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Essential characteristics and integrated management strategies of water resources in the arid and semiarid northwest of China

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Abstract
Water scarcity and related issues have become the most severe restrictions to sustainable development of the world. These problems are particularly crucial to some developing countries or regions in arid and semiarid areas. China, the largest developing country in the world, has been and is facing severe water scarcity and related issues in its northwest. Seeking feasible solutions to water scarcity and related issues has become one of the most important tasks in the large-scale west exploitation of China. This paper presents essential characteristics of water resources and strategies to water scarcity and related issues in the arid and semiarid northwest of China. The essential characteristics are natural shortage and extremely uneven spatial and temporal distributions of the water resources. The strategic solutions to the water problems in this region should be (1) rational economic structures and optimal industrial distributions copying with the water resources characteristics; (2) integrated development and effective utilization of local water resources; (3) large-scale south-to-north water transfer as a long-term goal for sustainable development of the region; (4) development and popularization of eco-water-saving technology; (5) equal allocation and cooperative development water resources in international cross-boundary rivers; (6) protection of culture, custom and religion of minority nationalities; (7) effective protection of water resources and water environments; and (8) a highly authoritative and qualified water resources management system. These strategies may also be suitable to the regions or countries with similar issues.

INTRODUCTION

Sustainable development in the new century is a common aspiration of every societal member throughout the world. However, several natural and human induced factors severely restrict realization of the aspiration. Water scarcity and related issues are the most severe restrictions. These problems are particularly crucial to developing countries or regions in arid and semiarid areas. In some developing countries or regions water scarcity has become the bottleneck of social progress, economic development and environmental security. This is typical in northwest China, which is one of the most important regions in the large-scale west exploitation of China but has been suffering from severe water scarcity by nature. The water scarcity is being aggravated by human economic activities (Feng & Li, 1997; Feng, 1999a, 2000a, 2000b). Seeking feasible solutions to the issues has been one of the most important tasks in the large-scale west exploitation of China (e.g. see, CAST et al., 1999; Water Resources Bureau of Shaanxi Province & Water Resources Society of Shaanxi Province, 1999). In fact, water scarcity and its impacts on regional society, economy and environment as well as probable national and international impacts have attracted worldwide concerns (e.g. see UNESCO, 1992; WWC, 1998, 2000; IWMI, 2000a; CAST et al., 1999). Several international, national and regional

symposia, conferences and workshops have been held and a large number of papers have been published on pertinent topics (e.g. see ASCE, 1998; Gupta & Onta, 1997; Kundzewicz, 1997; Loucks, 2000; Simonovic, 1997; Xia & Takeuchi, 1999; CAST et al., 1999; WWC, 2000). Many research programs have been put forward in many countries or regions, such as IWMI (2000b) and many others. Many strategies or solutions have been proposed to relevant problems, such as WWC (2000) and many others. Some of them have been put forward and some problems have been or are being solved. However, water scarcity and related problems are very complicated and the solutions might not be the same for same problems in different countries or regions due to different background of society, economy and environment, as well as essential characteristics of water resources. Therefore, each country or region should seek effective and efficient solutions that would be suitable to its own conditions. The purpose of this paper is to propose some integrated water resources management strategies based on the essential characteristics of water resources in the arid and semiarid region in northwest China.

ESSENTIAL CHARACTERISTICS OF WATER RESOURCES

Formation, distribution and transformation of water resources in space and time are very complex and difficult to be characterized. This paper only describes the following essential characteristics together with a brief introduction to the arid and semiarid northwest of China.

The Region

Administratively, northwest China includes the five northwest provincial administrative regions, Shaanxi Province, Gansu Province, Qinghai Province, Ningxia Hui Autonomous Region and Xinjiang Uygur Autonomous Region. Economically, it also includes Alashan League (a prefectural administrative region), the west part of Inner Mongolia Autonomous Region. Climatically, the arid and semi arid region of northwest China is recognized to be the region that its long-term annual mean precipitation is equal to or less than 400 mm within the above economic region. Geographically or hydrologically, the arid and semiarid region consists of two sub-regions. One is the arid and semiarid northwest continental river region, in which a small part belongs to semihumid to humid region due to long-term annual mean precipitation is greater than 400 mm in some "wet islands" in high mountains. The another is the region in the Yellow River basin that consists of part of Shaanxi, Gansu, Qinghai and Ningxia where long-term annual mean precipitation is equal to or less than 400 mm.

