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Management Implications to Water Resources Constraint Force on Socio-economic System in Rapid Urbanization: A Case Study of the Hexi Corridor, NW China

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Abstract As water has become the shortest resources in arid, semi-arid and rapid urbanization areas when the water resources utilization has approached or exceeded its threshold, water resources system slows down the socio-economic growth rate and destroys the projected targets to eradicate poverty and realize sustainable development. We put forward the concept of Water Resources Constraint Force (WRCF) and constructed a conceptual framework on it. Conceptual models on the interactions and feedbacks between water resources and socio-economic systems in water scarce regions or river basins indicate that, if the socio-economic system always aims at sustainable development, WRCF will vary with a normal distribution curve. Rational water resources management plays an important role on this optimistic variation law. Specifically, Water Demand Management (WDM) and Integrated Water Resources Management (IWRM) are considered as an important perspective and approach to alleviate WRCF. A case study in the Hexi Corridor of NW China indicates that, water resources management has great impact on WRCF both in Zhangye and Wuwei Region, and also the river basins where they are located. The drastic transformation of water resources management pattern and the experimental project – Building Water-saving Society in Zhangye Region alleviated the WRCF to some extent. However, from a water resources management view, WRCF in Zhangye Region still belongs to the severe constraint type. It will soon step into the very severe constraint type. In order to shorten the periods from the very severe constraint type finally to the slight constraint type, WDM and IWRM in the Hei River Basin should be improved as soon as possible. However, in the Shiyang River Basin, WRCF belongs to the very severe constraint type at present due to poor water resources management in the past. Though the socio-economic system adapted itself and alleviated the WRCF to some extent, the Shiyang River Basin had to transform the water supply management pattern to WDM, and seek IWRM in recent years. It is concluded

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that WDM and IWRM is a natural selection to alleviate the WRCF on the socio-economic system and realize sustainable development.

Key words water resources constraint force (WRCF) · socio-economic development · water demand management (WDM) · integrated water resources management (IWRM) · water scarcity · Hexi Corridor in NW China

1 Introduction

Water scarcity is one of the most prominent issues of discussion in global fora concerned with sustainable development. The overall conclusion of all global water scarcity analyses is that a large share of the world population – up to two-thirds – will be affected by water scarcity over the next several decades, particularly in Asia, Africa and the Americas (Shiklomanov 1991; Biswas 1991; Raskin et al. 1997; Seckler et al. 1998; Alcamo et al. 1997; Vorosmarty et al. 2000; Arnell 2004). It has been established that population growth, climate variability, regulatory requirements, project planning horizons, temporal and spatial scales, socio and environmental considerations, and transboundary considerations all contribute to the complexity of water resources problems (Simonovic 2000). However, the most obvious conclusion from the analyses is that water will be scarce in areas with low rainfall and relatively high population density (Rijsberman 2006). Namely, in arid, semiarid and rapid urbanization areas, water scarcity is on the focus (Knapp 1995). Currently, half the world's population resides in cities and the majority of projected population growth is expected to occur in cities (United Nations Centre for Human Settlements 2001; Cohen 2003; McGranahan and Satterthwaite 2003). Associated with the rapid increases in urbanization is the growth of urban water uses, combined industrial and domestic sectors (Falkenmark 1998a, b; Jury and Vaux 2005). Subsequently, water resources previously utilized for agriculture are transferred to urban systems to lessen the loss of industrial output. It has much great influence on agriculture and grain production (Zhang et al. 2002). Then, agricultural systems and rural areas have to transfer water from ecosystems in order to lessen their economic loss, and the eco-environment gradually deteriorates. The consequences of insufficient water availability can result in degradation to human health, ecosystems, agricultural, and industrial output, while increasing the potential for conflict (Postel et al. 1996). Ensuring the sustainable supply of water for ecosystem services, irrigated agriculture and urban areas is of increasing concern (Jewitt 2002; Khan et al. 2006; Lundqvist et al. 2005). However, total global water withdrawn for human uses has almost tripled in the last 50 years from 1,382 km^3 $year^{-1}$ in 1950 to 3,973 km^3 $year^{-1}$; projections anticipate worldwide human water consumption will further increase to 5,235 km^3 $year^{-1}$ by 2025 (Clarke and King 2004). Over half the available freshwater supplies are already used for human activities (Postel et al. 1996; Vorosmarty and Sahagian 2000). On the one hand, water has become a key restricting factor of the socio-economic development (Olli and Pertti 2001; Okadera et al. 2006; Guan and Hubacek 2006). On the other hand, a mass of arid and semiarid areas, especially in developing courtiers, are desiderated to eradicate poverty through rapid urbanization and industrialization. To resolve this conflict, we brought forth the concept of Water Resources Constraint Force (WRCF) and discussed it from an Integrated Water Resources Management (IWRM) view. The objective of our research was to find out WRCF in the typical river basins and analyze how water resources management impacts on the variation of WRCF.

2 Conceptual and Contextual Issues

2.1 The Conceptual Models on WRCF

2.1.1 "Wooden Barrel" Model

"Wooden Barrel Principle" is a concept from Economics and Management Science (Wang 2005). It indicates that how much water a wooden barrel can hold depends on the lowest board. As shown in Figure 1, the wooden barrel is made up of some boards of different height. The height of water can never reach the highest board. It means that an optimal individual does not equal to an optimal collectivity. This phenomenon is called "the highest board's effect." One more phenomenon is that, if the wooden barrel has a lowest board, the height of water can only reach the lowest board. It means that a weak individual will limit the collectivity's level. This phenomenon is called "the lowest board's effect." Another phenomenon is that, when all the boards of the wooden barrel have the same height, if they have gaps, water will escape through them. It means that bad cooperation between individuals will also limit the collectivity's level. This phenomenon is called "the sparse boards' effect."

Based on the above concept, we can suppose that: (1) Product *A* is made from and only from water and Product *B*; (2) per unit Product *A* needs per unit water and per unit Product *B*; and (3) we have 100 U Product *B* to produce 100 U Product *A* and water is less than 100 U.

Then: (1) if we have no water, we cannot produce Product *A*. Water becomes a key restricting factor for the production capacity, and we define the constraint intensity as 100%; (2) if we have 60 U water, we can produce 60 U Product *A*, and we define the constraint intensity as 40%; (3) if we have 100 U water, we can reach our target, and we define the constraint intensity as zero; and (4) if we have more than 100 U water, Product *B* will become the key restricting factor for the production capacity, and it's beyond our discussion.

From the above cases, we can see that, scarce water can lead to "the lowest board's effect" and limit the production capacity. In like manner, if Product *A* is made from water and some more kinds of products, or when we use water to produce different kinds of products, and if the limited water does not be rationally allocated among the different kinds of products, the production benefits cannot be maximized. Consequently, scarce water can lead to "the sparse boards' effect" and also limit the production capacity.

