

## DEVELOPMENT AND MANAGEMENT ISSUES

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### AN OVERVIEW OF WATER RESOURCES IN THE YELLOW RIVER BASIN<sup>1</sup>

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#### Abstract

The Yellow River basin, an important agricultural and industrial region and the “Cradle of Chinese Civilization,” is facing serious water shortage. The particular climatological and hydrologic conditions together with the disproportional development of economics are currently making sustainable water supply a rather complex and difficult task. Even so, the population still continues to increase, which poses considerable pressure on the already overburdened water resources in the study area. Traditional supply-oriented water resources management has proven to be insufficient to efficiently integrate the socio-economic development, environmental ecosystem, and limited renewable water resources. The Yellow River should be envisioned from broader perspectives, not only to recognize the symbolic dimension of the water resources management from a source of public goods or commodity water, but also to regard the river basin as an ecosystem worthy of preservation and protection for future generations. An overview on the availability and demand aspects of the water resources in the Yellow River basin is presented, and the present and future situations of the water shortage are evaluated. In addition, perspectives on a new demand-oriented water resources management plan, in an effort to shift water resources management towards sustainability in the Yellow River basin, are proposed.

Keywords: Yellow River, water resources, sustainable development, China

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<sup>1</sup> Reprinted with permission of the International Water Resources Association from the journal *Water International*, Volume 30, Number 2, June 2005, pages 225-238.

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The views expressed herein are those of the authors and do not necessarily reflect those of the United Nations.

## 1. Introduction

One of the greatest challenges facing humankind is the concept of sustainable development, which is related to economic development, water scarcity, and environmental degradation. This concept, proposed a decade ago, offers a scientific framework to keep economic development sustainable without jeopardizing the ecosystem. Recently, the issue concerning sustainable water resources management has arisen. Sustainable water resources management includes supply and demand aspects, policy implementation, and participatory planning and envisioning (Mylopoulos et al., 2003). In this new vision, the major issue is to integrate demand management into water supply planning to achieve rational balance between supply and demand of water resources (Döll and Hauschild, 2002; Hudson-Rodd and Shaw, 2002). Traditional, supply-oriented management has led to the overexploitation and depletion of freshwater resources. Therefore, new sustainable schemes with a good balance between water conservation, demand management, and the development of new supplies should be formulated. Actually, the scarcity of water resources has already led many countries to introduce the demand-oriented water management in the agricultural section in place of the existing supply-oriented water management during the past several years (Kijne, 2001).

In China, four major issues – water shortage, flood, water pollution, and groundwater overexploitation – have posed a great challenge for the water authorities. Of 500 large cities, more than 300 cities have been in shortage of water (Zhang and Zhang, 1995). China was and will continue to be confronted with serious water scarcity. Besides the insufficiency of available water resources, the distribution of water resources within the country is very imbalanced. The northern part of China, including the Yellow River basin, is particularly water scarce. The increased periods and lengths of the drying-up of the lower Yellow River, disappearance of natural lakes, and sustained declining of the groundwater levels all sounded the alarm for the water authorities in China. The Yellow River, known as the “River of Mother” for the Chinese, is the second longest river in China. It sustains more than 100 million people who depend upon the river and its tributaries for their daily life (Chang et al., 1998). Due to the devastating floods and high sediment loads, the Yellow River basin has been the focus of the water management in China during the past two millennia. Flood has been traditionally a major problem in the Yellow River basin and has caused millions of deaths over the millennia. For example, a flood in 1117 killed more than one million persons; 340,000 were killed in 1642; and 18,000 in 1933 (Ongley, 2000). Recently, with the rapid development of economics, water shortage issues in the Yellow River basin have become increasingly more serious. The basin has experienced persistent water shortages during the last several decades.

The Yellow River basin is ecologically fragile and has been seriously endangered by prevailing social and economic development during the past several decades. It is one of the basins suffering from water scarcity, and the limited water resources have been extensively overexploited to cover the increased demand (Xi, 1996; Chang et al., 1998; Xu et al., 2002). The Ministry of Water Resources (MWR, 1999) estimated that the

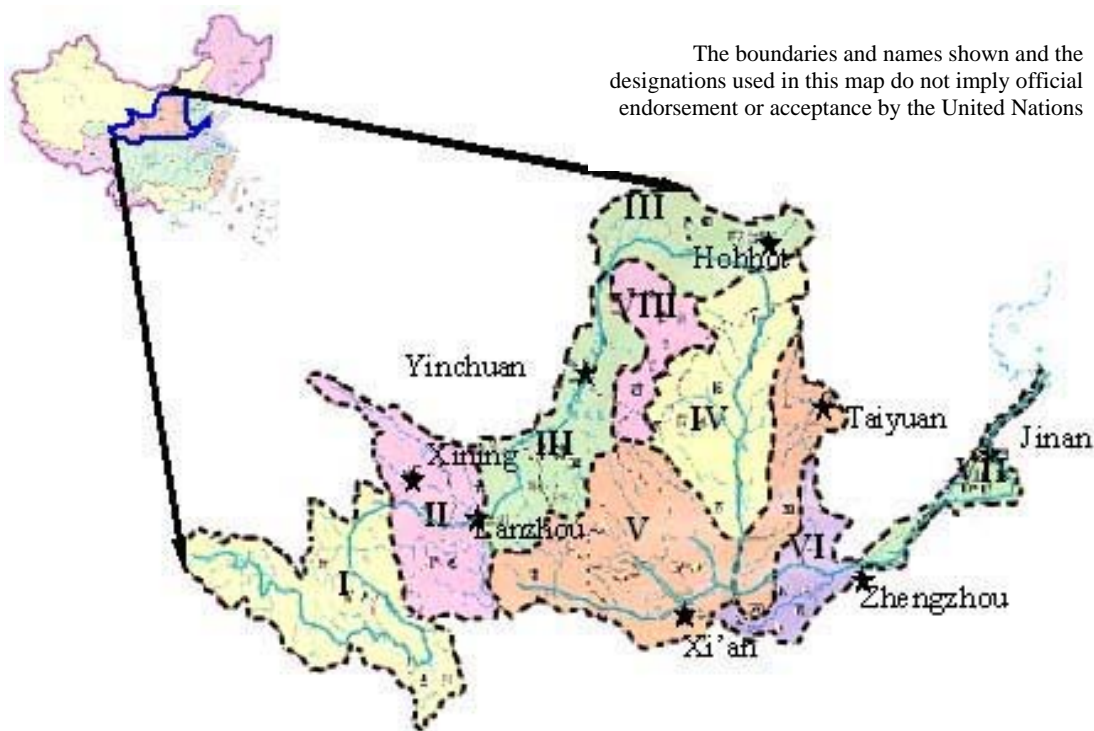
annual renewable water resources per capita was only 749 m<sup>3</sup>, which is less than one-third of the average in China, making the basin one of the driest area in the country. The average annual precipitation ranges from 100 to 800 mm, and evapotranspiration far exceeds annual precipitation over a large portion of the basin. Only the headwater areas experience a positive water balance, providing 56 percent of the water resources for the whole basin. The growing population, the increasing competed usage of water, and the degradation of ecosystem pose a serious threat to the sustainable water resources management in the Yellow River basin. The allocation of the limited water resources in the basin is one of the critical issues (Jha and Gupta, 2003). With the high rates of withdrawal due to the high population densities and other intensive water uses in the upper and middle reaches and tributaries, water shortage is becoming very serious in the downstream of the Yellow River basin. Large amounts of water are diverted from the upstream to irrigate cultivated land in Ningxia, Gansu, and Inner Mongolia, and it has considerably reduced the discharge in the downstream. The combination of less precipitation and high rates of water withdrawal resulted in the streamflow in the Yellow River to decline year by year. In 1972, the Yellow River dried up for the first time in the history of China, and no water flowed into the Bohai Sea over 15 days. From 1985 to 1997, the river dried up nearly every year with the dry period becoming progressively longer. In 1996, the channel in the downstream was dry for 133 days, and it reached 226 days in 1997.

