Case Study

Quantitative Analysis of Human-Water Relationships and Harmony-Based Regulation in the Tarim River Basin

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Abstract: In recent decades, the Tarim River basin in northwestern China has seen intense confrontation between economic development and environmental protection. How to balance sustainable socioeconomic development and harmony between humans and water has been a critical issue facing local governments for many years. This study proposes a quantitative method of harmony theory that contains three basic criteria, heath, development, and coordination, to address the harmony problem regarding the human–water relationship in the basin. Indicators were used to quantify levels of health, development, and coordination in the basin. An optimal scheme is proposed, based on the three aggregate indicators. The evaluation results indicate the following: (1) health conditions in the middle and lower reaches of the river basin are not optimal. Development conditions in the lower reach are slightly better, and coordination conditions there are the poorest; and (2) the Aksu and Kaidu-Kongqi rivers have a relatively harmonious state, but remaining districts have relative disharmony. Scenario simulation results show that human system development and water system health are equally important for a harmonious relationship. When the human and water systems achieve coordinated development, the degree of harmony increased from 0.4230 to 0.6618. Regulation results are of scientific and practical value in basin-scale water resource management in arid regions. **DOI: 10.1061/(ASCE)HE.1943-5584.0001118.** © *2014 American Society of Civil Engineers.*

Author keywords: Quantitative evaluation method; Water resources; Arid regions; Harmony degree calculation; Control scenario.

Introduction

In China, the principle of harmonious coexistence between humans and water was advanced in 1999. This has been gradually accepted and become one of the water control concepts and principles in the subsequent period. This harmonious principle should not only inform thought and slogans, but scientific and practical suggestions should also be proposed for basin-scale water resource management. Watershed management calls for a redefinition of watersheds from isolated natural systems to coupled human-natural systems, which are characterized by interactions between human activities and natural processes (Cai 2011). Some works have identified dominant effects on human-natural systems through coupling the two systems. When the water system and social or human systems are fully coupled, the adaptive behavior of those systems can be simulated. For example, Shafiee and Zechman (2014) proposed an agent-based modeling framework for sociotechnical simulation to research the influence of decisions and behaviors of human actors during contamination events. In arid regions, water is critical for human existence, socioeconomic development, and environmental protection (Maingi and Marsh 2002). However, there are more severe problems in these regions today than ever before. Rivers dry out in their middle and lower reaches, and freshwater shortages in many water-use areas have had harmful socioeconomic and environmental consequences (Chen et al. 2006). The relationship between human and water systems is increasingly effected by human activities within such arid areas.

The Tarim is the largest inland river basin in China, with unique ecological and hydrological processes. It is also well known for its vulnerable ecosystem. There are only four headstreams feeding the Tarim mainstream, i.e., the Hotan, Yarkand, Aksu, and Kaidu rivers, among which the Aksu is the primary water source, accounting for approximately 70% of the supply to the Tarim. Humans have transformed hydrologic processes through direct and indirect interference. Water from these tributaries is primarily consumed by different sectors of the national economy, such as domestic water consumption, ecological environmental water demand, and unavoidable evaporation loss in the plain area. The remaining water supplies the Tarim mainstream. Economic development consumes increasing water amounts in the source region, reducing the water supply on the mainstream. Previously, mountain rivers were the main supply of groundwater to rivers, reservoirs, canals, and field infiltration on entering the plains area. However, surface water recharge of groundwater has been affected by increased human activity (Ren et al. 2002). These phenomena have threatened the sustainable development of the area and deteriorated the ecological environment (Tao et al. 2008). Conflict between water resource protection and economic development is intensifying as a result of excessive exploitation of water resources to meet the needs of regional socioeconomic development. In 1970, approximately 321 km of the downstream section was completely cut off, and lakes at the end of the Tarim River, Lop Nor Lake, and Taitema Lake dried up in 1970 and 1972, respectively (Chen et al. 2007). The Government of China made many significant

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improvements to regulate streamflow of the Tarim River during the last few decades. For example, to aid the ecology, the government increased water diversion fivefold from Bosten Lake to the lower Tarim reaches during the high-flow period of 2000–2003. Thus, the 30-year shortage of surface water along 300 km of the lower reaches ended.

Nevertheless, the relationship between human activity and the water system of the Tarim River is complex. Much fundamental work has already been done. For example, Tao et al. (2011) described characteristics of water resource utilization in the Tarim River basin in terms of water quality and quantity, indicating that the water cycle and water quality have changed significantly because of human activity within the last 50 years. Hao et al. (2008) implied that this activity, rather than climate change, contributed to the cessation of streamflow and the drying-up of the river. By analyzing the relationship between ecological change and agricultural development, Xu et al. (2008) discussed water resource management and its ecological significance. Hao et al. (2008) assessed the effects of climate change and human activities on surface runoff. Using the Mann-Kendall test and regression and principal component analysis, Hao et al. (2009a) analyzed the effect of human activity on streamflow reduction and changes of total dissolved solids in the watercourse and groundwater of the mainstream. Chen et al. (2010, 2011) examined responses of groundwater and plant communities to a government-controlled seven-year recharge regime in the lower reaches of the river. They also suggested rational countermeasures to mitigate the desiccation tendency in water resource management and sustainable social, ecological, and economic development of the Tarim basin. Xu et al. (2010a) analyzed characteristics of hydro-climatic change in the basin.