In water scarce regions or river basins, if water is the shortest resources, the above phenomenon will be manifested as economic loss and environmental degradation due to water shortage. The growth rate of the socio-economic system will become slow, and the

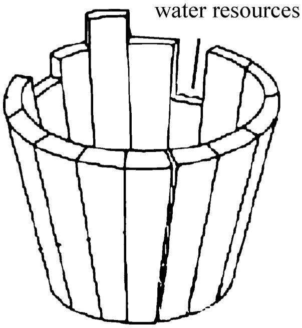


Figure 1 "Wooden Barrel" model on water resources constraint force.

sustainable development ability will be weakened step by step. Consequently, we should study this phenomenon and find out how water retards the socio-economic development.

2.1.2 Physical Dynamical Model

Study on the complex interactions and feedbacks between natural and human system is a key to sustainable development (Falkenmark 1986; Matondo 2002). On the interactions and feedbacks between water resources and socio-economic systems, Chinese scholars brought forth the concept of Water Resources Carrying Capacity in the late 1980s. This refers to the largest scale of population and economy which water resources system can sustain according to the securable technology and the socio-economic development level within a certain period (Li and Gan 2000). Besides, the total water resources should be rationally allocated; the socio-economic development should follow the principle of regional sustainable development and realize a benign circle of eco-environment. Scholars in other countries employ similar concepts to refer to this issue, including sustainable water utilization, available water resources, threshold of natural water resources, water stress index, etc. (Long et al. 2004). These concepts mainly refer to the holding power and the pressure force between water resources and socio-economic systems. Most interrelated studies are static research. Though it can open out the intrinsic principle of water resources and socio-economic systems, it cannot completely explain the dynamic development process of water resources and socio-economic systems. Consequently, we use the classical physical dynamical model to show the interactions and feedbacks between water resources and socio-economic systems.

As shown in Figure 2, the locomotory object represents the socio-economic system. It is abstracted as a particle, which is a basic concept in the classical physics. The horizon represents the natural system, including natural resources and eco-environment, which sustains the socio-economic system. The process the particle moves from the left to the right represents the socio-economic development. During this process, the socio-economic system has its own gravitation (G) and gives a pressure force to the natural system. Correspondingly, the natural system gives a holding power (N) to it. As the socio-economic system develops, the gravitation (G), the pressure force and the holding power (N) vary instantaneously. In sustainable conditions, they will become bigger until the socio-economic system reaches its threshold, which is decided by the carrying capacity of natural resources and eco-environment. In the direction which the socio-economic system moves forward to its threshold, a driving force (F) and a resisting force (f) exist. The driving force includes the pulling force from the demand of the socio-economic development and the pushing force from the supply outside. The resisting force is the friction between the socio-economic system and the natural system, which can be expressed by the arithmetic product of the holding power (N) and the friction coefficient (u). The

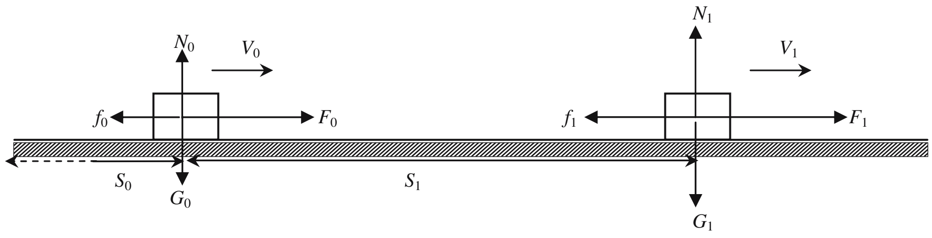


Figure 2 Physical dynamical model on water resources constraint force.

driving force and the resisting force also vary instantaneously. They both decide the velocity (V) of the particle. When the driving force is big and the resisting force is small, a high velocity will be obtained and the particle can complete the displacement S_1 in a short time. When the driving force is small and the resisting force is big, the particle will go slow and complete the displacement S_1 in a long time.

During a certain period and in a certain area, if water resources are the shortest, the maximum of the holding power (N) will be mainly decided by the water resources carrying capacity according to the Wooden Barrel Principle. On the other hand, the pressure force which the socio-economic system gives to the water resources system is tremendous when compared with the water resources carrying capacity, while the pressure force which the socio-economic system gives to other resources system is small when compared with other resources carrying capacity. Consequently, we can consider that the friction water resources system gives to the socio-economic system is by far the largest and the friction that other resources system gives to the socio-economic system is near zero. Subsequently, the resisting force on the socio-economic system is mainly decided by the friction which the water resources system gives to the socio-economic system. Consequently, in water scarce regions or river basins, it is important to study how to alleviate this friction to accelerate the socio-economic development.

2.2 What is WRCF?

2.2.1 A General Definition

As is seen from the above two conceptual models, when water is the shortest resources in a certain area, the friction water resources system gives to the socio-economic system will become one of the dominant exogenic forces on the socio-economic development. This kind of exogenic force will gradually slow down the socio-economic growth rate, so that the socio-economic system cannot reach its largest scale in an expected period. Consequently, we brought forth the concept of Water Resources Constraint Force (WRCF). This refers to the friction which water resources system gives to the socio-economic system and limits its growth rate.

In general, when the population, economic and urban scales approach or exceed the water resources carrying capacity, or the water resources utilization approaches or exceeds the threshold of natural water resources, water resources system will be highly stressed by the socio-economic system and give a strong constraint force directly to the socio-economic development. Then rapid socio-economic development cannot be guaranteed to eradicate poverty and the sustainable development cannot be achieved in water scarce regions or river basins. Consequently, through the study of water resources carrying capacity, water resources stress, and WRCF, the interaction and feedbacks between water resources and socio-economic systems can be roundly explained. Briefly, study on water resources carrying capacity, water resources stress is important for estimating the final results or the health state of the socio-economic system, while study on WRCF is important for monitoring and controlling the dynamic process of the socio-economic system.