In this paper, an overview on the availability and demand of water resources in the Yellow River basin is presented. The objective of this investigation is to review the current situation of water resources system and to envision the perspectives of sustainable water resources management mainly on the basis of Chang et al. (1998), Zhu and Zhang (1999), MWR (1999), and other related studies. As for the methodology for estimating and assessing water resources in China, refer to Zhu et al. (2004) or related materials. The paper begins with an introduction of the geographical and hydrologic conditions in the Yellow River basin and is followed by a presentation of the available water resources and major water demand. Thereafter, the projected water demand in 2010 and the assessment on the security of the water supply in the study area are presented. This investigation is mainly based on a review of a number of scientific articles and books related with different aspects of the concerned topic. Despite the fact that much research has been done and numerous reports have been written on issues related to the water resources issue in the Yellow River basin, few attempts have been made to synthesize the different results in a systematic and analytical manner. This investigation is an attempt to create an integrated picture of the various issues related to water resources in the Yellow River basin.

## **2. Study Area Description**

The Yellow River, the second longest river in China, originates in the Tibetan Plateau and empties into the Bohai Sea. The basin lies within 32°N to 42°N and 96°E-119°E. The length of the river is 5,464 km, and the catchment area is 752,000 km<sup>2</sup>. For the purpose to estimating the water availability and demand, the study area is physiographically divided into eight regions: river source-Longyangxia (UpLon),

Longyangxia-Lanzhou (LonLan), Lanzhou-Toudaoguai (LanTou), Toudaoguai-Longmen (TouLon), Longmen-Sanmenxia (LonSan), Sanmenxia-Huayuankou (SanHua), Huayuankou-river mouth (HuaMou), and Inland River basin, as shown in Figure 1. About 13.6 percent of the basin area is covered by forest, 15.9 percent is utilized for agricultural purposes, 37.1 percent is covered by grassland, and the rest (33.4 percent) is covered by water, dwellings, and other land uses. The total irrigated area in the basin is approximately 4.38 million ha, and irrigation is the major water user in the basin. There are several large irrigation schemes; most are associated with reservoirs and large water diversion schemes, and most of the irrigation water used in the basin is from the surface storage reservoirs. The amount of surface water withdrawn in 2001 was 33.7 km<sup>3</sup>, and the amount of groundwater withdrawn in the same year was about 13.8 km<sup>3</sup>. Both take 70.8 percent and 29.2 percent of the total amount of water withdrawn in 2001, respectively.



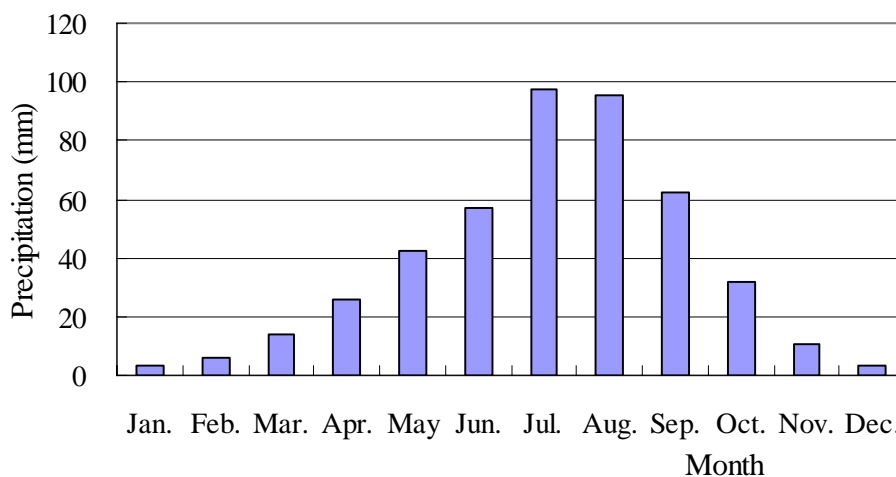
**Figure 1.** Map of the study area and its location in China

The Yellow River basin is characterized by complex climatic variability. In winter, northerly winds from high latitude areas bring dry and cold atmosphere into the basin, while the summer climate is dominated by warm and wet air masses. The headwater and southern side of the basin receive relative heavy precipitation, while the Loess Plateau in the middle stream of the basin is hot and dry in summer and receives little precipitation. The average annual precipitation in the Yellow River basin from 1950 to 1997 is 449.9 mm (Zhu and Zhang, 1999). The average annual precipitation over a period of 48 years from 1950 to 1997 are found to be 426.4, 289.8, 439.3, 561.2, and 674.2 mm over the major river sections from the river source to Huayuankou, respectively. The greatest precipitation occurs on the eastern side of the basin (Sanmenxia-Huayuankou) and the

smallest occurs in the upstream from Lanzhou to Toudaoguai, as shown in Figure 2. Similar characteristic was also shown by stream flow. It should be noted that there is essentially no rainfall in the low reach because of the “suspended” channel (Zhu et al., 2004). Approximately 80 percent of annual precipitation occurs between May and October. Figure 3 shows the seasonal variation of the precipitation. These characteristics pose a great challenge for the efficient use of surface water resources in the Yellow River basin.