However, most previous studies concentrated on specific processes, and lacked integrated research on the human–water relationship. Palmer (1965) proposed the Palmer Drought Severity Index to analyze the characteristics and trend of drought. Lautze et al. (2005) discussed the influence of population increase, human activity, and climate change on water systems. Lake and Bond (2007) concluded that the use of water with consideration of ecological sustainability is the foundation of long-term economic development. Hejazi and Markus (2009) studied effects of urbanization and climate variability on floods. Warburton et al. (2012) examined hydrologic effects of land-use change in South Africa. Most studies used qualitative or half quantitative analysis (Lake and Bond 2007; Simmons et al. 2007; Madani 2010). Based on long-term work of the author's research group, this paper proposes a quantitative method to analyze the human–water relationship in the Tarim River basin and investigates strategies of harmony-based regulation. The following are the main objectives of this research: (1) to consider the influences of various socioeconomic factors using three basic criteria in an index system; (2) to evaluate the basin's human–water relationship in recent years and analyze reasons for the low degree of harmony; (3) to propose different scenarios to scrutinize and compare human–water relationships; and (4) to advance practical strategies through scenario analysis for the improvement of human–water relationships. The results point to certain measures for sustainable and harmonious development of the river basin and provide direction in water resources management.

Study Area

The Tarim River basin is in the southern Xinjiang Uygur autonomous region of west China (Fig. 1). The main catchment covers an area of 4.355×10^5 km^2 (34°55′–43°08′N, 73°10′–94°05′E). The basin has an extreme drought desert climate with infrequent and low precipitation and strong potential evaporation. Average annual air temperature is 10.5–11.5°C. Monthly mean temperature is 20 to 30°C in July and −10 to 20°C in January. Mean annual precipitation is 116.8 mm, more than 80% of which falls during May–September (Zhang et al. 2010).

The Tarim River flows east to west along the northern marginal zone of the Taklamakan Desert and Tarim basin. There are nine drainage systems, those of the Aksu, Kashgar, Yarkant, Kaidu-Kongqi, Dina, Hotan, Keriya, Qarqan, and Weigan rivers, all of which previously flowed into the Tarim mainstream. Because of the influence of human activities and climate change, six rivers lost

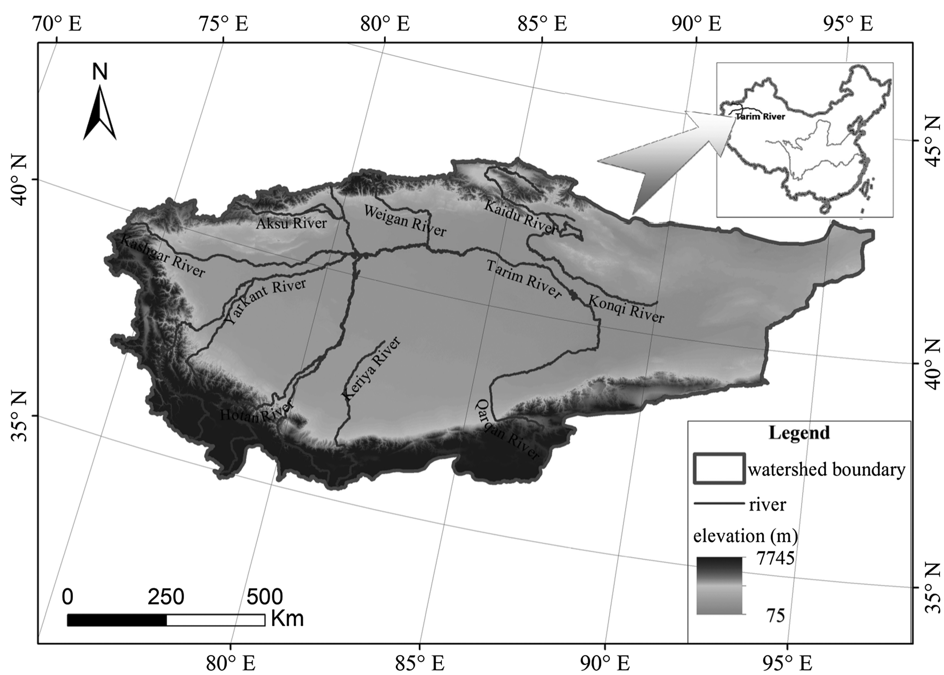

Fig. 1. Sketch map of Tarim River basin in western China

their surface water connections to the mainstream. At present, only three headstreams, the Hotan, Yarkant, and Aksu, have surface water flow to that mainstream. The Tarim basin is surrounded by mountains on three sides. The terrain gradually descends from west to east. The river in the Kunlun and Tianshan mountains carried large amounts of sediments to the foothills and plains. This accumulated sediment formed the largest type of alluvial-proluvial plain along the Tarim mainstream, which is 1,321 km in length from Xiaojiak to Tarim Lake. Because there are no other forms of water entering the mainstream, all runoff into the Tarim River is supplied from the headstreams. The Alaer hydrology station is regarded as the entrance to the mainstream. The upper and middle reaches begin at Alaer and Yinbazha, respectively, and Kala is the beginning of the lower reach.

Data and Quantitative Methods

Data

The authors suggest that three basic criteria, health, development, and coordination, should be considered when studying the relationship of human and water systems. Some indicators that can effectively reflect these criteria were selected to quantitatively analyze these criteria. Many indicators have been discussed in the water management literature toward balancing human water use and environmental needs. Sandoval-Solis et al. (2011) presented a water resource sustainability index to evaluate and compare different water management policies with respect to their sustainability. Veljković (2013) proposed indicators of sustainable development in the field of river basin management. Existing indicators focus on one aspect of water resources management. For example, the water resource sustainability index is calculated based on water supply and demand. The indicators proposed in this paper, by contrast, are relatively comprehensive, and include water resource status, human system development, and coordination between human and water systems. This aids comprehensive assessment of human–water relationships in the Tarim basin.