2.2.2 A Conceptual Framework

As WRCF has become one of the important exogenic forces of economic growth, most traditional economic growth theory models (Good and Reuveny 2006) and traditional resource and environmental economics (Matthias 2006) should be adjusted. At present, the system info of WRCF should be constructed and perfected. A conceptual framework of WRCF was put forward as follows:

(1) *Basic theories on WRCF*

The key to the study of the basic theories on WRCF is to borrow ideas from water resources science, modern economics and sustainable development. We should strike up the system info of WRCF itself, breaking through the framework of modern economic theories. Logically, the basic theories on WRCF mainly include the following issues:

- Conceptual model: Does WRCF exist in theory? How does it impact on the natural and socio-economic system?
- Birth mechanism: How does WRCF come into being?
- Influencing factors: What kinds of factors influence the birth and the variation of WRCF? Which are the dominant and subordinate factors?
- Influencing mechanism: How do the influencing factors react on the WRCF? How and when do the dominant and subordinate factors carry through the reciprocal transformation?
- Variation law: How does WRCF vary in temporal and spatial scales? e.g., does it change according to an inverted U-shaped curve or an S-shaped curve in a long temporal scale? Does it vary with a direct ratio to the water scarcity degree in a certain spatial scale?

(2) *Quantitative methods on WRCF*

Study of the quantitative methods on WRCF is to measure the intensity of WRCF, e.g., how much direct and indirect economic loss has been or will be caused due to water scarcity? What urbanization and industrialization level would have been or will be achieved in a certain period without the restriction of WRCF? How great impact did or will WRCF give to the social and eco-environmental systems? Such issues are difficult to answer, but they are the core to the study of WRCF. Only after we obtain the quantitative or semi-quantitative evaluation results, we can find out the variation law of WRCF and take specific measures to alleviate it. Logically, the quantitative methods on WRCF mainly include the following aspects:

- Assessment indicator system: It includes indicators on water resources, socio-economic and eco-environmental systems. It should be comprehensive, concise, measurable and comparable.
- Assessment model: Based on the historical and current values of the specific indicators in the assessment indicator system, an assessment model should be constructed to evaluate the temporal and spatial variations of WRCF.
- Pre-warning model: Based on the temporal and spatial variation laws of WRCF, a system dynamic simulated model should be established to forecast the future values of the specific indicators in the assessment indicator system in different development scenes. Then the variation trend of WRCF can be obtained by using the assessment model, and a pre-warning can be given from the results analysis.
- Analysis technique: As WRCF varies in temporally and spatially, we can use statistical techniques, Remote Sensing and Geographical Information System to analyze the temporal and spatial variations of WRCF.

(3) *Case studies on WRCF*

It is of great significance to validate and perfect the basic theories and quantitative methods on WRCF in different temporal and spatial scales, so as to provide decisionmaking bases for regional sustainable development. Specifically, it mainly includes the following steps:

- Choosing some typical water scarce regions or river basins.
- Analyzing the temporal and spatial variations of WRCF.
- Putting forward specific controlling measures to alleviate the WRCF, such as strengthening water resources planning and management, adjusting the traditional ways of water exploitation and utilization, and rationalizing the socio-economic development pattern.
- Comparing different case studies and distinguishing different influencing factors on WRCF.
- Studies on the temporal and spatial scales transformation of WRCF, e.g., when will a weak WRCF become strong? When and how will the strong WRCF become weak again? Are the variation laws of WRCF in a river basin scale the same as that in a regional scale? Can the variation laws of WRCF in a regional scale be popularized in a national or global scale?

(4) *Integrated studies on WRCF and other domains in water sciences*

The integration study between WRCF, water resources carrying capacity and water resources stress should be emphasized at first to clarify the interaction between water resources and socio-economic systems. Subsequently, the integration with other domains in water sciences should also be emphasized. At the same time, the micro-domains concerning WRCF, such as ecological water demand should also be stressed.

3 Management Implications on WRCF

3.1 A Hypothesis on the Variation Laws of the Dominate Factors of WRCF

According to our concept, WRCF is decided by two factors. One is the holding power (N), which water resources system gives to the socio-economic system. The other is the friction coefficient (u), which reflects the coordinated or conflict degree between water resources and socio-economic systems. Consequently, we should find out the variation laws of the two factors.

3.1.1 Logistic Growth Model and the Variation of the Holding Power (N)

Logistic growth is a basic assumption in population biology as “over long periods of time, in all populations of organisms N, the population size, fluctuates up and down around some average value” (Wilson and Bossert 1971). This logistic growth dynamic consists of an exponential population growth slowed down by an upper limit (carrying capacity) (Figure 3). It can simulate the biologic growth, and the dynamic process of the socio-economic development and natural resources exploitation (Meyer et al. 1999), e.g., “in the real world there are many wiggles, speedups, and setbacks, new S-curves growing out of old, separate curves for different sectors and regions of a national economy” (Kindleberger 1996); the process of urbanization (Northam 1975) and water resources exploitation and utilization (Gao and Liu 1997) can both be described by an S-shaped curve. As shown in Figure 3, the measured quantity (population scale, economic output, urbanization level, water resources utilization, etc. in a certain area) grows exponentially at the outset. However, natural systems cannot sustain exponential growth indefinitely. Rather, negative feedback mechanisms or signals from the environment slow

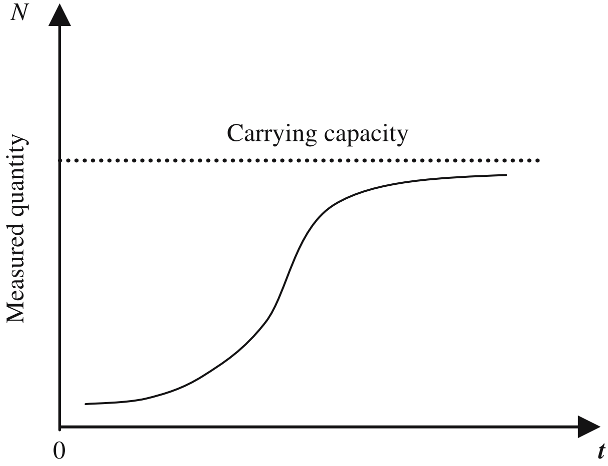


Figure 3 A single logistic growth model.

the growth, producing the S-shaped curve (Seidl and Tisdell 1999). Consequently, the holding power (N), which equals to the quantity of the socio-economic system, can be simulated by an S-shaped curve.

3.1.2 Hypothesis on the Variation Laws of the Friction Coefficient (u)

Variation of the friction coefficient (u) is decided by the coordinated or conflict degree between water resources and socio-economic systems. As the water resources carrying capacity is relatively constant, and water resources utilization for socio-economic system grows with an S-shaped curve, water resources left for ecosystems will decrease with an inverted S-shaped curve. We consider that water resources left for ecosystems can represent the health of the water resources system. Consequently, as shown in Figure 4, the socio-economic system grows with an S-shaped curve while the water resources system decreases with an inverted S-shaped curve. Moreover, as water resources utilization is close interrelated with the socio-economic growth, the two S-shaped curves in Figure 4 are symmetrical.