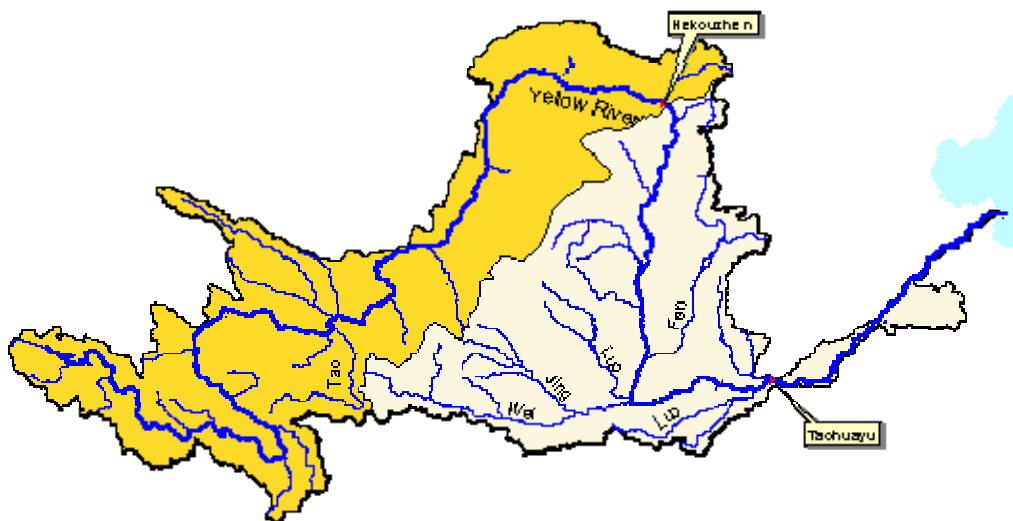
**Figure 2.** Average annual precipitation and runoff depth in the Yellow River basin



**Figure 3.** Monthly precipitation in the Yellow River basin

## 2.1 The Geography of the Yellow River Basin

Over the area of 752,000 km<sup>2</sup>, the Yellow River flows through seven provinces including Qinghai, Gansu, Sichuan, Shaanxi, Shanxi, Henan, and Shandong provinces, and two autonomous regions including Ningxia and Inner Mongolia. As shown in Figure 4, the headwater starts on the Bayankela Mountain and flows eastwards making a turn to the northeast near Lanzhou. The river runs northward for approximately 1,000 km and then turns eastward in the Inner Mongolia Autonomous Region. After passing Baotou City the main stem bends southward and flows again for another approximately 1,000 km along the boundary between Shanxi and Shaanxi provinces. At the confluence with the Wei River, it turns sharply to the east near Tongguan in Henan Province. After flowing eastern for approximately 400 km, the river turns northeast near Kaifeng City in Henan Province and flows through the Shandong Province into the Bohai Sea. The Yellow River basin is divided into three reaches: the upstream, middle stream, and downstream reaches. The upstream reach is situated on the Tibetan Plateau at an altitude of more than 3,000 m above sea level. It covers an area from the river source in the Bayankela Mountain to Hekouzhen in Inner Mongolia Autonomous Region with a length of 3,472 km. The middle stream is mainly situated on the Loess Plateau at an altitude of 1,000 to 2,000 m above sea level. It stretches from Hekouzhen in Inner Mongolia, running along the boundary between Shaanxi and Shanxi provinces to Huayuankou in Henan Province with a distance of 1,206 km. The downstream is situated on the alluvial plains in Henan and Shandong provinces, and stretches over 786 km from Huayuankou to the river mouth at the Bohai Sea.



**Figure 4.** Main stem and the major tributaries in the Yellow River basin

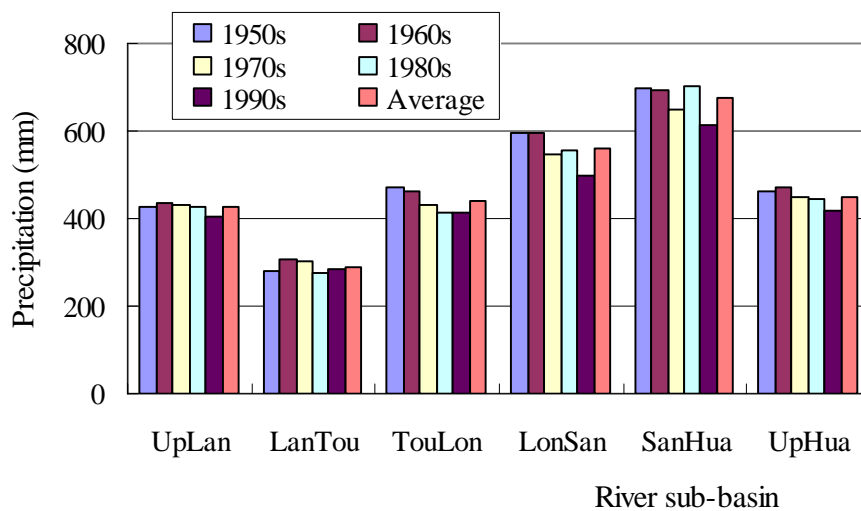
The topography in the Yellow River basin varies markedly from the source to the river mouth. The upstream is composed of mountainous terrain, rangeland, farmland and grassland. Only 9 percent of the area is cultivable with several well-irrigated sites in Ningxia Province and Inner Mongolia Autonomous Region. The middle stream has a diverse landscape on thick layers of deposited aeolian loess. The downstream reach is relatively homogenous and made up of the alluvial floodplain of deposited sediment. When the Yellow River runs through the Loess Plateau, the intensive soil erosion results in losses of a vast volume of silt that will be discharged into the river channels. On an average, the river carries 35 kg of suspended sediment per cubic meter of water. The maximum sediment concentration occurred in the main stem near Longmen on July 18, 1966 was 933 kg/m<sup>3</sup>. A total of 1,000 to 1,500 kg/m<sup>3</sup> were recorded for several times in tributaries including Huangpu, Wuding, and Kuye rivers, and 1,700 kg/m<sup>3</sup> was also recorded in Kuye River (Chen, 1996). An average of 1.6 billion tons of sediment enters the main stem channel at Huayuankou annually, of which about 1.2 billion tons are finally carried into the Bohai Sea.

## **2.2 Hydrologic Conditions in the Yellow River Basin**

Floods, sedimentation, and water shortage have been the dominant issues for the management of water resources in the Yellow River basin for thousands of years. With the development of economics in the basin during the past several decades, water resources and water pollution have becoming a barrier to the sustainable development in the study area. The water resources in the Yellow River are scarce, and the distribution of water resources is very uneven in time and space. In an average year, the basin drains out approximately 58 km<sup>3</sup>, which is equivalent to an annual runoff of 80 mm. Roughly 56 percent of the runoff comes from the headwater from the source to Lanzhou, where an average runoff of 145 mm is generated annually. However, the densely populated middle reach of the basin only generates an annual runoff of less than 70 mm, and hardly any streamflow is generated from Lanzhou to Hekouzhen. During the past several decades, both surface and groundwater resources have been over-extracted to a degree leading to drying-up of the main stem and several meters of the land subsidence in some places. River desiccation has a serious influence not only on water supply but also on dilution of effluents and on the aquatic and wetlands environment in the study area. For the water resources management in the Yellow River basin, the major challenges will be to: (1) mitigate desiccation by upstream discharge regulation; (2) manage conflict within and among upstream, middle stream, and downstream users; and (3) deal with the issue of water and soil conservation within the whole watershed, especially in the middle reach.

The Yellow River basin is characterized by a continental temperate climate with two distinct seasons: a warm wet summer with high precipitation and evaporation from June to October, and a dry cold season with low evaporation and precipitation from January to April. The rainy season usually contributes to about 50 to 80 percent of the annual precipitation, partly due to intensive rainstorms (Zhu and Zhang, 1999). Annual precipitation is only around 449.9 mm, but the annual potential evaporation rate may be three to four times higher than the annual precipitation. The variability in annual precipitation is also remarkable. In a wet year precipitation may be as high as 700 mm,

while in a dry year, only 200 mm. Due to the significant differences in the temporal and spatial distribution of precipitation, the amount of runoff also varies markedly from month to month, year to year, and between different regions. Figure 5 depicts the spatial and temporal distributions of average annual precipitation over the basin (Zhu and Zhang, 1999). The areas of the greatest precipitation are located in the southern and southeastern part of the basin, mainly on Qinling Mountain. The smallest precipitation occurs in the area from Lanzhou to Toudaoguai.