Health primarily refers to that of the water system, and is an indicator of river system ecological function, reliability, and resiliency. Health criteria reflect people's expectations, and they vary with different stages and health standards. Because of excessive exploitation and utilization of water resources, inflow during the 1990s from the lower reaches of the Tarim mainstream dropped by approximately 1,000,000,000 m^3 relative to that during the 1960s. The four source streams of the Tarim River have varying degrees of cutoff (Feng et al. 2001, 2005). Water pollution along the mainstream is serious, and water quality gradually deteriorates along the river course. A large amount of high-salinity water from farmland drainage enters the river from February through May, increasing dissolved salts and reducing water quality. Therefore, the indicators selected to represent health conditions include channel runoff requirement rates, flood control standards, water quality requirement rates, river system connectivity, and cultivated land salinization proportions.

Development primarily refers to that of the human system, and reflects achievement of sustainable economic and social development without the destruction of life-supporting systems. Development reflects a highly efficient utilization of resources, social development scale, and level of economic development. Irrigation quotas of regional crops in the Tarim basin are generally higher than the national average quota. Canal-system utilization coefficients of the four source streams and mainstream are lower than national ones. Per capita domestic water consumption of the four source streams are largely higher, but this is generally low for the mainstream at ~98 m^3/a. Per capita gross domestic product (GDP) in the basin has large regional variations. Therefore, the indicators selected to represent development conditions include regional population density, Engel's coefficients, per capita GDP, water consumption per 10,000 yuan industrial output value, irrigation water quota, canal system utilization factor, water-saving irrigation area proportions, per capita grain yields, per capita cultivated land, and per capita domestic water consumption.

Coordination primarily refers to that between the human and water systems, and implies that the two systems should be coordinated. Water systems provide necessary support and guarantees for human, economic, and social development. Human systems, in return, include measures to improve the virtuous cycle of the water system. Coordination can be reflected by conditions of water quality and quantity, development of a system of laws and regulations, accuracy of monitoring sites and system construction, management systems and levels, degree of public participation, extent of water savings, and construction of the water market. Consequently, the indicators were selected according to standards of water demand requirement rate, water resource utilization rate, urban sewage treatment rate, construction of monitoring stations and information systems, management systems and levels, and public awareness of river protection.

Data of different regions in the basin, obtained from the Tarim River basin water resources bulletin, statistical yearbook, and hydrological bureau monitoring, are displayed in Table 1. A quantitative evaluation and harmony-based regulation are examined using an indicator analysis to determine the degree of human–water harmony in seven basin regions.

Methodology

Calculation of Subharmony Degrees

Indicators selected were both quantitative and qualitative (Table 1). The dimension of quantitative indicators varies. To facilitate calculations and comparative analysis, the analytical method of fuzzy membership was used to quantitatively describe a single indicator. The fuzzy membership function is $\mu_j(x) = f_j(x)$, and each indicator is mapped on [0, 1] with the membership grade $\mu_j \in [0,1]$ (Zuo et al. 2008). The membership function is determined based on user experience or expert system analyses and is inevitably subjective. When using this method, representative values should be determined carefully. In this paper, several year's actual values, expert advice, and people's expectations were taken into account, giving great flexibility and comparability.

Each indicator has a subharmony degree (SHD) with range [0, 1]. To quantify the harmony degree of a single indicator, the authors assumed five representative values for each (10 for bidirectional indicators). These five are: (1) worst value, (2) poor value, (3) passing value, (4) better value, and (5) optimal value. SHD of the positive indicators (SHD_{Pi}) increase with increasing indicator values, such as per capita water resources. However, SHD of the negative indicators (SHD_{Ni}) decreases with increasing indicator values, such as water consumption per 10,000 yuan industrial output. SHD of the bidirectional indicators (SHD_{Bi}) increases then decreases with increasing indicator values. Eqs. (1)–(3) are used to calculate SHD. Feature node values of each indicator are shown in Table 2. The SHD of each indicator can be obtained:

Table 1. Indicator Data for Tarim River Basin in 2007

Criterion layer	Indicator layer	Unit	Aksu River	Yarkant River	Hotan River	Kaidu-Kongqi River	Mainstream upstream	Mainstream midstream	Mainstream downstream
Health indicators	Channel runoff requirement rate	%	1.95	1.85	0.8	2.79	0.71	0.54	0.31
	Flood control standards	Year	20	20	20	30	10	5	5
	Water quality requirement rate	%	1	1	0.9	0.9	0.4	0.4	0.4
	River system connectivity	%	1	0.4	0.5	0.6	0.8	0.4	0.2
	Cultivated land salinization proportion	%	37	35	41	41	60	60	60
Development indicators	Regional population density	Person/km^2	31.43	23.77	22.41	19.42	9.07	9.07	9.07
	Engel's coefficient	%	35.1	35.1	35.1	35.1	40.3	40.3	40.3
	Per capita GDP	Yuan	8,108	8,362	5,258	10,826	18,026	18,045	15,836
	Water consumption per 10,000 yuan of industrial output	m^3	158	246	114	114	215	215	215
	Irrigation water quota	10^4 m^3/km^2	116	144	142	87	125	125	125
	Canal system utilization coefficient		0.405	0.489	0.363	0.458	0.422	0.422	0.422
	Water-saving irrigation area proportion	%	74.2	51.2	49.5	66.8	100	100	100
	Per capita grain yields	Kg	1,278	1,042	424	590	398	398	1,355
	Per capita cultivated land	m^2	3,113	707	1,673	1,567	3,207	3,207	3,207
	Per capita domestic water consumption	m^3/a	113	134	122	50	98	98	98
Coordination indicators	Water demand requirement rate	%	0.855	1.133	0.909	0.556	0.859	0.707	1.098
	Water resources utilization rate	%	0.8053	0.7776	0.7643	0.5344	0.5716	0.5716	0.5716
	Urban sewage treatment rate	%	98	70	94	92	80	60	30
	Construction of monitoring stationand information system	Qualitative	0.8	0.5	0.5	0.6	0.5	0.5	0.4
	Management system and level	Qualitative	0.8	0.75	0.65	0.8	0.65	0.55	0.55
	Public awareness of river protection	Qualitative	0.8	0.7	0.7	0.7	0.6	0.5	0.4