We suppose that the arithmetical product of the variation degrees of the socio-economic and water resources systems represents the friction coefficient (u), i.e., when the socio-economic and water resources systems both vary acutely, there will be no enough time to

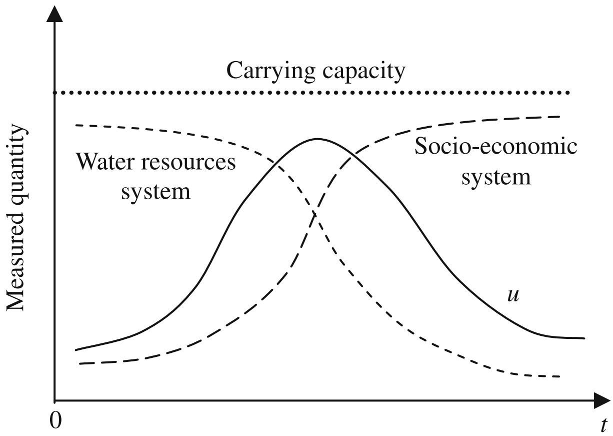


Figure 4 Friction coefficient between water resources and socio-economic systems.

adjust the water demand and supply for rapid socio-economic development, and the conflict degree between water resources and socio-economic systems will become remarkable; When the socio-economic and water resources systems become steady-going, there will be enough time to adjust the water demand and supply for slow socio-economic development, and the coordinated degree between water resources and socio-economic systems will become remarkable. Consequently, as shown in Figure 4, corresponding with the developmental tracks of the socio-economic and water resources systems, the friction coefficient (*u*) varies with a normal distribution curve. The precondition of this hypothesis is that the socio-economic system always aims at sustainable development.

3.2 Water Resources Management Impact on WRCF

As the holding power (*N*) grows with an S-shaped curve and the friction coefficient (*u*) varies with a normal distribution curve, WRCF, their arithmetic product, will also vary with a normal distribution curve. That is, over long periods of time, WRCF on the socio-economic system approaches zero at the outset, and then grows exponentially. Afterwards, its growth becomes slow, and then it turns down. It decreases slowly at first and then rapidly. Finally, it approaches zero again step by step. Figure 5 shows an optimistic future for sustainable development in water scarce regions or river basins. However, this optimistic variation law of WRCF is based on the hypothesis that we can well adapt and harmonize water resources and socio-economic systems. Specifically, effective water resources management plays an important role on alleviating WRCF.

As shown in Figure 5, water resources management includes water supply management and water demand management, and water demand management includes three stages (Ohlsson 2000; Appelgren and Klohn 1999; Xu and Long 2004). With evolution of water resources management, the variation of WRCF falls into eight stages, and the WRCF can fall into four types: slight, moderate, severe and very severe constraint.

3.2.1 The Stage of Water Supply Management

At the stage of water supply management, the variation of WRCF falls into three stages:

- O–A: At the outset of the socio-economic development, water is not the shortest resources, and the key restricting factor for the socio-economic development goes

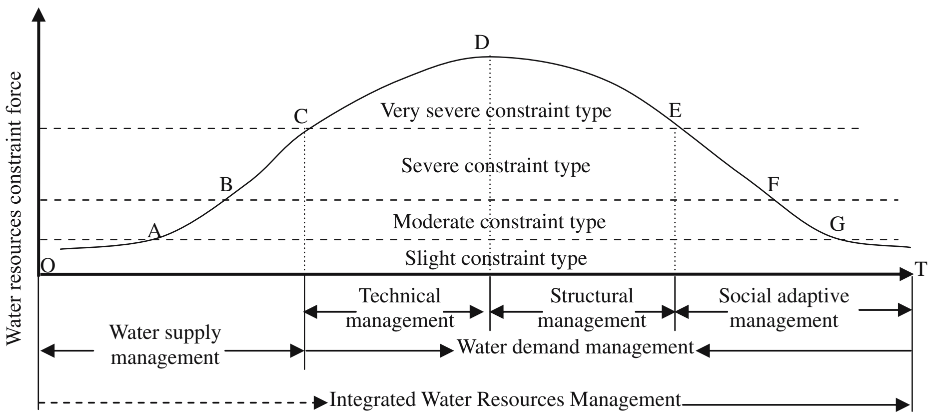


Figure 5 Water resources management impact on the variation law of WRCF.

beyond water. Here WRCF equals to zero. With the gradual development of the socio-economic system, the amount of water use and the WRCF grows slowly. However, water is relatively abundant compared with its little demand at this stage, water resources system gives slight constraint to socio-economic system, and there is almost no need for water resources management.

- A–B: At this stage, the socio-economic system begins to develop rapidly. Rain-harvesting cannot satisfy the growing water demand. Engineering efforts such as dam-building, pipelines, and aqueducts diverting river water are concerned to achieve more water. Water supply management, mainly focusing on surface water supply, begins to come into practice. WRCF also begins to grow rapidly, and water resources system gives moderate constraint to socio-economic system.
- B–C: At this stage, the socio-economic system accelerates to develop further. The problem is perceived as water scarcity, pure and simple (Ohlsson 2000). The solution is to mobilize more water. The means to do so are found in increasingly large-scale engineering efforts, and the groundwater is largely abstracted. The water resources utilization approaches or almost exceeds its threshold. Water resources system gives severe constraint to socio-economic system. There is almost no water to increase the supply and limiting the water demand begins to be considered.

3.2.2 The Stage of Water Demand Management

Water demand management refers to the activities that aim to reduce water demand, improve water use efficiency and avoid the deterioration of water resources. It offers sustainable water management solutions in the face of increasing water scarcity and growing conflicts over water use (Frederick 1993). It includes three stages:

(1) C–D: *Technical management*

At this stage, water scarce regions or river basins are seeking intensive and high technology such as drip-irrigation, recirculation of waste-water, and water-efficient appliances to save water and improve the end-use efficiency. People always attempt to alleviate WRCF by technology, without drastic changes of their socio-economic structure. However, the invention, application and popularization of technology are limited in certain areas and periods, and its function is also limited. Though it slows down the growth rate of water demand, water resources guaranteeing the security of ecosystem are still deprived by the socio-economic system. Consequently, though the growth rate of WRCF reins up, it still continues to grow, and gives a very severe constraint to the socio-economic development.

(2) D–E: *Structural management*

At this stage, people have to look for more efficient measures to alleviate the very severe constraint force. As the socio-economic system has self-adapting functions, water scarce regions or river basins will adjust their socio-economic structures in the first instance. The solution, then, becomes a conscious effort to redirect water to cities and industries, yielding some 20–70 times higher economic returns to water compared to agriculture (Ohlsson 2000). The means are found by changing or creating rules and regulations, administrative bodies, organizational arrangements, water agencies and economic incentives (e.g., pricing policies) to bring more water-efficient modes of usage into practice. Thus, the socio-economic development can still continue while the WRCF begins to fall. However, it still gives very severe constraint to the socio-economic development.