**Figure 5.** Average annual precipitation distribution along the Yellow River

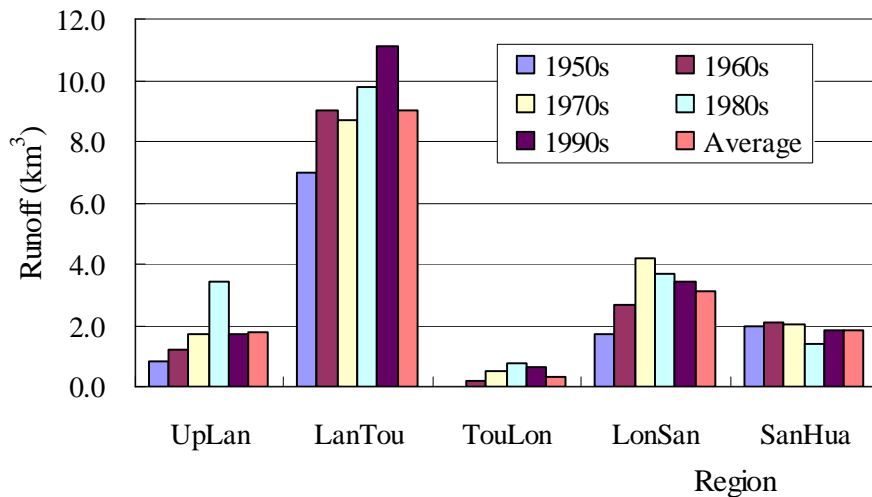
### 3. Available Water Resources in the Yellow River Basin

The limited water resources in the Yellow River basin cannot meet both current and future demands in the study area. With only 2.6 percent of the nation's water resources, the basin has to meet the needs of 9 percent of the total cultivated area and 12 percent of the total population in China. The precipitation and streamflow are not only insufficient in absolute terms, but also very much unevenly distributed temporally and spatially. Of the annual precipitation of 400-600 mm, about 70 percent fall in the rainy season from June to September, and the precipitation between July and August accounts for nearly 50 percent of the annual precipitation. It was and will continue to be a great challenge for the rational water supply in the Yellow River basin.

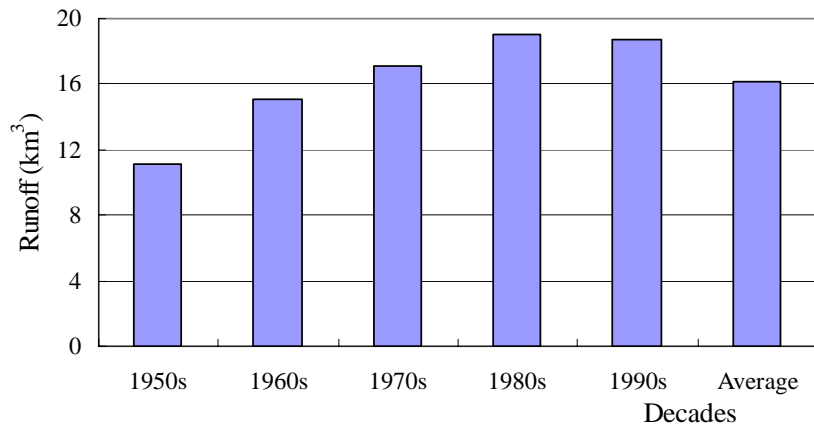


### 3.1 Surface Water Resources

The available surface water resource is estimated by the naturalized streamflow sequences, which represents the natural flows that would have occurred in the absence of water uses and water management facilities (Muttiah and Wurbs, 2002). It is usually obtained by adjusting the measured flows recorded at gauging stations and removing the impacts from the filling/releasing of upstream reservoirs, water diversions, and return flows from both surface and groundwater sources. For sites with relatively undeveloped basins, small adjustments may result in good estimations. In extensively developed river basins such as the Yellow River basin, however, quantifying and removing all effects of human activities is by no means an easy task. Figure 6 gives the amount of water resources affected by human activities in different river segments from the river source to Huayuankou over various periods (Zhu and Zhang, 1999). It is obvious that a major effect occurred in the area from Lanzhou to Toudaoguai, and the amount increased year by year with the largest value in the 1990s at  $11.1 \text{ km}^3$ . This amount of water was mainly diverted for irrigation. Relatively, the amount on water resources affected by human activities from Toudaoguai to Longmen is the smallest one with the average of  $0.33 \text{ km}^3$ . Figure 7 further shows the long-term changes of the water resources affected by human activities from the river source to Huayuankou. From the 1950s to the 1990s, it increased gradually. The change between the 1980s and the 1990s, however, was very small. This may result from the serious drought that occurred in the study area during the 1990s and the corresponding water-saving policy initiated by central and local water authorities.