Table 2. Human–Water Harmony Evaluation Indicators and Feature Node Values for Tarim River Basin

Criterion layer	Indicator layer	Worst value	Poor value	Passing value	More value	Optimal value	Indicator direction	Calculation methods	Meaning
Health indicators	Channel runoff requirement rate	0	0.3	0.6	0.8	1	Positive	The number of days that the runoff is less than the minimum/365	The shortage of water
	Flood control standards	0	20	50	100	200	Positive	Got form the water resources bulletin	The rich of water
	Water quality requirement rate	0	0.3	0.6	0.8	1	Positive	The length of unqualified river/total length	The pollution of water
	River system connectivity	0	0.4	0.8	0.9	1	Positive	The length of cutoff river/total length of river	The integrity of the drainage
	Cultivated land salinization proportion	100	60	20	10	0	Negative	The area of cultivated land salinization/total area of land	The effect of irrigation
Development indicators	Regional population density	100	60	20	10	1	Negative	Gross population/area	The population carrying capacity
	Engel's coefficient	60	50	40	30	20	Negative	Personal food expenditure/total spending	The level of social development
	Per capita GDP	100	1,000	3,000	10,000	20,000	Positive	GDP/gross population	The level of economic development
	Water consumption per 10,000 yuan of industrial output	400	250	100	40	10	Negative	Water consumption of industry/industrial output	The efficiency of industrial water use
	Irrigation water quota	300	150	90	60	30	Negative	Got form the water resources bulletin	The efficiency of agricultural water use
	Canal system utilization coefficient	0	0.4	0.7	0.9	1	Positive	Got form the water resources bulletin	The efficiency of carrying water
	Water-saving irrigation area proportion	0	40	60	90	100	Positive	Water-saving irrigation area/total area of land	The efficiency of agricultural water use
	Per capita grain yields	0	200	370	450	550	Positive	Gross output of grain/gross population	The carrying capacity and safety degree of development
	Per capita cultivated land	67	333	2,667	4,000	6,667	Positive	Total area of cultivated land/gross population	The restriction factor of social security
	Per capita domestic water consumption	0 300	60 250	90 220	120 200	150 180	Bidirectional	Domestic water consumption/gross population	The foundation of the survival of mankind
Coordination indicators	Water demand requirement rate	0	0.3	0.6	0.8	1	Positive	Water withdrawal/water demand	The human water demand satisfaction
	Water resources utilization rate	0 1	0.1 0.9	0.2 0.8	0.3 0.6	0.4 0.4	Bidirectional	Water supply/total water resources	The extent of exploitation and utilization of water resources
	Urban sewage treatment rate	0	30	60	90	100	Positive	Treated wastewater/total wastewater	The effort to improve the human–water relationship
	Construction of monitoring station and information system	0	0.3	0.6	0.8	1	Positive	Expert scoring method	The efficiency of management
	Management system and level	0	0.3	0.6	0.8	1	Positive	Expert scoring method	The ability of management
	Public awareness of river protection	0	0.3	0.6	0.8	1	Positive	Expert scoring method	The public consciousness

$$\text{SHD}_{Ni} = \begin{cases} 1 & x_i \le e_i \\ 0.8 + 0.2\left(\frac{d_i - x_i}{d_i - e_i}\right) & e_i < x_i \le d_i \\ 0.6 + 0.2\left(\frac{c_i - x_i}{c_i - d_i}\right) & d_i < x_i \le c_i \\ 0.3 + 0.3\left(\frac{b_i - x_i}{b_i - c_i}\right) & c_i < x_i \le b_i \\ 0.3\left(\frac{a_i - x_i}{a_i - b_i}\right) & b_i < x_i \le a_i \\ 0 & a_i < x_i \end{cases} \quad (1)$$

$$\text{SHD}_{Pi} = \begin{cases} 0 & x_i \le a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right) & a_i < x_i \le b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right) & b_i < x_i \le c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right) & c_i < x_i \le d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right) & d_i < x_i \le e_i \\ 1 & e_i < x_i \end{cases} \quad (2)$$

$$SHD_{Bi} = \begin{cases} 0 & x_i \le a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right) & a_i < x_i \le b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right) & b_i < x_i \le c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right) & c_i < x_i \le d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right) & d_i < x_i \le e_i \\ 1 & e_i < x_i \le f_i \\ 0.8 + 0.2\left(\frac{g_i - x_i}{g_i - f_i}\right) & f_i < x_i \le g_i \\ 0.6 + 0.2\left(\frac{h_i - x_i}{h_i - g_i}\right) & g_i < x_i \le h_i \\ 0.3 + 0.3\left(\frac{i_i - x_i}{i_i - h_i}\right) & h_i < x_i \le i_i \\ 0.3\left(\frac{j_i - x_i}{j_i - i_i}\right) & i_i < x_i \le j_i \\ 0 & j_i < x_i \end{cases} \quad (3)$$

Calculation of Harmony Degree

A determination matrix was created for five health, 10 development, and six coordination indicators using the analytic hierarchy process (Zhang 2009; Tong et al. 2012). This is based on the importance of each indicator, to obtain basis weights and final weight using a variable weighting method. Based on this process, the health, development, and coordination degrees of the Tarim basin were calculated using the following equations (Zuo 2012):

$$\text{HED}(T) = \sum_{i=1}^{n1} w_i \text{SHD}_1[Y_1^i(T)] \quad (4)$$

$$\text{DED}(T) = \sum_{i=1}^{n2} w_i \text{SHD}_2[Y_2^i(T)] \quad (5)$$

$$\text{HAD}(T) = \sum_{i=1}^{n3} w_i \text{SHD}_3[Y_3^i(T)] \quad (6)$$

where $Y_i(T)$ = indicator value at T moment; $\text{SHD}_{\alpha i}[Y^i(T)]$ and w_i s = subharmony degree and final weight of each indicator; $\text{HED}(T)$, $\text{DED}(T)$, and $\text{HAD}(T)$ indicate the health, development, and coordination degrees at T moment, respectively; and

Table 3. Judgment Standards for Harmony Levels

Harmony level	Range of HWHD
Complete harmony	$0.8 \le \text{HWHD} \le 1.0$
Fair harmony	$0.6 \le \text{HWHD} < 0.8$
Fair disharmony	$0.4 \le \text{HWHD} < 0.6$
Nearly complete disharmony	$0.2 \le \text{HWHD} < 0.4$
Complete disharmony	$0 \le \text{HWHD} < 0.2$

Note: HWHD = human–water harmony degree.