From the viewpoint of integrated water resources management, the water issues relative to the region in the Yellow River basin should be dealt with in integrated manners on the Yellow River scale. Therefore, this paper only deals with the arid and semiarid northwest continental river region, which is the largest arid and semiarid region in China. The area of the arid and semiarid northwest continental river region is 2,292,464 km^2 ranging from E73°35' to 106°35' and N34°18' to N47°19', which is about 50.5% of the arid and semiarid area, 69.0% of the continental river area and 24.0% of the total area of the mainland of China. Figure 1 shows the region and its relation to the mainland of China. The areas of the region and its sub-regions and some comparisons are listed in Table 1.

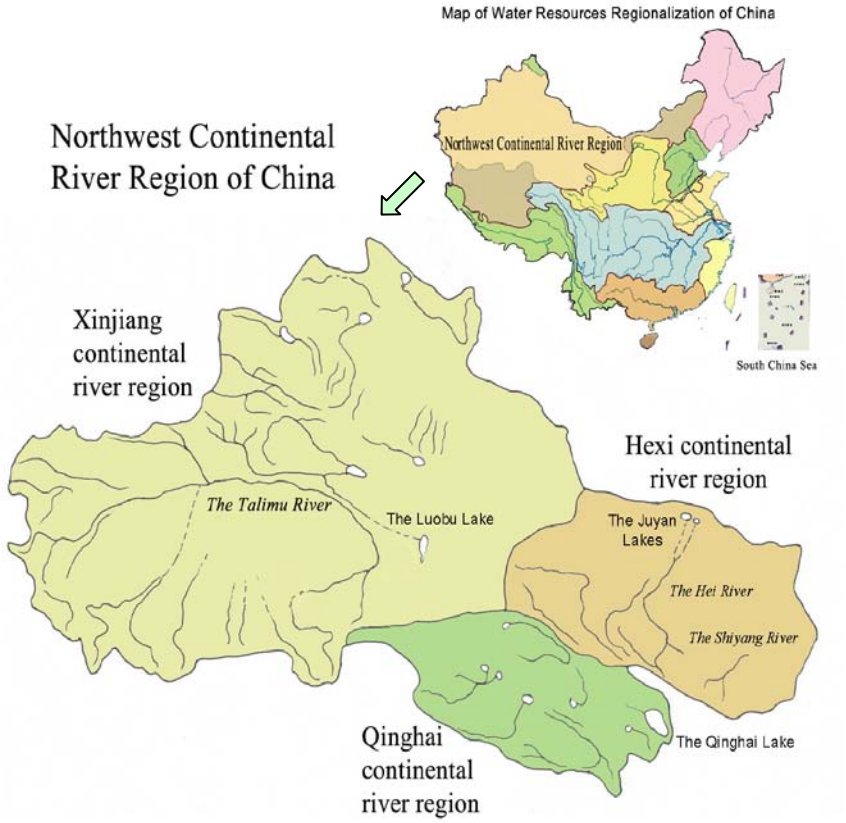

Figure 1. Illustration of the arid and semiarid northwest continental river region and its location in the mainland of China (produced according to the Institute of Planning and Design of Water Resources and Hydropower, the Ministry of Water Resources, 1989).

