water consumption ($10^8 \text{ m}^3 \text{ year}^{-1}$)	0.02	0.43	0.01
	Industrial water consumption ($10^8 \text{ m}^3 \text{ year}^{-1}$)	0.03	1.82	0.01
	CODCr (mg/L)	6.87	15	15
Ecological system	Forestland (km ²)	0	0.31	1.88
	Grassland (km ²)	2.30	13.12	1.24
	Ecological water demand ($10^8 \text{ m}^3 \text{ year}^{-1}$)	0.001	0.85	0.0004

Table 4. Key inputs of WRCC model for the three sub-basins of YTRB in the baseline years.

The WRCC index was 2.61, 0.98, and 0.05 for the upper, middle, and lower sub-basins, respectively (Table 5). The upper sub-basin had a severe water deficiency problem, with a WRCC index greater than 1. This should be attributed to the small quantity of available water resources caused by the arid climate and undeveloped hydraulic facilities. The middle sub-basin is at risk of water resource deficiency as the WRCC index is around 1. The lower sub-basin has ample water resources available, with a WRCC index lower than 1 due to the humid climate. Therefore, the evaluation score of the water resource system reached 0.80 in the lower sub-basin, followed by the middle and upper sub-basins, with 0.11 and 0.0004 (Table 6). The evaluation score of the economic system was the greatest in the middle sub-basin, followed by the lower and upper sub-basins. This makes sense as the middle sub-basin has the greatest urbanization rate, and the second greatest GDP per capita and GDP per cubic meter of water, as it supports 90% of the residents of the entire YTRB. The score of the ecological system was 0.80 for the upper sub-basin and 0.60 for the other two sub-basins due to the water quality being at the I/II level and the high percentage of grassland (Table 6). The integrated sustainability indices of the three sub-basins was 0.09, 0.31, 0.50 for the upper, middle, and lower sub-basins, respectively, all smaller than 1, which indicates a benign development status.

System	Indices	Upper Sub-Basin	Middle Sub-Basin	Lower Sub-Basin
Water recourses	Water resource per capita $(10^4 \text{ m}^3 \text{ year}^{-1})$	0.04	0.15	1.37
water resources	Water resource per ha $(m^3 year^{-1})$	4923	8587	97339
system	WRCC index	2.61	0.98	0.05
	GDP per capita (10^4 dollars year ⁻¹)	0.13	0.37	0.45
Economic system	GDP per cubic meter of WR (dollars m^{-3} year ⁻¹)	1.35	2.53	6.49
Economic system	Urbanization rate (%)	19.38	55.12	8.00
	GDP (10^8 dollars year ⁻¹)	1.97	47.71	3.44
Ecological	$CODCr (mg L^{-1})$	6.87	15	15
Ecological	Forestland percentage (%)	0.06	1.84	37.54
System	Grassland percentage (%)	88.33	79.05	24.94

Table 5. Outputs of WRCC model for the three sub-basins in the baseline years.

Table 6. Output of the index evaluation system for the three sub-basins in the baseline years.

Score	Upper Sub-Basin	Middle Sub-Basin	Lower Sub-Basin
Water resources system	0.004	0.11	0.80
Economic system	0.20	0.43	0.26
Ecological system	0.80	0.60	0.60
Integrated sustainability	0.09	0.31	0.50

3.3. WRCC Status of YTRB in the Planning Years

The scheduled development mode was obtained based on historical datasets from the Statistical Year Book of the Tibet Autonomous Region [31]: (1) The growth rates of the population, GDP, and urbanization are scheduled and presented in Figure 4a–c; (2) The hydraulic facilities were not changed in the planning years and the available water resource rate was 1%, 4%, and 1% for the upper, middle, and lower sub-basins, respectively, in the planning years; (3) The constriction of the water quality requirements with regard to CODCr was no more than 20 mg/L and the decreasing rate of forest land and grass land was no more than 0.1%.