$n1$, $n2$, and $n3$ = number of indicators of health, development, and coordination, respectively.

Based on the previous analysis, human–water harmony includes the human and water systems and their coordination. Therefore, the human–water harmony degree should contain three aspects: health, development, and coordination. The calculation method is shown as follows:

$$\text{HWHD}(T) = \text{HED}(T)^{\beta_1} \cdot \text{DED}(T)^{\beta_2} \cdot \text{HAD}(T)^{\beta_3} \quad (7)$$

where HWHD(T) = human–water harmony degree at time T; and $\beta 1$, $\beta 2$, and $\beta 3$ = final weights of the health, development and coordination degrees at time T, respectively. Reflecting the equal importance of health, development, and coordination for a regional human–water relationship, initial indicator weights were defined by $\beta 1 = \beta 2 = \beta 3 = 1/3$. Next, the final indicator weight was obtained by applying the variable weighting method to each district in the basin.

Harmony Grading Standards

Values of human–water harmony degree were divided into five levels at an interval of 0.2 (Zuo 2012), as shown in Table 3.

Scenario Simulation of Harmony-Based Regulations

Considering the maximum degree of human–water harmony as the objective, multiple scenarios were created to simulate and calculate the harmony degree. After a set of harmony behaviors were combined in accord with the target value of harmony degree, the optimal or quasi-optimal harmony behavior was chosen from these behaviors. The authors selected a river reach with a relatively low harmony degree as an example. Four different development scenarios were created for a comparison with 2007, based on the development and program of the Tarim basin: (1) the situation in 2007; (2) a situation of improved water system indicators; (3) a situation of improved human system indicators; and (4) a situation of improved simultaneous human system and water system indicators.

Results and Discussion

Analysis of Human–Water Harmony Degree in Tarim River Basin

First, the SHD for the various indicators of health, development, and coordination in the basin were calculated by the quantitative single-indicator method. Next, weighted values of various indicators and harmony degrees were obtained using calculation steps (Tables 4 and 5 and Fig. 2).

Calculation results for harmony degree in the basin (Fig. 2) indicate that health conditions of the Kaidu-Kongqi (0.67) and Aksu (0.62) rivers, which are source streams, are relatively acceptable. Conditions of the Yarkant (0.60) and Hotan (0.59) rivers and upper reaches of the mainstream (0.55) were also adequate. In contrast, health conditions in the middle (0.48) and lower (0.42) reaches of the mainstream were not optimal. These results can be attributed to

Table 4. Subharmony Degree of Health, Development, and Coordination Indicators for Tarim River Basin

Indicator layer	Aksu River	Yarkant River	Hotan River	Kaidu-Kongqi River	Mainstream upstream	Mainstream midstream	Mainstream downstream
Channel runoff requirement rate	1.0000	1.0000	0.8000	1.0000	0.7100	0.5400	0.3100
Flood control standards	0.3000	0.3000	0.3000	0.4000	0.1500	0.0750	0.0750
Water quality requirement rate	1.0000	1.0000	0.9000	0.9000	0.4000	0.4000	0.4000
River system connectivity	1.0000	0.3000	0.3750	0.4500	0.6000	0.3000	0.1500
Cultivated land salinization proportion	0.4725	0.4875	0.4425	0.4425	0.3000	0.3000	0.3000
Regional population density	0.5143	0.5717	0.5819	0.6116	0.8207	0.8207	0.8207
Engel's coefficient	0.6980	0.6980	0.6980	0.6980	0.5910	0.5910	0.5910
Per capita GDP	0.7459	0.7532	0.6645	0.8165	0.9605	0.9609	0.9167
Water consumption per 10,000 yuan of industrial output	0.4840	0.3080	0.5720	0.5720	0.3700	0.3700	0.3700
Irrigation water quota	0.4695	0.3300	0.3420	0.6230	0.4268	0.4268	0.4268
Canal system utilization coefficient	0.3050	0.3890	0.2723	0.3580	0.3220	0.3220	0.3220
Water-saving irrigation area proportion	0.6947	0.4680	0.4425	0.6453	1.0000	1.0000	1.0000
Per capita grain yields	1.0000	1.0000	0.7350	1.0000	0.6700	0.6700	1.0000
Per capita cultivated land	0.6670	0.3480	0.4723	0.4586	0.6810	0.6810	0.6810
Per capita domestic water consumption	0.7533	0.8933	0.8133	0.2500	0.6533	0.6533	0.6533
Water demand requirement rate	0.8550	1.0000	0.9092	0.5557	0.8587	0.7073	1.0000
Water resources utilization rate	0.5840	0.6224	0.6357	0.8656	0.8284	0.8284	0.8284
Urban sewage treatment rate	0.9600	0.6667	0.8800	0.8400	0.7333	0.6000	0.3000
Construction of monitoring stationand information system	0.8000	0.5000	0.5000	0.6000	0.5000	0.5000	0.4000
Management system and level	0.8000	0.7500	0.6500	0.8000	0.6500	0.5500	0.5500
Public awareness of river protection	0.8000	0.7000	0.7000	0.7000	0.6000	0.5000	0.4000