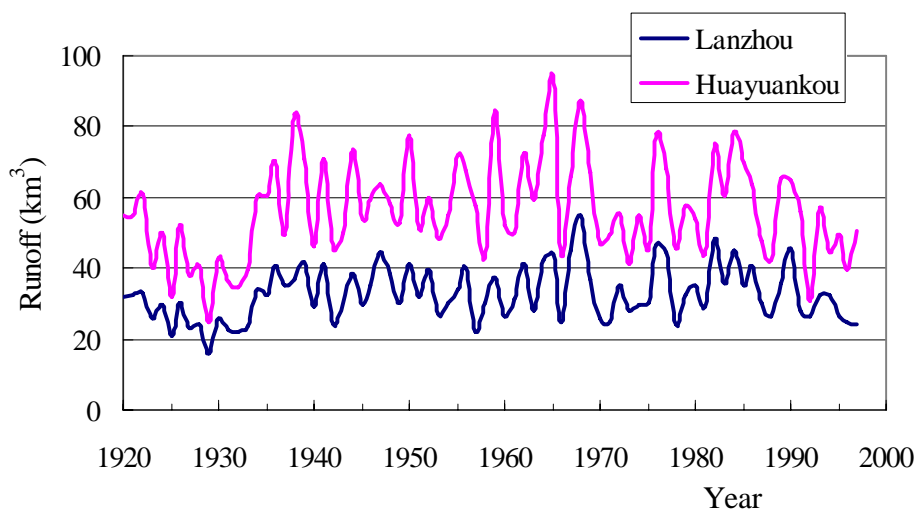


**Figure 6.** The runoff affected by humankind activities in different area

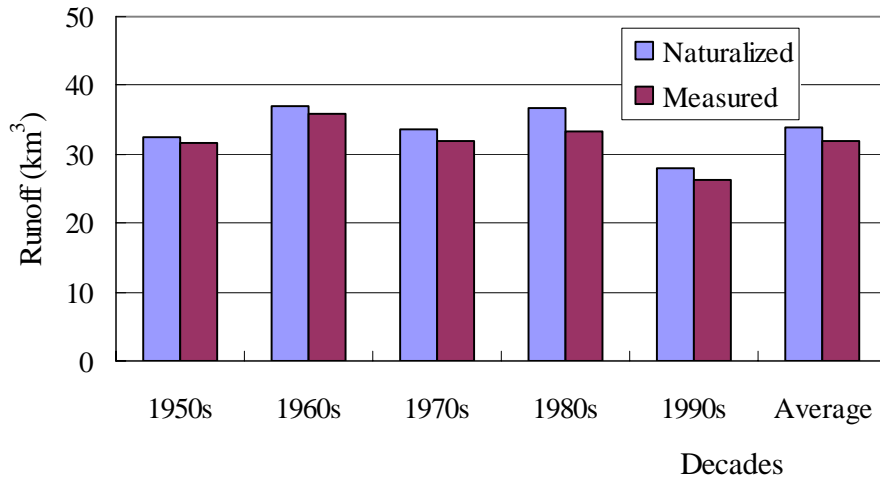


**Figure 7.** The runoff affected by humankind activities at the upstream of the Huyuankou

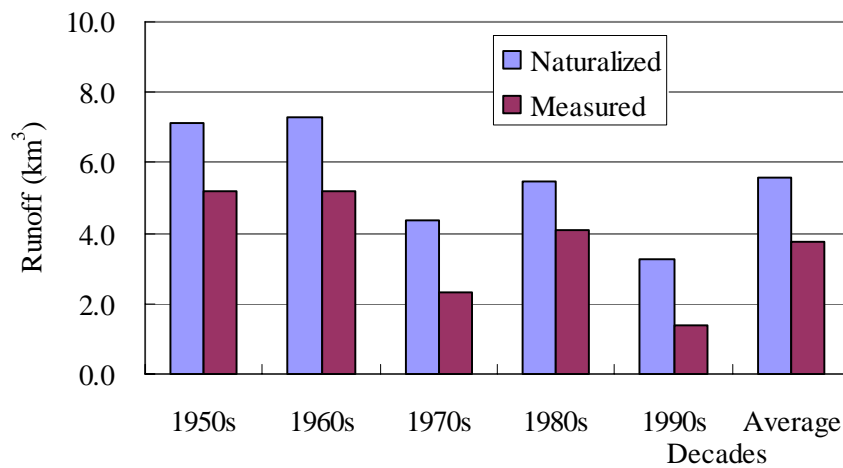
Based on the amount of water resources affected by human activities, the measured streamflow sequences can be adjusted to the naturalized streamflow time series. Figure 8 gives the naturalized streamflow sequences estimated by the Yellow River Conservancy Commission for Lanzhou and Huayuankou stations (Zhu and Zhang, 1999). The average annual runoffs at two gauging stations are 32.8 km<sup>3</sup> and 55.9 km<sup>3</sup>, respectively. Adding the runoff from the tributaries from Huayuankou to the river mouth, it is estimated that the annual runoff in the Yellow River basin is 58 km<sup>3</sup>. However, it should be pointed out that the average runoff after the 1950s is marginally below this value, and the figure from the 1990s only averaged 43 km<sup>3</sup> annually, being 25 percent lower (Zhu et al., 2004). Figure 9 gives the comparison between the measured and naturalized runoff in two areas: the river source to Lanzhou and Sanmenxia to Huayuankou. As expected, the effect in upstream was small, as shown in Figure 9a. On the contrary, the effect of human activities on streamflow in the middle or downstream reaches of the river would be significant, as shown in Figure 9b.



**Figure 8.** Annual naturalized runoff at Lanzhou and Huayuankou (1920-1997)



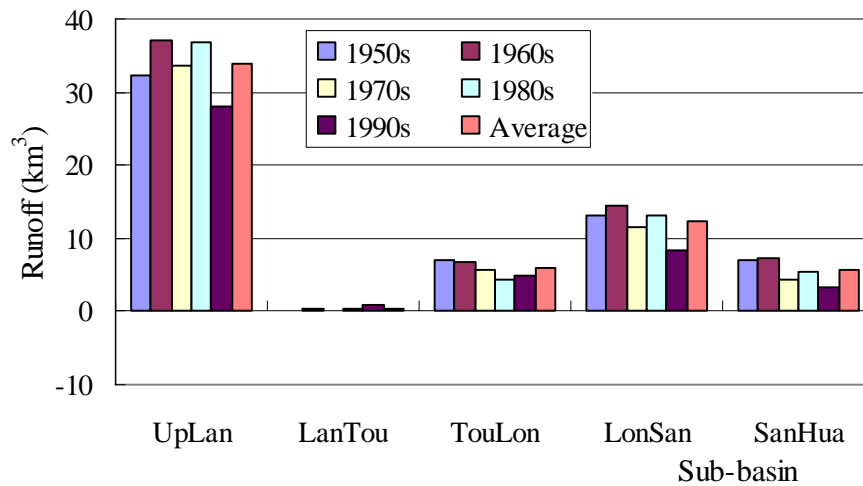
**Figure 9a.** Comparison of the observed and naturalized runoff at Lanzhou station



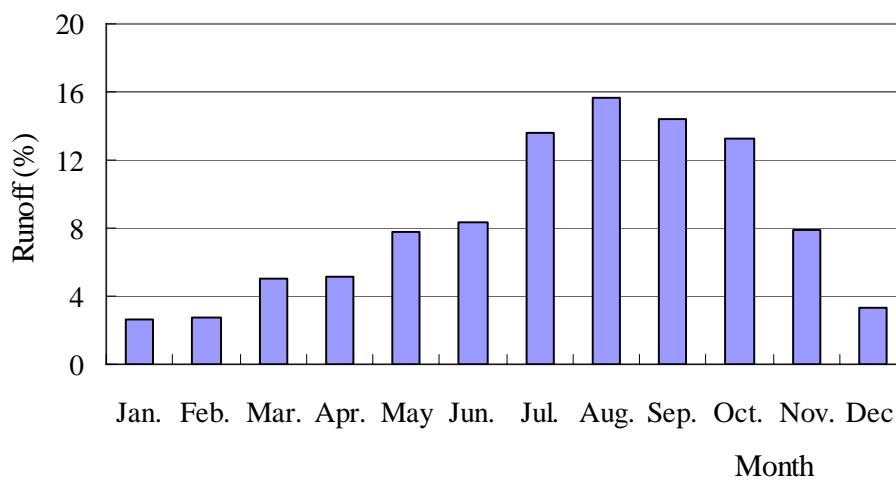
**Figure 9b.** Comparison of the observed and naturalized runoff from Sanmenxia to Huayuankou

As stated in previous section, the Yellow River basin suffers from both great spatial and temporal distribution of water resources, other than only an actual water insufficiency problem. Figure 10 shows the changes of the naturalized runoff in different river sections over various periods (Zhu and Zhang, 1999). Although only a small population and a few irrigated areas are within the river source to Lanzhou, most of the available surface water resources are generated there. The average annual runoff produced in this area is  $33.8 \text{ km}^3$ , and accounts for more than 56% of the total surface runoff generated in the Yellow River basin. In contrast, very low surface runoff is

generated from Lanzhou to Toudaoguai, while a large amount of surface water is withdrawn for irrigation there annually. The seasonal distribution of the annual runoff from the river source to Huayuankou is given Figure 11. The temporal unevenness of the surface water resources is easily understood. More than 30 percent of the runoff occurred in only two months, August and September, and the runoff generated over four months from July through October accounts for nearly 60 percent of the total annual runoff (Zhu and Zhang, 1999).