(3) E–T: *Social adaptive management*

Very severe WRCF means a huge risk for sustainable development. Thus, water scarce regions or river basins will seek the outside for help after a self-adaptation. That is, when the socio-economic development reaches a high level, water scarce regions or river basins will have the economic ability to transfer water from water abundant regions, or internationally import the water-consumptive productions, which is a strategy of relying on virtual water (Guan and Hubacek 2006). Thus, water scarcity will become relative, since the water consumption depends on the social willingness and the economic rationality of employing more labor and technology-intensive, but less water-consumptive modes of production. At the stage of social adaptive management, the variation of WRCF falls into three stages:

- E–F: WRCF begins to decline rapidly. However, water system still gives severe constraint to the socio-economic development.
- F–G: WRCF declines rapidly with the improvement of social adaptive management further. WRCF changes into the moderate constraint type.
- G–T: WRCF approaches zero step by step and the social adaptive management is perfect. The socio-economic system can completely satisfy human's demand and it will stop increasing at last. Then there is no WRCF and the relationship between water resources and socio-economic systems is harmonious.

3.2.3 Integrated Water Resources Management on WRCF

The above mentioned has drawn an outline that WRCF varies at different stages of water resources management. However, the borderlines of the four stages do not exist absolutely in reality. At a higher hierarchy of water resources management, a lower hierarchy of water resources management may keep on working, e.g., at the stage of structural management, adjusting the socio-economic structure becomes the dominant orientation of water resources management, while technical management is still important. In fact, as water is needed in all aspects of life and is vital to its social, economical and environmental dimensions, effective water management requires a comprehensive consideration of all related aspects, e.g., technical, social, environmental, institutional, political and financial (Zarghaami 2006). Then Integrated Water Resources Management (IWRM) has been greatly advocated (Jewitt 2002; Al Radif 1999). It refers to a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Mudege and Taylor 2001). It is an approach, a perspective, a way of looking at problems and a must, though there are as many obstacles standing in the way of the realization of IWRM as there are opportunities in support of it (Van der Zaag 2005). Therefore, when the socio-economic scale did not approach or exceed the water resources carrying capacity before, WRCF on socio-economic development was not so significant, and it is unnecessary to use IWRM approach to alleviate it. However, when the utilization of water resources have approached or exceeded its threshold nowadays, water resources system severely retards the socio-economic development. It is of great importance to study this phenomenon and find a solution from IWRM approach.

4 A Case Study

4.1 Study Area and Data Acquisition

The Hexi Corridor, an important sector of the Silk Road and a typical water scarce region in NW China, ranges from 92°21′ to 104°45′E and from 37°15′ to 41°30′N, with a total area of 27.6×10^4 km^2. It is one of the key regions during the great development of West China and has five administrative areas including Wuwei Region, Jinchang Region, Zhangye Region, Jiayuguan Region, and Jiuquan Region, which can be approximately carved up by three inland river basins, including the Shiyang River Basin, the Hei River Basin and the Shule River Basin. Exceptionally, a part of the upper and lower reaches of the Hei River Basin is beyond its boundary. As shown in Figure 6, the Shiyang River Basin lies in the east, including Wuwei Region and Jinchang Region. The Hei River Basin lies in the center, including Zhangye Region, Jiayuguan Region, Suzhou District and Jinta County in Jiuquan Region, Qilian County in Qinghai Province, and Ejina Banner in Inner Mongolia Autonomous Region. The Shule River Basin lies in the west of the Hexi Corridor, including most part of Jiuquan Region except Suzhou District and Jinta County. By calculated, the average annual total water resources in the Shiyang River Basin, the Hei River Basin and the Shule River Basin are 17.46×10^8 m^3, 41.59×10^8 m^3 and 22.78×10^8 m^3, respectively, which add up to 81.83×10^8 m^3 (Li et al. 2002). In 2003, water resources per capita are 730, 2,092 and 3,754 m^3, respectively. The utilization ratios of water resources have reached 154, 112 and 76.4%, respectively, much higher than 40%, the internationally recognized alarm line (Falkenmark and Carl 1992).Thus, their eco-environmental and socio-economic problems have been on the focus (Wang 2002; Wang and Cheng 1999).

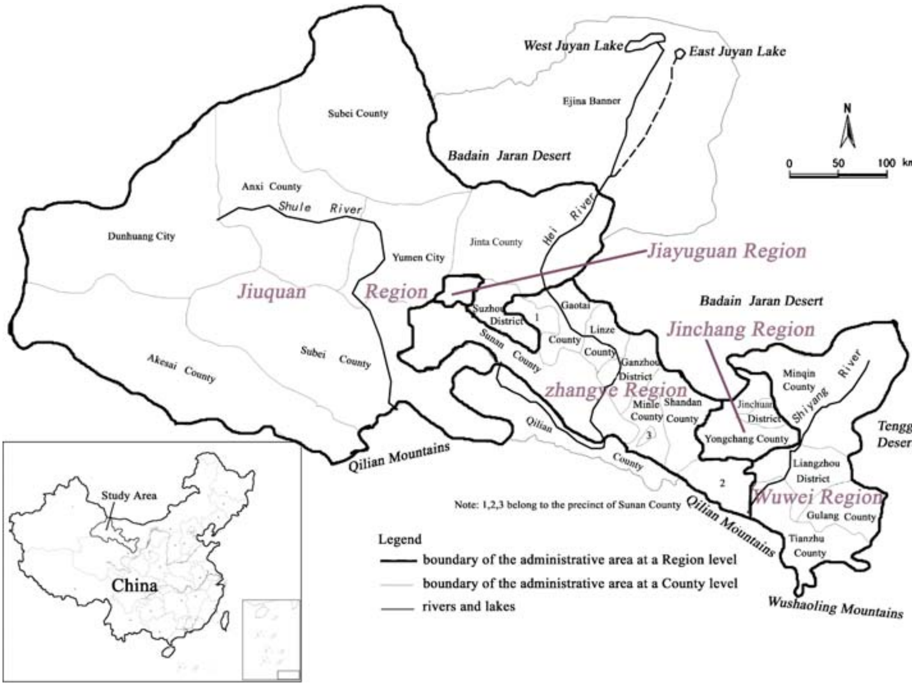


Figure 6 Map of the Hexi Corridor, NW China.