Table 5. Weights of Health, Development and Coordination Indicators for Tarim River Basin

Indicator layer	Aksu River	Yarkant River	Hotan River	Kaidu-Kongqi River	Mainstream upstream	Mainstream midstream	Mainstream downstream
Channel runoff requirement rate	0.2775	0.2591	0.2982	0.2708	0.2816	0.3030	0.3601
Flood control standards	0.4290	0.4006	0.3758	0.3747	0.3836	0.3753	0.3386
Water quality requirement rate	0.1298	0.1212	0.1256	0.1399	0.1744	0.1556	0.1404
River system connectivity	0.0804	0.1423	0.1256	0.1313	0.0886	0.1022	0.1032
Cultivated land salinization proportion	0.0833	0.0768	0.0748	0.0833	0.0717	0.0640	0.0577
Regional population density	0.1117	0.0928	0.0924	0.0926	0.0764	0.0764	0.0784
Engel's coefficient	0.0879	0.0791	0.0798	0.0832	0.1008	0.1008	0.1034
Per capita GDP	0.0830	0.0741	0.0831	0.0725	0.0659	0.0659	0.0707
Water consumption per 10,000 yuan of industrial output	0.1167	0.1400	0.0937	0.0976	0.1398	0.1398	0.1434
Irrigation water quota	0.1192	0.1345	0.1329	0.0913	0.1275	0.1275	0.1308
Canal system utilization coefficient	0.1565	0.1216	0.1513	0.1347	0.1520	0.1520	0.1559
Water-saving irrigation area proportion	0.0882	0.1075	0.1127	0.0887	0.0633	0.0633	0.0649
Per capita grain yields	0.0632	0.0568	0.0764	0.0598	0.0912	0.0912	0.0649
Per capita cultivated land	0.0913	0.1303	0.1078	0.1146	0.0899	0.0899	0.0922
Per capita domestic water consumption	0.0823	0.0634	0.0698	0.1650	0.0931	0.0931	0.0954
Water demand requirement rate	0.3311	0.2767	0.3042	0.4114	0.3182	0.3396	0.2547
Water resources utilization rate	0.2620	0.2441	0.2417	0.1795	0.1983	0.1809	0.1832
Urban sewage treatment rate	0.1447	0.1867	0.1521	0.1476	0.1745	0.1809	0.2419
Construction of monitoring station and information system	0.0874	0.1110	0.1114	0.0952	0.1107	0.1010	0.1111
Management system and level	0.0874	0.0887	0.0976	0.0792	0.0969	0.0967	0.0979
Public awareness of river protection	0.0874	0.0929	0.0932	0.0870	0.1014	0.1010	0.1111

poor flood prevention standards and the lack of a fixed channel in some areas, especially in the Tarim downstream. These conditions contribute to significant river cross flow. Because of inefficient utilization of water resources of the source streams, inflow into the mainstream has decreased (Hao et al. 2009b). This seriously affects the ecological environment of the middle and lower reaches of the mainstream. Each region generally has serious problems with land salinization, with proportions from 37 to 60%. Water quality levels of the mainstream, which range from class V to inferior class V, are poor during the dry season.

The order of development degrees were as follows:

- lower reaches of the mainstream, relatively high, above 0.60;
- Aksu River (0.588);
- middle and upper reaches of mainstream (0.587);
- Kaidu-Kongqi River (0.55); Hotan River (0.52); and
- Yarkant River (0.51).

The development situation in the lower reaches of the mainstream was slightly better than that in the upper and middle reaches. This is primarily because of the location of crops. The selected indicators reveal an imbalance of population, land, and water

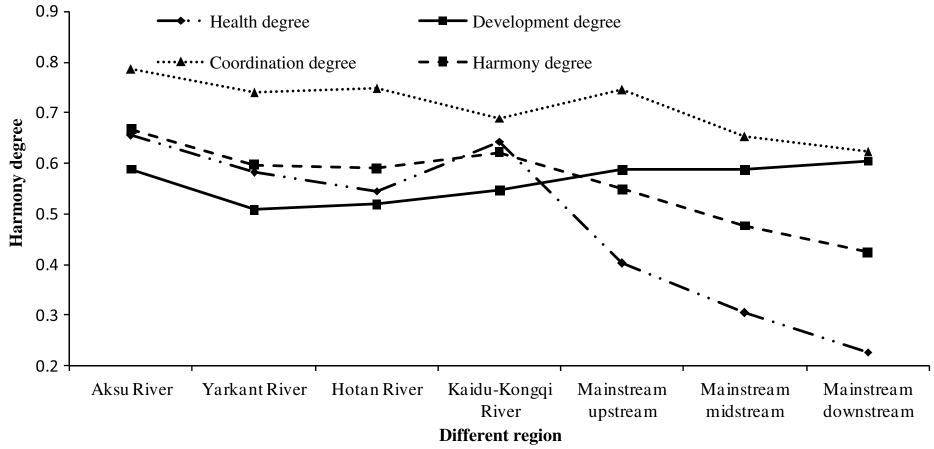

Fig. 2. Calculation results of harmony degree

resources. Population around the source streams is the largest in the river basin, where water resources are relatively abundant (Xu et al. 2010b); however, land resources there are relatively scarce. This situation restricts the socioeconomic development of this area. Economic development varied greatly by district. Per capita GDP of the Hotan Basin was clearly lower than other regions. Thus, its trend of economic development was comparatively lower. Water resource utilization efficiency was the worst. The greatest efficiency, around the Yarkant River, was 0.489.