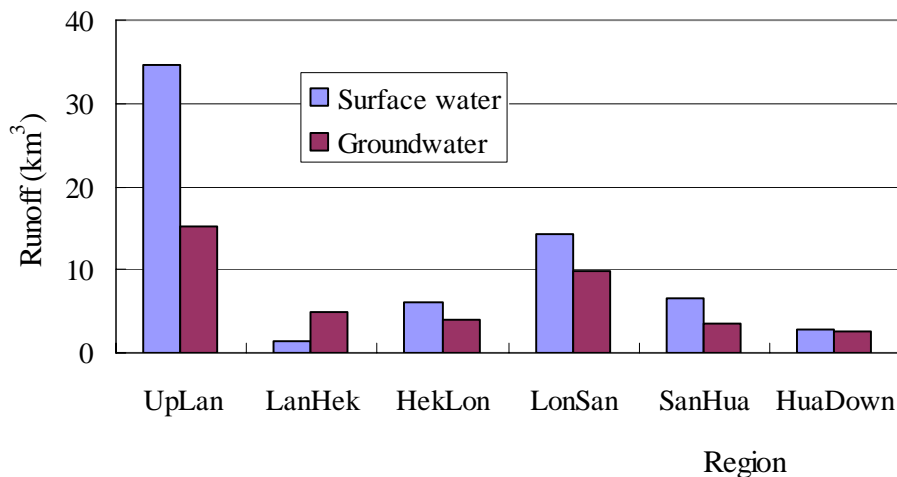
**Figure 10.** Naturalized runoff distribution over different periods



**Figure 11.** Temporal distribution of annual natural runoff from the river source to Huayuankou

### 3.2 Groundwater Resources

In some studies, groundwater is neglected in the estimation of the available water resources. At global scale this is acceptable, because renewable groundwater resources usually represent only a small proportion of the total river runoff, e.g., 5% for Africa (Shiklomanov, 2000). However, for basins located in arid regions such as the Yellow River basin, renewable groundwater can represent a significant part of the total volume of renewable water resources. In the study area, the mean value of the available groundwater resources is estimated at nearly 40 km<sup>3</sup> annually, and it varies greatly in space. In terms of absolute value, the largest groundwater resources are located in the area from the river source to Lanzhou at 15.2 km<sup>3</sup> per year. The smallest value is found in the area from Huayuankou to the river mouth at 2.5 km<sup>3</sup> annually. The spatial distribution of the groundwater resources has quite similar characteristics with that of surface water resources, as shown in Figure 12.



**Figure 12.** Spatial distribution of available surface and groundwater resources

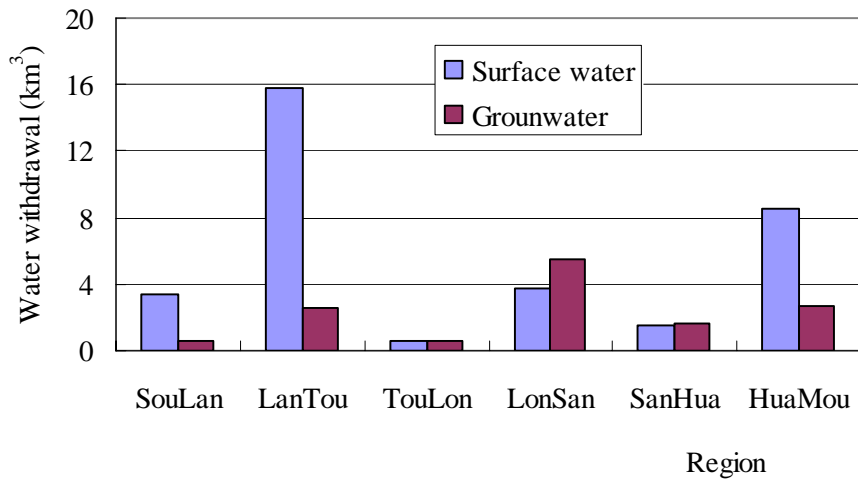
Due to the overexploitation of groundwater, both serious groundwater table depression and land subsidence occurred in some portions of the Yellow River basin. For example, the groundwater table has dropped more than 3.7 m annually in western Taiyuan City from 1980, and it reached 4.2 m annually from 1984 to 1987. The land subsidence was 2.3 cm annually from 1980 to 1985, and the land surface has subsided 1.23 m in some locations in the city by 1982. From the 1970s, the groundwater table in Xi'an City dropped 1 to 5 m annually, and the area of the core of depression reached more than 300 km<sup>2</sup> (Qin et al., 1998). After considering the feasibility for groundwater exploitation, the available water resources estimated on the basis of the hydrologic record from 1956 to 1979 is 73.5 km<sup>3</sup>, as shown in Figure 13 (Chen, 1996). In addition, 47.3 percent of the available water resources are generated from the river source to Lanzhou.

In contrast, only 5 percent and 5.4 percent of the available water resources are generated from two areas: Lanzhou to Toudaoguai and Huayuankou to the river mouth.