As river basin may account for both the ecological and socio-economic properties of an area (Reid and Ziemer 1997), we had better take river basin as the basic study unit. However, the socio-economic growth rate is decided by the driving force and the resisting force. Before we find a quantitative method to measure them, we can find WRCF only by comparing two regions with different water resources conditions and similar socio-economic conditions, such as population, economic and investment scales, industrial structures, geographical location, historical culture, national policy, etc. In the Hexi Corridor, Wuwei and Zhangye belong to typical agricultural oases, Jinchang and Jiayuguan belong to typical industrial cities in arid areas, and the character of Jiuquan Region is just between them. Consequently, when we compare the growth rate of the socio-economic system in the three inland river basins, it is hard to distinguish the effects between the driving force and the resisting force. Fortunately, Wuwei and Zhangye Region are both key regions in the Ancient Silk Road and the New Asia-European Railway, and they have similar geographical and historical conditions. Other conditions can also satisfy the above postulation (see Table I). Then we chose them as the comparison objects. Based on the investigation data and statistical data originally from the past years *Gansu Water Resources Communique*, *Statistical Yearbooks and Water Conservancy Annals of Wuwei*, and *Zhangye*, respectively, we compared their urbanization processes and industrial structure variations to find out the existence of WRCF. Then we took the Shiyang River Basin and the Hei River Basin where they are located as the basic study unit to discuss how water resources management dealt with the existing WRCF.

4.2 Identification of WRCF on the Socio-economic Development

4.2.1 Identification of WRCF on Urbanization

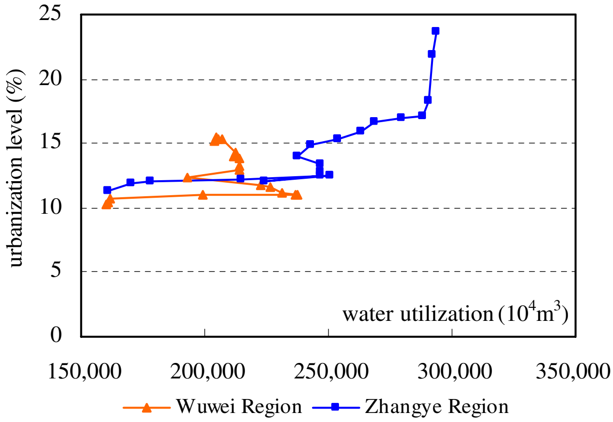
Urbanization level is an important symbol to show the modernization for a country or a district (Qiu 2004). In some sense, it can represent the socio-economic development. Figure 7 shows the urbanization process and the variation of water utilization in Wuwei and Zhangye Region from the year 1985 to 2003. It indicates that the urbanization level and the total water utilization were both similar in 1985. While in 2003, the urbanization level and

Table I Major water resources and socio-economic conditions in Wuwei and Zhangye Region in 2003

	Water resources available (10^8 m^3)	Per capita water resources (m^3)	Utilization ration of water resources (%)	Total population (10^4 person)	Gross domestic product (10^8 RMB)	Industrial structure (%:%:%)	Urbanization level (%)	Fixed assets investment (10^8 RMB)
Wuwei Region	14.77	765	126	193.02	87.4	31:33:36	15.41	43.03
Zhangye Region	17.0	1,341	111	126.81	83.8	35:33:32	23.67	42.07

Total water resources in Zhangye Region is 26.5×10^8 m^3. However, in normal years, Zhangye Region should transfer 9.5×10^8 m^3 water resources to the lower reaches. According to the international standards (UNDP 1990), Wuwei belongs to the severe water scarce region (per capita water resources between 500 and 1,000 m^3). Zhangye belongs to the moderate water scarce region (per capita water resources between 1,000 and 1,700 m^3).

Figure 7 The process of urbanization and water utilization in Wuwei Region and Zhangye Region.



the total water utilization in Zhangye Region were both much larger than it was in Wuwei Region. As shown in Figure 7, total water utilization in Wuwei Region rose with the increase of urbanization level at first, but later turned downward. This phenomenon appeared not because water demand in Wuwei Region rose at first and then turned down, but because Wuwei Region had to reduce water utilization when the water resources utilization approached and exceeded its threshold. As water utilization was reduced, the development of high water-consumptive agriculture and industry were confined, and then the urbanization process in Wuwei Region was also restricted. In Zhangye Region, though the urbanization level increased 0.685% at an annual average growth rate, much faster than that in Wuwei Region (0.289%), it still increased more slowly than the average level in China (more than 1% increase every year). Moreover, the growth rate of total water utilization in Zhangye Region obviously slowed down in recent years. It can be concluded that the utilization of water resources in Zhangye Region also approached the threshold of natural water resources.

Anyhow, the foundation and main driving forces of urbanization are generally similar in Wuwei and Zhangye Region, but water resources in Wuwei Region are relatively scarcer and gave more severe constraint on the urbanization process, so the urbanization process in Wuwei Region is relatively slower than that in Zhangye Region. In other words, Wuwei Region has larger WRCF than Zhangye Region, and then the urbanization level in Wuwei Region increased more slowly.

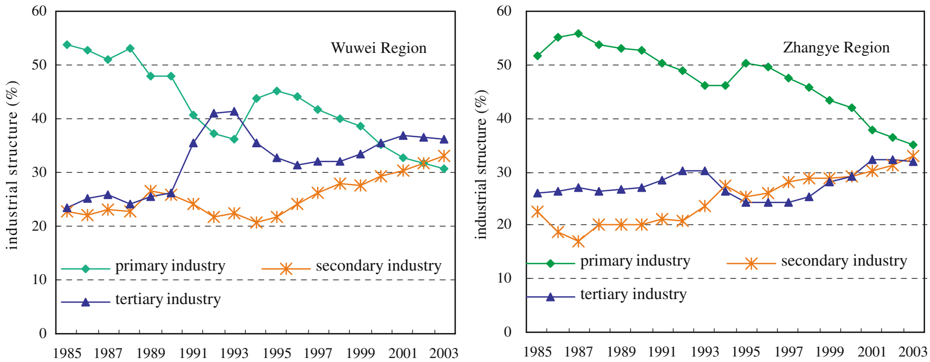


Figure 8 Changes of the industrial structure in Wuwei and Zhangye Region.

4.2.2 Identification of WRCF on Economic Development

WRCF on economic development is manifest as slowing down the growth rate of high water-consumptive agriculture and industry. As shown in Figure 8, industrial structure in Wuwei Region was very similar to that in Zhangye Region in 1985. However, they differed from each other afterward.