Precipitation

Northwest continental river region of China is situated in the center of the Euro-Asia continent and ranges from the arid and semiarid temperate and frigid zones. Arid climate with obvious continental monsoon climatic characteristics privileges in this region. Precipitation in this region is very scarce and unevenly distributed in both space and time. Long-term annual mean precipitation overall the region is 135.4 mm. The precipitation is generally less than 100 mm excepting some "wet islands" in high mountains. The values of the average precipitation in the three sub-regions are 139.0 mm in the Xinjiang continental river region, 122.6 mm in the Hexi continental river region, and 138.1 mm in the Qinghai continental river region, respectively (Table 1). On river basin scales, minimum long-term annual mean precipitation occurs in the Talimu River basin. The average pre-

cipitation in this basin is only 102.0 mm. Measured long-term annual mean precipitation at a weather station close to the edge of the Takelamagan Desert is only 7.1 mm and close to zero in the center of the desert in this basin. Maximum precipitation occurs in the meddle Asian river basins, where the long-term annual mean precipitation is 468.2 mm with the maximum of over 800 mm in the high mountains in upper stream area of the Yili River basin. Most part of the precipitation in the continental river region occurs in its rain season (generally, from June to September but different from west to east in the region: earlier in the west and later in the east) and 60-80% of the precipitation is distributed in about four months (the Bureau of Hydrology of the Ministry of Water Resources, 1989; Feng & Li, 1997).

Surface Water Resources

Similar to precipitation, surface water resources (stream runoff) in this region are very unevenly distributed in both space and time with more complicated variation because of complicated runoff generation mechanism. The total runoff in this region is 80.6 Gm^3 (billion cubic meters) which is equivalent to 35.2 mm in depth overall the region or 35,200 m^3/km^2. It means that the surface water resources might be only capable of carrying 35 persons per square kilometer providing that each person occupies the basic water requirement of 1,000 m^3 per year (OIEAU, 1998). Furthermore, the runoff is very unevenly distributed in space. For instance, in the Hexi continental river region, the runoff depth is only 14.0 mm or 14,000 m^3/km^2 which is only capable of carrying 14 persons on the 1,000 m^3 basic water requirement level. Surface water resources in other sub-regions are listed in Table 1.

Table 1. Water resources and their major characteristics in the arid and semiarid northwest continental river region of China*

Region	Area (km^2)	Precipitation		Surface water (Gm^3)	Ground water (Gm^3)	Total water resources**		
		mm	Gm^3			Gm^3	m^3/km^2	m^3/capita
Hexi continental river region	488,708	122.6	59.9	6.9	7.0	8.1	16,574	1,871
Xinjiang continental river region	1,484,470	139.0	206.4	66.5	52.8	75.1	50,590	5,826
Qinghai continental river region	319,286	138.1	44.1	7.2	5.5	7.6	23,803	14,340
Total/average	2,292,464	135.4	310.4	80.6	65.3	90.8	39,608	5,115
National continental river region	3,321,713	153.9	511.3	106.4	82.0	120.1	36,156	
Ratio of total to the national (%)	69.0		60.7	75.8	79.6	75.6	109.5	
National***	9,545,322	648.4	6,188.9	2,711.5	828.8	2,812.4	294,636	2,253
Ratio of total to the national***(%)	24.0		5.0	3.0	7.9	3.2	13.4	

* Data sources: the Bureau of Hydrology of the Ministry of Water Resources, the State Statistical Bureau.

** The water resources per capita are estimates for 2000.

***Do not include the areas of Taiwan, Hong Kong and Macao.

On river basin scales, runoff in this region comes from two sources: precipitation and glaciers. Precipitation generates 75.8% and glaciers 24.2% of the runoff in the continental region. The percentages are variable in different rivers or river reaches in different sub-regions. For instance, the glaciers generate 30-40% of the runoff in some rivers or river reaches in the Hexi continental river region and 30-60% in the Xinjiang continental river region. In addition, runoff has its third source: groundwater. In the runoff depleting zones in lower reaches of the continental rivers that geographically locate in the dry

plains, the runoff from groundwater discharge shares a large proportion to total runoff in the river basins. Only in the runoff generating zones in upper reaches of the continental rivers that locates in high mountains is the runoff generated mainly by precipitation and glaciers.

Seasonal distributions of surface water resources in the region depend on the sources of runoff. The distribution is the same as the precipitation in the rivers or river reaches that precipitation dominates major part of the runoff. In the rivers or river reaches that glaciers' melted water is the major part of the runoff, most of the runoff occurs in July and August because of higher temperature. In these rivers or river reaches the melted water during July and August maybe up to 55% of the annual total. In groundwater discharge areas the maximum percentage in continuous four months can be 40-50% and in a few cases even up to 80% of the annual total.