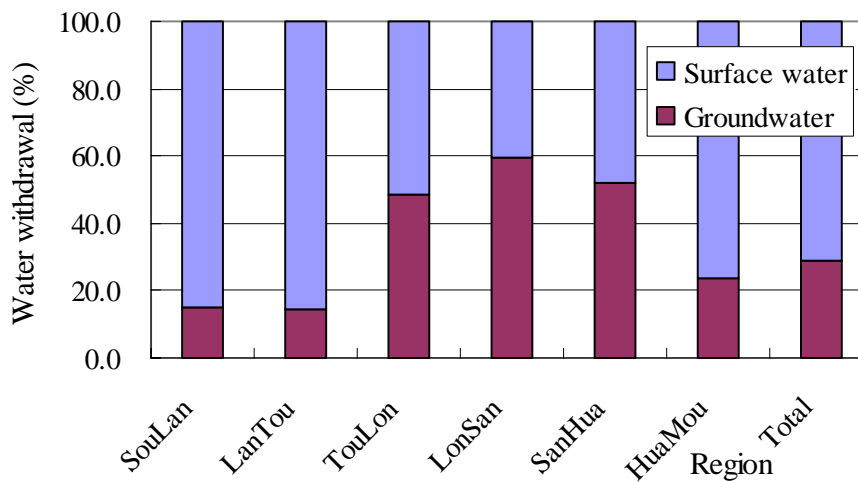


**Figure 13.** Spatial distribution of available water resources in the Yellow River basin

Figure 14 shows the amount of water resources withdrawn for different regions in 2001 (YRCC, 2003). As expected, the region from Lanzhou to Toudaoguai diverted the largest amount of surface water ( $15.8 \text{ km}^3$ ), accounting for 47.1 percent of the total amount of surface water withdrawn in the same year. The region from Huayuankou to the river mouth has the second largest share at 25.5 percent of the total withdrawal for surface water. In contrast, the region from Longmen to Sanmenxia has the largest share of groundwater withdrawal ( $5.5 \text{ km}^3$ ), accounting for 40.7 percent of the total groundwater withdrawn in 2001. Figure 15 further shows the ratio of surface water withdrawal to groundwater withdrawal in different regions. The headwater has the largest shares of surface water withdrawal: 85.1 percent and 85.8 percent of the water resources in river source to Lanzhou and Lanzhou to Toudaoguai were provided by surface water. The water resources downstream of Huayuankou to the river mouth were also mainly supplied by surface water with 71.2 percent of the share. It should be noted that the above assessment on available water resources are based on a stable climatic condition and does not take into account the possible global climate change caused by the increasing of greenhouse gases in the atmosphere. Integration of the global warming processes into the water resources management is especially important in arid/semi-arid regions such as the Yellow River basin, where the hydrologic characteristics are usually very sensitive to seemingly insignificant climate changes. This will be further investigated in the ongoing studies.



**Figure 14.** Water withdrawal in different regions in 2001



**Figure 15.** The ratio of surface/groundwater withdrawal in 2001

### 3.3 Reservoir Development

Development of reservoirs may lead to transformation of streamflow and change the spatial and temporal distribution of the runoff and, thereby, increase the available water resource during low-flow seasons and dry periods. Reservoirs began to be constructed several thousands years ago. However, as an objective on a global scale, most of the reservoirs were developed in the 20<sup>th</sup> century, and nearly all the large dams with the capacity of more than 50 km<sup>3</sup> have been constructed during the past 50 years (Shiklomanov, 2000). Reservoirs are the basis for large-scale water resource systems regulating the extent and duration of streamflow as well as protecting populated areas from floods and inundations. Due to the requirements on water supply from agricultural,

industrial, and domestic uses as well as the need from flood control and hydropower generation, nearly 3,000 reservoirs have been developed in the Yellow River basin during the past 50 years (Chen, 1996). Table 1 lists the large dams built along the main stem of the Yellow River, and their locations are shown in Figure 4. Presently, the total capacity of the reservoirs in the Yellow River basin is more than 70 km<sup>3</sup>, far exceeding the annual streamflow runoff (58 km<sup>3</sup>) in the basin. In other words, the efficiency of water resources development in the study area far exceeds the safety critical value. Once a serious drought that lasted for a long period (e.g. the drought in the 1930s) occurred, water supply in the Yellow River basin will be a great challenge for water authorities and government.

**Table 1.** Reservoirs on the Main stem of the Yellow River

Name	Basin area	Dam height	Water level	Total capacity	Effective capacity
	(10 <sup>4</sup> km <sup>2</sup> )	(m)	(m)	(km <sup>3</sup> )	(km <sup>3</sup> )
Longyangxia (D1)	13.1	178	2,600	24.70	19.35
Liji Xia (D2)	13.7	165	2,180	1.65	0.06
Liuji Xia (D3)	18.2	147	1,735	5.70	4.15
Yanguoxia (D4)	18.3	55	1,619	0.22	0.01
Bapanxia (D5)	21.6	33	1,578	0.05	0.01
Daxia (D6)	22.8	71	1,480	0.09	0.06
Qingtongxia (D7)	27.5	42.7	1,156	0.57	0.32
Sanshengong (D8)	31.4	9	1,055	0.08	0.02
Wanjiashai (D9)	39.5	90	980	0.90	0.45
Tianqiao (D10)	40.4	47	834	0.07	0.04
Sanmenxia (D11)	68.8	106	335	9.64	6.04
Xiaolangdi (D12)	69.4	173	275	12.65	5.05

#### 4. Water Uses in the Yellow River Basin

Before 1950, only a very small amount of water was withdrawn and used in the Yellow River basin. With the rapid development of economics since the 1950s, particularly after the 1980s, the rapid increased demand on water has put great pressure on the limited water resources in the study area. Due to the progressive population growth and socioeconomic development, the demand on freshwater resources in the Yellow River basin will continue to grow in the future. The rate of water utilization in the Yellow River basin ranks the second highest after the Hai River basin among major river basins in China. Almost half of the total annual runoff has been used for agriculture, industry, and domestic purposes, of which agriculture has the highest share of water withdrawal. The amount of water use is generally influenced by a variety of factors such as population, level and type of economic activities, and weather conditions. The level of water use may differ across various sectors. For example, the industrial sector use water mainly as production input; instead the domestic sector uses water mainly as a direct consumption (Hussain et al., 2002). In this study, the water uses are aggregated into four



sectors: domestic use including livestock uses in rural areas, agricultural, industrial, and environmental and in-stream flow requirements.

#### 4.1 Domestic Water Use

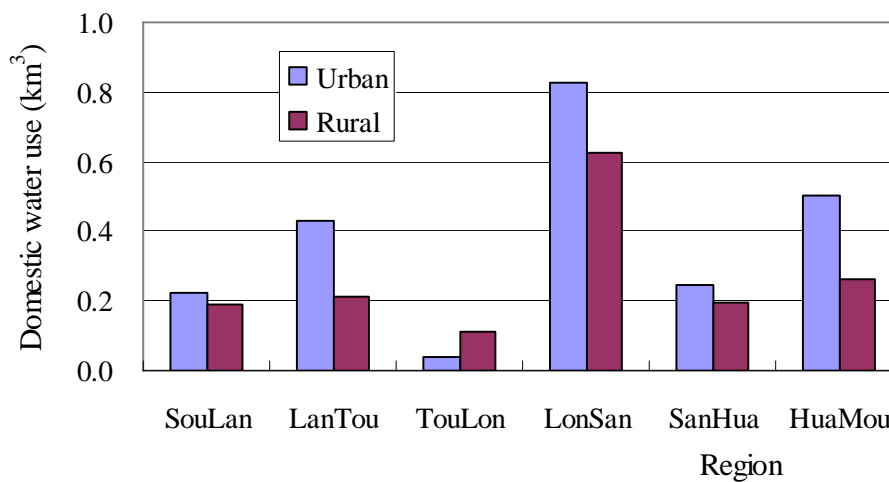
Domestic water use includes residential uses as well as the water use by commerce and public institutions such as schools and government offices. It is usually estimated as the product of the water use per capita and the total population. The Yellow River basin is responsible for the domestic water supply for more than 100 million people. However, the population is not evenly distributed in the basin. As shown in Figure 16, the highest population number is found in the area from Longmen to Sanmenxia (45.1 percent), mainly centered in the Wei River basin, which has been one of the economic, cultural, and political centers for thousand years. The second highest area is from Huayuankou to the river mouth in Henan and Shandong provinces (13.2 percent). These are also two of the most densely populated areas in China. The headwater from the river source to Longyangxia has the lowest population at only 0.4 percent.