The total water demand of the planning years was estimated as the sum of the water demand of the ecological system and economic system for the three sub-basins (Figure 4a, Table 7). It increases constantly together with the water demands of the economic system and ecological system over the planning years (Figure 4b,c). In the economic system, the increased water demands of the industrial and agricultural fields are the main reasons for the elevation of the total water demand, as more water is needed to support the increasing population in the planning years over three sub-basins (Table 7, Figure 4a). The total water demand is greatest in the middle sub-basin, followed by the upper and lower sub-basins; it is the same true for the GDP (Figure 4f). The average GDP of the planning years was around 2.25×10^8 dollars year⁻¹, 54.60×10^8 dollars year⁻¹, and 3.94×10^8 dollars year⁻¹ for the upper, middle, and lower sub-basins. In the ecological system, the water demand increased consistently in response to the increased water demand of economic system, which makes sense as more water is needed to dilute the increasing polluted water to ensure that the water quality meets the CODCr requirement (Figure 4d,e).

Table 7. Water demands of the two systems and scheduled GDP for the three sub-basins in the planning years.

WRCC Model	odel Economic System					
Inputs	GDP (10 ⁸ Dollars Year ⁻¹)	Total WD * $(10^8 \text{ m}^3 \text{ Year}^{-1})$	Domestic WD (10 ⁸ m ³ Year ⁻¹)	Agricultural WD (10 ⁸ m ³ Year ⁻¹)	Industrial WD (10 ⁸ m ³ Year ⁻¹)	Ecological WD (10 ⁸ m ³ Year ⁻¹)
Upper sub-basin	2.25	2.08	0.02	2.03	0.02	0.002
Middle sub-basin	54.60	23.40	0.62	19.37	2.53	0.88
Lower sub-basin	3.94	0.68	0.02	0.58	0.06	0.0004



Note: WD * denotes water demand.

Figure 4. Key inputs of WRCC model in the planning years.

In the water system of the planning years, the available water quantity fluctuates in Figure 5, mainly due to the annual fluctuations of the total water resource predicted by the HIMS model using the future climate dataset. This was 0.50×10^8 m³ year⁻¹, 20.20×10^8 m³ year⁻¹, and 11.54×10^8 m³ year⁻¹ for the upper, middle and lower sub-basins with unchanged available water resource rates (Table 8). This increased by 5% and 10% in the middle and lower sub-basins relative to that of the baseline years due to the precipitation increase in the semi-arid area and humid area in the future period [32]. However, it decreased by 12% in the upper sub-basin as a result of the declined precipitation in the arid area, which is similar to the runoff reduction of 13.9% in the upper sub-basin [33].

The WRCC index of the planning years was 4.29, 1.19, and 0.06 for the three sub-basins, with a changing shape close to that of the available water resource (Figure 5b). It is greater than 1 in both the upper and middle sub-basins, while far less than 1 in the lower sub-basin. In the upper sub-basin, the water deficiency problem will become more severe in the planning years, as the water demand quantity is 4.29 times that of the available water resource in the planning years, which is greater than 2.61 of the baseline years (Figure 5b, Table 8). This is probably due to the declined available water resource and the increased domestic and industrial water resource demand in the planning years. The middle sub-basin has a water deficiency problem that appears in the planning years with a WRCC index of 1.19, even though it does not have this problem with the WRCC index of 0.98 in the baseline years. The available water resource is fully utilized to support the economic system and ecological system in the baseline years. The lower sub-basin has ample water resources, with a WRCC index of 0.06, which is less than 1 and indicates that much of the available water resource remains unused.

The water resource per capita decrease in the three sub-basins (Figure 5c), which makes sense due to the great population growth rate in the three sub-basins (Figure 4a). Particularly, the urbanization rate of the upper sub-basin keeps increasing in the planning years (Figure 4b), with the greater water consumption of urban residents than of rural residents [34]. The GDP per capita decreases as the growth rate of the population is greater than that of the GDP (Figure 5d,e). Meanwhile, the GDP per cubic meter of water decreases over the three sub-basins due to the lack of improved water use efficiency over three sub-basins.



Figure 5. Key outputs of the WRCC model for the three sub-basins in the planning years.