Ground Water Resources

Groundwater is an important part of the water resources in the northwest continental river region. Total amount of the groundwater in this region is 65.2 Gm^3, of which 42.7 Gm^3 is in the flooding plains and underground basins and 26.8 Gm^3 is exploitable. Spatial and temporal distribution of groundwater are also uneven, typically in space (see Table 1). Exploitable groundwater is generally distributed in the flooding plains.

Total Water Resources

Total quantity of water resources in the northwest continental river region is 90.8 Gm^3, which is equivalent to 39,608 m^3/km^2. It means that the total water resources could carry 39 persons per square kilometer providing that each person occupies the 1,000 m^3 basic water requirement. The total amount of water resources is an algorithmic sum of the surface and ground water resources and their repeat that is calculated in both surface and ground water resources (the Bureau of Hydrology of the Ministry of Water Resources, 1989). This means that 50.1 Gm^3 is the repeated quantity of water resources, which is 68.9% of the surface water resources and 84.5% of the ground water resources, respectively. The percentages are much larger than those in other regions. It is a special feature of the water resources in the arid and semiarid northwest continental river region. In some rivers runoff and groundwater exchange several times in the process of water depletion from the outlet of the rivers at mountains to the end of the rivers or from the head to the end of the rivers. In some rivers where groundwater discharge is dominant, the percentage of the discharge is up to 50-90% of the runoff (Tang et al., 1992).

It is obvious that the water resources in the arid and semiarid northwest continental river region are very scarce by nature. The total amount of water resources in this region is only 3.2% of the national total. The average volume of the water resources per square kilometer in this region is only 13.4% of that overall the mainland of China (Table 1).

Human Impacts on the Water Resources

The arid and semiarid northwest continental river region is abundant in natural resources. Particularly, there are abundant land, light and heat energy resources that are appropriate for agriculture. This region in fact has already become one of China's major food produc-

tion bases. In the past several decades agriculture in this region made considerable development and contributions to China's food security. Meanwhile, industries in this region also made notable development. However, the food production was based on large-scale land reclamation and farmland irrigation. The increasing irrigation farmland and developing industries consumed a large quantity of water resources. This caused a series of water and water-related issues and severely impacted sustainable development of the region. Foe example, in the Hexi continental river region, a typical river basin facing severe water scarcity and other water-related issues is the Shiyang River basin. In the Shiyang River basin, large-scale water resources development in its middle reach caused oasis degradation and desert encroachment in lower reach. The total area of irrigation farmland in this basin increased from 13,400 ha in 1949 to 24,500 ha in 1979 and further to 29,000 ha by 1990 (Liu at al., 1983; Meng et al., 1994). Correspondingly, irrigation water increased from 0.58 Gm^3 in 1950s to 0.77 Gm^3 in 1970s and to over 0.90 Gm^3 in 1990s. The total amount of water resources in the lower reach of the basin decreased from 0.57 Gm^3 in 1950s to 0.38 Gm^3 in 1970s and further to less than 0.25 Gm^3 in 1990s with worsened water quality (Tan, 1983; Meng et al., 1994).

Another typical sample is the Hei River basin in the Hexi continental river region. In this river basin, large-scale water resources development in its middle reach caused considerable decrease in the water resources in its lower reach. The long-term annual mean runoff in upper reach with high mountains is 3.80 Gm^3. However, according to Wang et al. (1999) the runoff flowed to the lower reach was only 1.23 Gm^3 in 1950s, and further decreased to 1.11 Gm^3 in 1960s, 0.98 Gm^3 in 1970s and 0.69 Gm^3 in 1990s. It induced dry up of the Juyan Lakes, aggravation of desertification, degradation of ecosystems of the lower reach area in the basin.