In Wuwei Region, industrial structure varied acutely due to water scarcity. As the irrigated area and agricultural output in Wuwei Region increased rapidly during the late 1980s, the water resources utilization began to approach and exceed the threshold of natural water resources. Eco-environmental problems in the lower reaches of the Shiyang River Basin became a focus (Ma et al. 2005). Then Wuwei Region had to reduce agricultural water consumption and develop the tertiary industry, which is less water-consumptive. Thus, the industrial structure in Wuwei Region reached 31:33:36 in 2003 instead of 54:23:23 in 1985, which can be described by "the tertiary industry > the secondary industry > the primary industry" instead of "the primary industry > the secondary industry > the tertiary industry." This structure seemed rational but didn't accord with the low economic developmental level. It was the result of severe WRCF on the economic development.

However, in Zhangye Region, industrial structure varied disciplinarily (Figure 8). As water resources are relatively more abundant, and Zhangye Region used its superiority of geographical location to deprive some eco-environmental water demand in the lower reaches of the Hei River Basin, water use in Zhangye Region did not exceed the threshold of natural water resources before 2003. Thus, Zhangye Region still developed its agriculture energetically based on some advantaged conditions, such as extensive land resources and plenteous sunlight. The evolution of industrial structure in Zhangye Region still followed Clark's Law (Clark 1940). It reached 35:33:32 in 2003 instead of 52:22:26 in 1985, which can be described by "the primary industry > the secondary industry > the tertiary industry" instead of "the primary industry > the tertiary industry > the secondary industry." This structure accorded with the economic developmental level, and it indicated that Zhangye Region had stepped into the well-balanced process of industrialization. However, as the utilization of water resources began to approach and exceed the threshold of natural water resources in recent years, Zhangye Region also had to adjust its socio-economic structure to alleviate its WRCF.

4.3 Water Resources Management Responding to the WRCF

4.3.1 Water Resources Management Innovation in the Hei River Basin

As water gave a severe constraint force to the rapid development of socio-economic system in the Hei River Basin, the pattern of water resources management in the Hei River Basin began to transform drastically since the middle 1990s. Water demand management began to come into force as an important part of integrated river basin management instead of water supply management. Moreover, as water problems became serious throughout the country, and water resources management in the Hei River Basin achieved some experience since 1990s, the Ministry of Water Resources (MWR) of China initiated an experimental project – Building Water-saving Society in Zhangye Region in early 2002. This project was the first of its kind in China. During this project, technical measures such as water saving, irrigation district renovation, farmland area reduction and wastewater reuse proved to be useful to reduce the water demand, but it is even more important to introduce non-technical demand management measures such as institutional reform, water pricing adjustment and cropping pattern optimization so as to ensuring the sustainable operation of the water management system (Chen et al. 2005). Through this project, the following successes were achieved in Zhangye Region:

- Perspicuity of water use rights to strengthen the water-saving consciousness of the public. In Zhangye Region, every water user receives a water quota that is fixed by the government, and water use rations for cultivated area per hectare, industrial output value per ten thousand RMB, etc. are also controlled by the government. Then water right cards and water tickets were introduced as symbols of water use rights. After getting the water rights card, the water user can apply for water tickets to the irrigation district through a Water User Association. When he wants to irrigate his farmland, he is obliged to show water right cards and the corresponding amount of water tickets. If the amount of water tickets is not enough for him, he can buy some water tickets from others according to the uniform price established by the government, but he will be assessed upon some extra fees by the Water User Association. If the amount of water tickets is surplus for him, he can sell them to others, and he will obtain some bonus stocks. By this method, the public got to know that water is also a kind of economic goods. Then they began to treasure and save it, and adjust the water use structure according to the economic benefits.
- Optimization of water resources to improve the water use efficiency. Water resources planning in the Hei River Basin and every county in Zhangye Region were all authorized. Water quota and water use rations for per ten thousand RMB output value of each sector were established. Water use structure in every county and irrigation district was adjusted, aiming to improve the water use efficiency. By this method, water use for cultivated area per hectare decreased to 24.6 m^3 in 2003 instead of 28.7 m^3 in 2000, and water use for GDP per ten thousand RMB decreased to 2,444 m^3 in 2003 instead of 3,234 m^3 in 2000 in Zhangye Region.
- Adjustment of industrial structure to accelerate the growth rate of economy. During the project, Zhangye Region follows the basic principle "developing industries which are water-saving, and reducing industries which are water-consumptive." Then the status of a grain-producing base established by the Central Government of China in 1950s is no longer emphasized by the government. The farmers are encouraged to plant some water-saving cash crops instead of cereal crops. Moreover, industrialization and urbanization is considered as the basic orientation of the socio-economic development. The secondary and tertiary industry is strengthened.
- Allocation of water resources to the lower reaches to restore the eco-environment. According to the water distribution plan fixed by the State Council of China in 1997, in normal years, i.e., when the upper reaches discharge 15.8×10^8 m^3 water resources, Zhangye Region should transfer 9.5×10^8 m^3 water resources to the lower reaches of the Hei River Basin. This plan has been successfully implemented since 2000 (see Table II). In 2002, the Hei River flowed into the East Juyan Lake, which had dried up for 10 years. In 2003, the Hei River flowed into the West Juyan Lake, which had dried up for 43 years. It helped to restore the eco-environment in Ejina Oasis and harmonize the relationship between the middle and lower reaches in the Hei River Basin.

As the above successes in water resources management were achieved in Zhangye Region, the intensity of WRCF on the socio-economic development was alleviated to some extent. However, it has been found that the water use rights system is hard to implement well and that water use rights trading is not popular. The barriers to implementing a water use rights system are social and administrative in nature. Water use rights trading faces

Table II Water transfer in Zhangye Region to the lower reaches of the Hei River Basin since 2000 (unit: 10^8 m^3)

Year	2000	2001	2002	2003	2004	2005
Water distribution plan	15.8, 8.0	15.8, 8.3	15.8, 9.0	15.8, 9.5	15.8, 9.5	15.8, 9.5
Water discharge from upstream	14.62	13.13	16.11	19.03	14.98	18.10
Water transfer to downstream	6.5	6.38	9.23	11.61	8.55	10.50

As water transfer may be accepted by the public in the middle reaches step by step, in the water distribution planning, in normal years, i.e., when the upper reaches discharge 15.8×10^8 m^3 water resources, Zhangye Region can transfer less than 9.5×10^8 m^3 water resources to the lower reaches before 2003.

management, legal, administrative, and fiscal barriers (Zhang 2006). Therefore, from the water resources management view (Figure 5), we consider that, WRCF in Zhangye Region belongs to the severe constraint type at present, and it will soon step into the very severe constraint type. In order to shorten the periods from the very severe constraint type to the severe constraint type and finally to the slight constraint type, water demand management in Zhangye Region should be further strengthened. Specifically, social adaptive management and integrated water resources management in the Hei River Basin should be improved as soon as possible.