The order of coordination degree was as follows:

- Aksu River (0.78) was relatively good;
- Hotan River (0.75);
- Upper reaches of the mainstream (0.74);
- Yarkant River (0.74);
- Kaidu-Kongqi River (0.69), middle reaches of the mainstream (0.65); and
- Lower reaches of mainstream had the worst figure at 0.62.

Because of the implementation of comprehensive treatment work and unified regulation of water in the Tarim basin, the coordination degree of the mainstream improved drastically. The urban sewage treatment rate exceeded 90% in the Aksu, Hotan, and Kaidu-Kongqi river areas, although it was relatively low in the mainstream area. Owing to continuous implementation of other engineering and nonengineering measures, relationships between the water and human systems have notably improved.

Generally, human–water harmony degrees of the Aksu and Kaidu-Kongqi rivers were high, exceeding 0.60 (Fig. 2). The Yarkant (0.60) and Hotan (0.59) rivers had the next highest degrees. The upper, middle, and lower reaches of the Tarim mainstream had the lowest degrees, reflecting a relatively disharmonious state. These results imply that if the health, development, and coordination degrees are all relatively high, the human–water relationship degree is also high. Therefore, to improve the harmony degree in the Tarim basin, the water and human systems must be simultaneously enhanced to increase the degrees of health, development, and coordination. This would result in continual improvement of the human–water relationship and harmony level.

Harmony-Based Regulation of Human–Water Relationship in Tarim River Basin

Scenario Simulation of Harmony-Based Regulation

According to the development situation and program of the Tarim River Basin, different development scenarios were examined and compared with the year 2007. This researcher use as an example the lower reaches of the Tarim mainstream, whose harmony degree was low. Various simulation scenarios are listed in Table 6.

Scenario I represents the situation in 2007. Scenario II denotes a condition in which the water system indicators improved. The enhanced indicators include the channel runoff requirement rate, flood control standard, water quality requirement rate, river system connectivity, cultivated land salinization proportion, water demand requirement rate, water-saving irrigation area proportion, and water resources utilization rate. Scenario III is a condition under which the indicators of the human system increased. The enhanced indicators include regional population density, Engel's coefficient, per capita GDP, water consumption per 10,000 yuan industrial output, irrigation water quota, canal system utilization factor, per capita grain yield, per capita cultivated land, per capita domestic water consumption, urban sewage treatment rate, construction of monitoring stations and information systems, management system and level, and public awareness of river protection. Water and human systems both improved in scenario IV. Simulated results are displayed in Table 7 and Fig. 3.

The results of each scenario are illustrated in Fig. 3. In Scenario I, the resulting health degree was 0.2260 and coordination degree 0.6218 for the downstream area of Tarim River basin. Values were comparatively low among the various districts in the basin, and the health condition of the water system was poor because of the critical shortage of water resources. In Scenario II, the health and coordination degrees were considerably improved by enhancing the water system indicators. By increasing indicators of the human system within scenario III, the development and coordination degrees were enhanced, and protection measures used to develop the regional socioeconomy and improve the human–water relationship significantly increased those degrees. Although the total harmony degree rose from 0.4 to 0.5 by increasing the indicators of the water and human systems, the harmony level still indicated some disharmony in the downstream area of the Tarim mainstream within scenarios II and III. The indicators of the water and human systems all improved in scenario IV, with the health, development, and coordination degrees exhibiting notable improvement relative to that in scenario I. The harmony degree increased from 0.4230 to 0.6618, and the harmony level reflected reasonable harmony.

Strategy Analysis of Harmony-Based Regulation

The foregoing analysis suggests that, when the human–water relationship was harmony-based controlled in the Tarim River basin,

Table 6. Simulation Scenarios for Lower Reaches of Tarim River Mainstream

Criterion layer	Indicator layer	Scenario I	Scenario II	Scenario III	Scenario IV
Health indicators	Channel runoff requirement rate	0.31	0.6	0.31	0.6
	Flood control standards	5	20	5	20
	Water quality requirement rate	0.4	1	0.4	1
	River system connectivity	0.2	0.8	0.2	0.8
	Cultivated land salinization proportion	60	40	60	40
Development indicators	Regional population density	9.07	9.07	5	5
	Engel's coefficient	40.3	40.3	30	30
	Per capita GDP	15,836	15,836	17,000	17,000
	Water consumption per 10,000 yuan of industrial output	215	215	200	200
	Irrigation water quota	125	125	105	105
	Canal system utilization coefficient	0.422	0.422	0.5	0.5
	Water-saving irrigation area proportion	100	100	100	100
	Per capita grain yields	1,355	1,355	1,500	1,500
	Per capita cultivated land	3,207	3,207	6,000	6,000
	Per capita domestic water consumption	98	98	120	120
Coordination indicators	Water demand requirement rate	1.098	2	1.098	2
	Water resources utilization rate	0.5716	0.4	0.5716	0.4
	Urban sewage treatment rate	30	30	50	50
	Construction of monitoring stationand information system	0.4	0.4	0.8	0.8
	Management system and level	0.55	0.55	0.8	0.8
	Public awareness of river protection	0.4	0.4	0.8	0.8

Table 7. Subharmony Degree and Final Weight of Simulation Scenarios for Downstream of Tarim River Mainstream