The Talimu River basin in the Xinjiang continental river region, the largest continental river basin in China, is a particularly typical human impacted river basin. In this river basin, large-scale land reclamation in 1950s increased 36,500 ha irrigation farmland by later 1950s and the total area of irrigation farmland accounted to be 124,500 ha by 1980 (Tang et al., 1992; The Panel of China Water Resources Regionalization, 1989). This resulted in a large amount of water resources development and consumption in the reclamation area and severe degradation of natural environment and ecosystems. For example, the area of poplar diversifolia woods in the river basin decreased 28,500 ha during the two decades from later 1950s to later 1970s and further decreased 46,700 ha. The Taitema Lake and the Luobu Lake dried up one after another (Tang et al., 1992; Yuan et al., 1999).

In short, water resources development in the arid and semiarid northwest continental river region, on one hand, has promoted social-economic development in the region, and on the other hand, has induced severe environmental issues. Facing the opportunities of the large-scale west exploitation, this region is also facing severe challenges including water-related impacts on society, economy and environment. In order to realize the goal of the large-scale west exploitation and promote sustainable development of the region, water scarcity, the bottleneck of sustainable development of the region, and all other water-related issues have to be solved in integrated manners.

INTEGRATED MANAGEMENT STRATIGIES OF WATER RESOURCES

According to the essential characteristics of water resources in the arid and semiarid northwest continental river region and water-related problems that impact sustainable water resources development and utilization of the region, the following strategies might be suitable to integrate water resources management in the northwest continental river region.

Rational economic structures and optimal industrial distributions

The arid and semiarid northwest continental river region is one of the most important regions in the large-scale west exploitation. In fact, the exploitation has promoted and is speeding up social-economic development of this region. However, due to its weak background of economy and environment, particularly the dry climate, weak natural environment or ecosystems and water scarcity, development of this region should be carefully planned according to its natural resources and other conditions, as well as the experiences and lessons in water resources development in the past time in the region, throughout China and the world. A rational economic structure should be one that can make optimal utilization of local water and other natural resources and develop mainstay industries with regional characteristics, such as the south Xinjiang cotton base, the Hexi grain crop base, the Talimu oil and natural gas base. Meanwhile, this region needs to speed up the development of its secondary and tertiary industries. Proper proportions of the three industries to GDP (Gross Domestic Product) with regional characteristics are much better than just to stimulate other region's developing patterns. All the industries should be water-saving and environmental friendly. Specific attention should be agricultural water-saving technology and reuses of urban and/or industrial wastewater.

Integrated development and effective utilization of local water resources

Integrated water resources management in the continental river region should intensify integrated development, scientific allocation and effective utilization of local water resources. In this region, more attention should be paid to multi-objective and multi-purpose development of the local water resources. On one hand, the multi-functions of water resources, such as urban water supply, irrigation, hydropower, water-related recreation etc., should be comprehensively considered. On the other hand, the water resources should be rational allocated to the society, the economy and the environment so that realizes the three general objectives of water resources development: social progress, economic development and environmental security. This should be based on a reliable water demand prediction for different water use sectors. Particularly, the water allocation should be well planned on regional scale and at least on river basin scales to ensure a proper quantity of water resources for lower reaches of the rivers so that protect and reconstruct damaged hydro-ecosystems in the lower reaches.

Large-scale south-to-north water transfer

Large-scale interbasin water transfer is recognized as one of the best measures to solve water scarcity. In China, large-scale south-to-north water transfer has been a common term in both science and politics. Three large-scale south-to-north water transfer projects:

the East Line Project, the Middle Line Project and the West Line Project have been well investigated (Changjiang (the Yangtze River) Water resources Commission, 2000). The principal purpose of the three projects is to transfer water from the Yangtze River basin to north China, specifically, the North China Plain, including Beijing, the capital city of China. However, from the viewpoint of sustainable development, the arid and semiarid northwest continental river region is the most water scarce region in China and needs more water to reconstruct a safe ecological environment for the nation. Therefore, large-scale south-to-north water transfer for this region might be most necessary for a sustainable China.