4.3.2 Water Resources Management Adaptation to WRCF in the Shiyang River Basin

Water resources management in the Shiyang River Basin mainly focused on the water supply during the past ten decades. Water demand management was absent, water use efficiency was very low, water rights were not clearly defined by authorities, and the public had little consciousness of water saving. After the water resources utilization exceeded its threshold, the groundwater was still exploited. Furthermore, lack of integrated river basin management caused its terminal lake – Qingtu Lake, which was once the second largest inland lake in China, to completely dry up in 1950s and be buried under a 3–4 m layer of sand drift. Moreover, Minqin Oasis, which is located in the lower reaches and below the poverty level, began disappearing in Badain Jaran and Tengger Deserts. As the eco-environmental problems were very serious and water resources management was unbalanced, WRCF grew fast. Consequently, the socio-economic system in the Shiyang River Basin had to begin its self-adaptation during the past five decades. This mainly includes the following aspects:

- Decreasing the projected growth rate of economy.
- Obliged to adjust its industrial structure.
- Compelled to emigrate its ecological refugee.

However, though self-adaptation alleviated the WRCF to some extent, it still couldn't stop agricultural irrigation encroaching upon the ecological water demand. On June 28, 2004, the Hongyashan Reservoir, Asia's largest reservoir in desert area, recorded its first dry-up since its completion in 1958. It seemed that water problems in the Shiyang River Basin are becoming more serious.

As water gave a very severe impact on the eco-environment in Minqin Oasis, and sustainable development of the socio-economic system in the Shiyang River Basin was badly restricted, the Central Government of China began to pay much attention to it, e.g., Wen Jiabao, prime minister of China, has given eight orders to avoid Minqin Oasis becoming the second 'Lop Nur' since 2001. Subsequently, integrated water resources management came into force step by step in recent years, and the following occurrences are signals for the Shiyang River Basin to transform its pattern of water resources management:

- Research on water transfer projects from the Yellow River and the Yangtse River to the Shiyang River has been practically considered in recent years. As the Shiyang River Basin and Minqin Oasis have insufficient water resources for self-restoration, a common cognition has been achieved that, the long-distance water transfer projects, including Datong River project and the western route of the South–North Water Transfer Project of China, should be practically considered though it is not the ultimate solutions. Besides, Virtual water trading has been taken into account in such research.
- In 2002, the Shiyang River Basin Management Bureau was established. It is directly governed by the Water Resources Hall of Gansu Province, aiming to manage the Shiyang River Basin integratedly and perfectly.
- In 2002, the Key Restoration Planning in the Shiyang River Basin began to be compiled by Gansu Province, and it came into force on February 25, 2006.
- In 2004, the Shiyang River Basin began to popularize the experimental project – Building Water-saving Society in Zhangye Region. Yongchang County, Jichuan District in Jinchang Region, and Minqin County, Liangzhou District in Wuwei Region were chosen as four of the ten key regions to popularize the experimental project by Gansu Provincial Government.
- In 2006, Gansu Provincial Government authorized a series of documents to advance the integrated water resources management in the Shiyang River Basin, such as *Management Measures on Surface Water in the Shiyang River Basin*, *Notice on Strengthening Groundwater Management in the Shiyang River Basin*, and *Stipulations on Water Affairs in the Shiyang River Basin*. Besides, *Management Byelaw*s *of the Shiyang River Basin* has stepped into the lawmaking procedure.
- On April 5, 2006, water distribution from Xiying Reservoir in Liangzhou District (the middle reaches) to Minqin County (downstream) was successfully completed. This project was the first of its kind in the Shiyang River Basin.

From the above analysis, it can be seen that, WRCF in the Shiyang River Basin belongs to the very severe constraint type at present due to poor water resources management in the past. Though the socio-economic system adapted itself and alleviated the WRCF to some extent, the ultimate way out still depends on water demand management and integrated water resources management.

5 Recommendations and Conclusions

As water has become the shortest resources in arid, semi-arid and rapid urbanization areas when the water resources utilization has approached or exceeded its threshold, the friction water resources system gives to the socio-economic system will become one of the dominant exogenic forces on the socio-economic development. It will slow down the socio-economic growth rate, destroying the projected targets to eradicate poverty and realize sustainable development. Consequently, we named this kind of friction as Water Resources Constraint Force (WRCF). Then we constructed a conceptual framework on the system info of WRCF, including *Basic Theories*, *Quantitative Methods*, *Case studies* and *Integrated studies*. It is suggested that its birth mechanism, influencing factors, influencing mechanism, variation law, and its control in typical water scarce regions or river basins should be emphasized at present, conforming to the urgent need of rapid socio-economic development in developing areas.

Conceptual models on the interactions and feedbacks between water resources and socio-economic systems in water scarce regions or river basins indicate that, if the socio-economic system always aims at sustainable development, WRCF will vary with a normal distribution curve, which falls into eight stages and four types: slight–moderate, severe–very severe, very severe–severe, moderate–slight. Rational water resources management plays an important role on this optimistic variation law. Specifically, Water Demand Management (WDM) and Integrated Water Resources Management (IWRM) are considered as an important perspective and approach to alleviate WRCF. As water resources and socio-economic systems both have a self-adapting ability, when the socio-economic scale did not approach or exceed the water resources carrying capacity before, WRCF on socio-economic development was not so significant, and it is unnecessary to use WDM and IWRM approach to alleviate it. However, when the water resources utilization has approached or exceeded its threshold nowadays, water resources system severely retards the socio-economic development, and it is important to study this phenomenon and find a solution from IWRM approach.

A case study in the Hexi Corridor of NW China indicates that, the foundations and main driving forces of the socio-economic development are generally similar in Wuwei and Zhangye Region, but water resources in Wuwei Region are relatively scarcer and gave more severe constraint on the socio-economic development, including urbanization and evolution of industrial structure. Water resources management has great impact on WRCF both in Zhangye and Wuwei Region, and also the river basins where they are located:

(1) In the Hei River Basin, the drastic transformation of water resources management pattern since the middle 1990s and the experimental project – Building Water-saving Society in Zhangye Region in early 2002 alleviated the WRCF on socio-economic development to some extent. However, from the water resources management view, WRCF in Zhangye Region still belongs to the severe constraint type. It will soon step into the very severe constraint type. In order to shorten the periods from the very severe constraint type finally to the slight constraint type, water demand management and integrated water resources management in the Hei River Basin should be improved as soon as possible.
(2) In the Shiyang River Basin, WRCF belongs to the very severe constraint type at present due to poor water resources management in the past. Though the socio-economic system adapted itself and alleviated the WRCF to some extent, the Shiyang River Basin had to transform the water supply management pattern to water demand management, and seek integrated water resources management in recent years. It is a natural selection to alleviate the WRCF on the socio-economic system and realize sustainable development.

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