WRCC Model Outputs	Available Water Resource (10 ⁸ m ³)	WRCC Index	Water Resource per Capita (10 ⁴ m ³)	Water Resource per ha (10 ⁴ m ³)	GDP per Capita (10 ⁴ Dollars)	GDP per Cubic Meter of Water (Dollars)
Upper sub-basin	0.50	4.29	0.03	0.43	0.13	1.09
Middle sub-basin	20.20	1.19	0.13	0.86	0.35	2.33
Lower sub-basin	11.54	0.06	1.15	10.86	0.39	5.77

Table 8. Averaged key outputs of WRCC model for the three sub-basins in the planning years.

3.4. Integrated Sustainability of the Three Sub-Basins in the Planning Years

The sustainability was evaluated using the index evaluation system for the water resource, economic, and ecological systems of the three sub-basins. The integrated sustainability index was calculated based on the scores of the three systems for each sub-basin. The sustainable scores and averaged scores are shown in Figure 6 and Table 9, respectively. If the evaluation score was closer to 1, the sustainable level was higher.

The evaluation score of the water resource system was the greatest for the lower sub-basin, with 0.79, followed by 0.07 for the middle sub-basin and 0.0004 for the upper sub-basin (Table 9). The upper and middle sub-basins have a water deficiency problem, while the lower sub-basin has ample water resources due to the humid climate. As the water per capita and water per ha are relatively low in the upper sub-basin and high in the lower sub-basin, the evaluation score for the water resources system does not show obvious annual variance in the upper sub-basin as it does in the lower sub-basin (Figure 6) The evaluation score for the economic system was 0.25, 0.35, and 0.21 for the upper, middle, and lower sub-basins, respectively. Although the GDP increased for the three sub-basins, the GDP per capita and GDP per cubic meter of water were low and not enhanced over the planning years. The evaluation score for the ecological system was around 0.60 over the planning years, which should be attributed to the precondition that the areas of forest and grass have a reduction rate of no more than 0.1%, and the CODCr is no more than 20 mg/L. The low evaluation scores of the economy reduce the integrated sustainability score for all three sub-basins, particularly the lower sub-basin (Figure 6). The integrated sustainability score for the three sub-basins in the planning years was 0.04, 0.23, and 0.47, which is lower than those for the baseline years with 0.09, 0.31, 0.50. Therefore, the scheduled development model is not appropriate in the future period for all three sub-basins.



Figure 6. Evaluation score of the three systems and integrated sustainability for the three sub-basins in the planning years.

Table 9. Average evaluation score of the three systems and integrated sustainability of the three sub-basins in the planning years.

Score	Upper Sub-Basin	Middle Sub-Basin	Lower Sub-Basin
Water resources system	0.0004	0.07	0.79
Economic system	0.25	0.35	0.21
Ecological system	0.60	0.60	0.60
Integrated sustainability	0.04	0.23	0.47

4. Discussion

The scheduled development mode for the planning years was evaluated using the WRCC system, composed of the HIMS model, WRCC model, and an index evaluation system. The upper sub-basin had a water deficiency problem in the baseline years due to the arid climate, and the problem was more severe for the planning years with a WRCC index of 4.29, total water resource demand of 2.15×10^8 m³ year⁻¹, and available water resource of 0.50×10^8 m³ year⁻¹. The reduced available water resource and increasing water resource demand are the main reasons leading to this problem. The evaluation score for the economic system decreased even though the absolute GDP is 2.25×10^8 dollars year⁻¹ in the planning years, which is greater than that of the baseline years of 1.97×10^8 dollars year⁻¹. The large population growth rate and unimproved water use efficiency both contribute to the low evaluation score of the economical system. The integrated sustainability score did not increase due to the low evaluation scores of the water resources system and economic system.

The middle sub-basin was on the risk of water deficiency in the baseline years due to the semi-arid climate and large water resource demand, and continues to suffer from this problem in the planning years with the WRCC index of 1.19. The total water resource demand reached 24.04×10^8 m³ year⁻¹, even though the available water resource increased to 20.20×10^8 m³ year⁻¹ in the planning years due to climate change. The large population growth rate leads to an increase in water resource demand that cannot be covered by the available water resource in the absence of improved water use efficiency, therefore, the water resource per capita decrease. Meanwhile, the conflict between the large population growth rate and the small increase in the GDP causes the reduction of GDP per capita in the planning years. The low evaluation scores of the economic system and water resources system are the main reasons for the reduction in the integrated sustainability score in the planning years.