Development and popularization of eco-water-saving technology

Eco-water-saving technology should and will be major water-saving technology in the 21st century. Currently, in the arid and semiarid northwest continental river region, water resources are almost used in traditional manners that are highly water consumed. Particularly, farmland irrigation is the largest water user and consumes over 90% of total water supply in this region. However, irrigation water application efficiency, the ratio of irrigation water demand to supply, in this region is only between 0.2 to 0.4 and is the lowest in China. Most of the water supplied to farmland is consumed in evaporation and infiltration in channels and fields. Though the efficiency can be raised using available water-saving irrigation techniques, such as sprinkler irrigation, trickle irrigation etc., the facilities are cost and lower beneficial for large area grain crops in this region. Furthermore, the available water-saving irrigation techniques may impact groundwater recharge and cause degradation of hydro-ecosystems or water environment. Therefore, development and popularization of eco-water-saving techniques, which are able to produce more grain by less water, will be considerably important in this region. According to the basic conditions of water resources and their utilization, soil and plants or crops, climate and ecological environment, more attention should be paid to the metabolism of plants for lower water consumption and saline tolerance, and biotechnology for wastewater treatment and biodegradation or separation of heavy metals and other toxins in water purification. These technologies have been recognized to be possible in the new century (World Commission on Water for the 21st Century, 1999; Panel on Biotechnology of the World Commission on Water for the 21st Century, 1999).

Equal allocation of water resources in international cross-boundary rivers

There are many international cross-boundary rivers in the world, so are in China. In the northwest continental river region of China, there are several international cross-boundary inflow and outflow rivers. Development of the water resources in these international cross-boundary rivers would be very sensitive. Relevant countries should friendly cooperate in development and allocation of the water resources based on equality and mutual benefit.

Protection of culture, custom and religion of minority nationalities

The northwest continental river region is a region that inhabits over twenty minority nationalities. Different nationalities have their own background of culture, custom, religion etc. Some of the culture, custom and religion of the minority nationalities are closely in

relation to water resources. In water resources development, the traditional culture, custom and religion of the minority nationalities have to be well respected and protected. Specifically, the large-scale west exploitation will inevitably impact on the traditions of the minority nationalities. Therefore, not only in water resources development but also in a complete range the protection of these rights of the minority nationalities should be put into important agenda.

Protection of water resources and water environments

Protection of water resources and water environments is of paramount important in the arid and semiarid northwest continental river region. Desert or Gobi is dominant landscape in this region. Furthermore, human economic activities have severely impacted natural ecological environment or ecosystems, such as the river dry out, lake dry up, oasis degradation, and water environmental aggravation (Feng, 1999b). The desert in this region is a major source of sandstorms that impact not only this region but also most part of the mainland of China. All of these are associated with water resources. For sustainable utilization of water resources, protection of water resources and water-related environmental issues should be regarded as an important aspect of integrated water resources management. Reconstruction of damaged ecosystems or natural environments is also important in this region.

An highly authoritative and qualified water resources management system

A highly authoritative and qualified water resources management system is necessary and important in this region. On one hand, almost all the rivers involve different administrative regions. On the other hand, in administrative regions, water resources management is authorized by several governmental sectors. This situation severely restricts integrated water resources management and has to be abrogated. In water resources management in this region, an "one dragon" water resources management system is much better than the current "multi dragons" systems.

CONCLUSIONS

Natural water scarcity and water-related environmental degradation have been restricting social-economic development in the arid and semiarid northwest continental river region of China. Facing the opportunity of the large-scale west exploitation, this region has to seek feasible solutions for sustainable water resources development and utilization. Integrated water resources management is the essential approach for this purpose. According to the essential characteristics of water resources: natural shortage and extremely uneven distributions in space and time, the proposed strategic solutions to the water issues may be feasible in this region, and may also be suitable to the regions or countries with similar issues.

However, water resources management is a complicated system engineering. It should be based on complete understanding of the essential characteristics of water resources and their relation to sustainable development in the concerned regions. A detailed investigation and assessment of indicators for sustainable water resources development and utili-

zation may be beneficial for integrated water resources management and should be carried out throughout the world.

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