	Scenario I		Scenario II		Scenario III		Scenario IV	
Indicator layer	SHD	Weight	SHD	Weight	SHD	Weight	SHD	Weight
Channel runoff requirement rate	0.3100	0.3601	0.6000	0.3568	0.3100	0.3601	0.6000	0.3568
Flood control standards	0.0750	0.3386	0.3000	0.3624	0.0750	0.3386	0.3000	0.3624
Water quality requirement rate	0.4000	0.1404	1.0000	0.1096	0.4000	0.1404	1.0000	0.1096
River system connectivity	0.1500	0.1032	0.6000	0.0996	0.1500	0.1032	0.6000	0.0996
Cultivated land salinization proportion	0.3000	0.0577	0.4500	0.0717	0.3000	0.0577	0.4500	0.0717
Regional population density	0.8207	0.0784	0.8207	0.0784	0.9111	0.0804	0.9111	0.0804
Engel's coefficient	0.5910	0.1034	0.5910	0.1034	0.8000	0.0907	0.8000	0.0907
Per capita GDP	0.9167	0.0707	0.9167	0.0707	0.9400	0.0780	0.9400	0.0780
Water consumption per 10,000 yuan of industrial output	0.3700	0.1434	0.3700	0.1434	0.4000	0.1542	0.4000	0.1542
Irrigation water quota	0.4268	0.1308	0.4268	0.1308	0.5250	0.1278	0.5250	0.1278
Canal system utilization coefficient	0.3220	0.1559	0.3220	0.1559	0.4000	0.1542	0.4000	0.1542
Water-saving irrigation area proportion	1.0000	0.0649	1.0000	0.0649	1.0000	0.0734	1.0000	0.0734
Per capita grain yields	1.0000	0.0649	1.0000	0.0649	1.0000	0.0734	1.0000	0.0734
Per capita cultivated land	0.6810	0.0922	0.6810	0.0922	0.9500	0.0772	0.9500	0.0772
Per capita domestic water consumption	0.6533	0.0954	0.6533	0.0954	0.8000	0.0907	0.8000	0.0907
Water demand requirement rate	1.0000	0.2547	1.0000	0.2623	1.0000	0.2918	1.0000	0.3018
Water resources utilization rate	0.8284	0.1832	1.0000	0.1589	0.8284	0.2099	1.0000	0.1829
Urban sewage treatment rate	0.3000	0.2419	0.3000	0.2491	0.5000	0.2307	0.5000	0.2386
Construction of monitoring stationand information system	0.4000	0.1111	0.4000	0.1144	0.8000	0.0892	0.8000	0.0922
Management system and level	0.5500	0.0979	0.5500	0.1008	0.8000	0.0892	0.8000	0.0922
Public awareness of river protection	0.4000	0.1111	0.4000	0.1144	0.8000	0.0892	0.8000	0.0922

the water and human systems simultaneously attained better results. This harmony-based control includes the following five aspects:

1. Unified control and management of water resources in the basin should be strengthened. The source streams, mainstream, upper and lower reaches, ecology, domestic, and industrial water consumption should be uniformly coordinated to guarantee water supply to source streams and strengthen ecological programs of the mainstream. Ecological water consumption in the lower reaches should be particularly ensured.
2. The construction of the water-right system and water market should be enhanced. Actual water demand of each water user should be forecasted and allocated fairly, scientifically, and reasonably to establish a water market and encourage people to conserve and protect water resources through the market price mechanism.
3. Investments should be increased. To comprehensively govern the Tarim basin, it is vital to increase investments and capital support. For example, investments in diversion works to cultivate new plants that can endure alkali soils and drought in the basin should be researched, and vegetation coverage area should be increased to improve the ecology.
4. Legal construction should be reinforced. In March 2005, "Water Resources Management Regulations of the Tarim River Basin (Revised Draft)" was implemented. Water resource

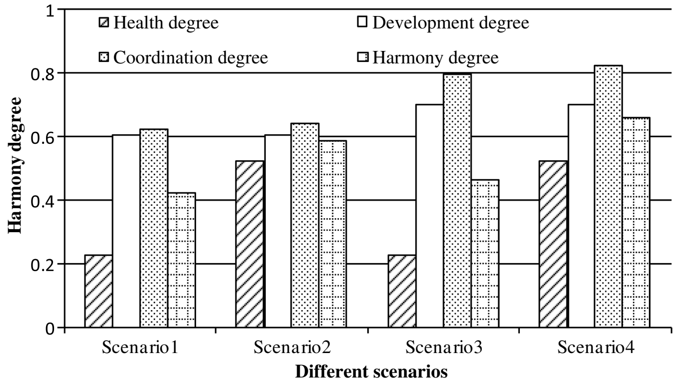

Fig. 3. Harmony degree of human–water relationship in simulation scenarios for Tarim River

management in the basin must follow the regulations. These regulations can guide development, utilization, protection, and management of the Tarim River from the perspectives of water conservation and environmental protection. However, further improvement and refinement for greater operational control of water according to the law and for promoting harmony between humans and water are required.

5. A water-saving basin should be established. To achieve this aim, many measures can be implemented, such as enhancing advocacy to improve public awareness of water saving, optimizing water supply methods, spreading water-saving irrigation technology with high standards, and improving the rate of water reuse.

Conclusions

The essence of Chinese water resource management is human–water harmony. The harmony theory and methods can reveal the nature of a harmonious relationship (Zuo et al. 2013). In addition, this theory is viewed as one that is correct, positive, consistent with dialectical materialism, and helpful in addressing social, economic, political, cultural, and religious problems (Zuo et al. 2008). In the present study, human–water harmony embraced three basic criteria: health, development, and coordination. Based on this method, the following conclusions are obtained.

1. Calculation of harmony degree and scenario simulation of regulation, which is included in the quantitative analysis of harmony-based regulation, provides support to quantitative analysis of the human–water relationship in the river basin.
2. In the Tarim River basin area, the harmony levels of the Aksu and Kaidu-Kongqi rivers indicate very harmonious states. However, the remaining districts are in relative disharmony, which is closely related to actual water resource consumption and management there.
3. The indicators of the water and human systems were regulated and controlled simultaneously to significantly improve the harmony degree and relationship between humans and water.
4. Suggestions and measures were forwarded to improve the harmony degree between humans and water, including engineering and nonstructural measures, management experience, regulations, and policies.

The results of the present study may be used as a reference for management of water resources toward maintaining the health of the river system, protection of the eco-environmental system, and economic and social sustainable development in the Tarim River basin.

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