The lower sub-basin has ample water resources, a less-developed economic system, and a WRCC much lower than 1 in the humid area. Though the total water resource demand increases to $0.06 \times 10^8 \text{ m}^3 \text{ year}^{-1}$, the available water resource is much greater, with $11.54 \times 10^8 \text{ m}^3 \text{ year}^{-1}$. In the economic system, the growth rate of the population is greater than that of the GDP, therefore the GDP per capita continues to decrease in the planning years. The unimproved water use efficiency causes the reduction of GDP per cubic meter of water. Therefore, the evaluating score for the economic system is low and reduces the integrated sustainability index for the planning years. The integrated sustainability score for the planning years is lower than that in the baseline years, even though it continues to increase slightly due to the increasing available water resource.

To increase the absolute values of population, urbanization rate, and GDP cannot help but elevate the scores of the water resource system and economic system for all three sub-basins. The scheduled development mode is not appropriate due to the decreased sustainability scores for the water, economic, and ecological systems and the integrated sustainability index. To improve the score of the water and economic systems is important for the upper and middle sub-basins. These two two sub-basins need to improve their water use efficiency to meet the increasing water demand of the economic and ecological systems with the limited available water resource in the water resource system. To increase the quantity of available water resource is the other way to improve the evaluation score of the water resources system and the integrated sustainability score, by constructing hydraulic facilities or conducting water division from the lower sub-basins. In the economic system, optimizing water resource allocation is necessary, besides the greater water resource investment from the industrial perspective for the achievement of the greater GDP production. Another option is to slow down the population growth rate to match that of the GDP to ensure the elevation of the GDP per capita. In the lower sub-basin, water resources should be used fully and allocated with appropriate proportions between to the economic and ecological systems and among the three perspectives of the economic system. In addition, slowing down the growth rate of the population is also necessary in the lower sub-basin to increase the evaluation score of the economic system.

5. Conclusions

Studying the water resource carrying capacity is important in the YTRB due to the conflicts among the ample water resources, low level of economic development, and fragile environment. This paper evaluated the scheduled development mode of the three sub-basins in the planning years using the WRCC system. The scheduled development mode is not appropriate due to the decreased sustainability of the three sub-basins, more severe water deficiency problems for the upper and middle sub-basins, and the declining water resource/GDP per capita over the three sub-basins.

Under the scheduled development mode, the upper and middle sub-basins will increase their GDP by 15%, with 0.13×10^8 and 0.35×10^8 dollars year⁻¹. The integrated sustainability of the upper and middle sub-basin will be around 0.04 and 0.23 lower in the planning years than the historical records with 0.09 and 0.31. In the water resources system, the water deficiency problem will become more severe in the upper sub-basin, with a WRCC index of 4.29, and will appear in the middle sub-basin with a WRCC index of 1.19. The major reasons for this are the declining available water resource, high population growth rate, and unimproved water use efficiency. In the economic system, the GDP per capita and GDP per cubic meter of water decrease as a result of the unmatched growth rates of the population and GDP. To improve the sustainability and solve the water deficiency problems, it is necessary to enhance the water use efficiency using technologies in the fields of agriculture and industry, slow down the population growth rate, and increase the growth rate of the GDP.

With the scheduled developing mode, the GDP of the lower sub-basin will increase by 15%, with 0.39×10^8 dollars year⁻¹, and the integrated sustainability will decrease to 0.47 in the planning years, with little change over the three systems. In the water resource system, there are ample water resources available for utilization in the lower sub-basin, with available water resource of 11.54×10^8 m³, and a WRCC index of around 0.06. In the economic system, the GDP increases while the GPD per capita and GDP per cubic meter water decline in the planning years due to the unimproved water use efficiency and large population growth rate. In the ecological system there is little change in the CODCr and a rate of decrease of less than 0.1% for grasslands and forests. Further work is necessary to identify an optimized development strategy that will enhance the water use efficiency over the three sub-basins and identify reasonable water resource allocation between the economic system and ecological system in order to obtain the maximum growth rate of the GDP and the appropriate population growth rate according to the water resource carrying capacity.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/9/1131/s1, Equations of water resources system, Equations of economic system, and Equations of ecological system.

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