**Figure 16.** Spatial distribution of the population in the study area

During the past several decades, urban growth has far outpaced the general growth of population in all countries, both developed and developing (Helweg, 2000). China is also not an exception. With the growth of population and the development of economics, more and more people have and will continue to move into urban areas. The rapid urbanization has greatly boosted the domestic water uses. In rural areas, the rising income levels have enabled more rural households to turn to piped systems, and the amount of domestic water uses in rural areas has also increased significantly. According to Jin and Young (2001), the total annual domestic water use in China was only 1 km<sup>3</sup> in 1949. It then increased from 2 km<sup>3</sup> in 1965 to 20 km<sup>3</sup> in 1993. This amount further increased to 54 km<sup>3</sup> in 1998. In the Yellow River basin, the amounts of domestic water uses are 1.14

and 1.35 km<sup>3</sup> in urban and rural areas (including livestock uses) in 1990, respectively. These values have increased to 1.84 and 1.52 km<sup>3</sup> in 1993, and further reached 2.27 and 1.6 km<sup>3</sup> in 2001, as shown in Figure 17. Of the 3.87 km<sup>3</sup> of the domestic water uses withdrawn in 2001, surface water accounts for 37.8 percent and groundwater 62.2 percent (YRCC, 2003). In other words, nearly two-thirds of the domestic water resources were supplied by groundwater. As expected, the region from Longmen to Sanmenxia withdrew the highest share of domestic water for both urban and rural areas at 0.8 and 0.6 km<sup>3</sup>, and accounts for 36.4 percent and 39.2 percent, respectively. The region from Huayuankou to the river mouth is the second one after Longmen to Sanmenxia. The area from Lanzhou to Hekouzhen also withdrew much water for urban domestic uses (0.4 km<sup>3</sup> per year).



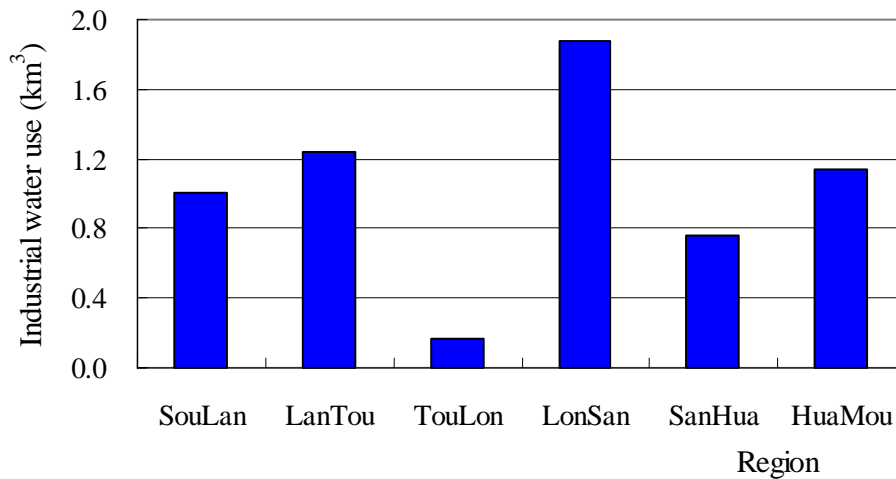
**Figure 17.** Domestic water uses in different regions in 2001

#### 4.2 Industrial Water Use

Industrial water use is usually estimated as a function of the industrial gross domestic products (GDP) and the specific industrial water use per GDP. The industry in the Yellow River basin has been developed rapidly over the last decades, and the amount of industrial water use has also experienced a drastic increase. Between 1980 and 1993, the industrial water use increased from 2.79 to 5.45 km<sup>3</sup> in the Yellow River basin, and this value further reached 6.19 km<sup>3</sup> in 2001. In the industrial water uses in 2001, surface water accounts for 45.1 percent and groundwater accounts for 54.9 percent of the total amount (YRCC, 2003). Although the rate of groundwater is not as high as that for domestic water uses (54.9 percent versus 62.2 percent), it also plays a major role for the industrial water supply in the Yellow River basin.

The spatial distribution of the industrial water uses in 2001 is given in Figure 18. Similar to the domestic water uses, the region from Longmen to Sanmenxia has the highest share of industrial water uses (30.4 percent); the region from Lanzhou to Toudaoguai has the second highest share (20 percent). The area from Toudaoguai to

Longmen has the smallest share (2.7 percent). The shift of the economic development from eastern to middle and western China implies that the Yellow River basin would become more critical as a source of water for the growing industries in the future.



**Figure 18.** Spatial distribution of the industrial water uses in 2001

### 4.3 Agricultural Water Use

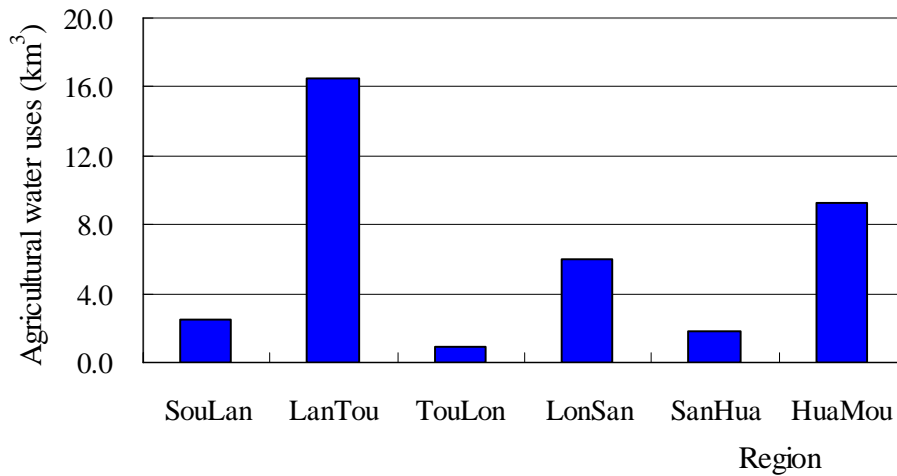
The amount of irrigation water use is a function of irrigated area, type of irrigated crop, and climatic conditions. According to Goklany (2002), agriculture accounts for 38 percent of the land use, 66 percent of the freshwater withdrawals, and 85 percent of the freshwater consumption worldwide. In the United States, it accounts for one-third of surface water withdrawals and two-thirds of groundwater withdrawals and is responsible for 85 percent of water consumption. The Yellow River basin is considered to be a typical agriculture area with approximately 85 percent of water being used by the agricultural sector presently. In the study area, there are a number of large irrigation districts, particularly in three regions – Lanzhou-Hekouzhen, Longmen-Sanmenxia, and Huayuankou-river mouth – where approximately 35.98 km<sup>3</sup> of water is used to irrigate about 5.28 million ha of land annually, which accounts for 88.3 percent of the total irrigated area and 88.4 percent of the total amount of irrigation water in the Yellow River basin, as shown in Figure 19 (Chang et al., 1998). Most of these irrigation districts have limited reservoir storage and depend largely on the daily streamflow in the river.



**Figure 19.** Spatial distribution of irrigated area in the study area

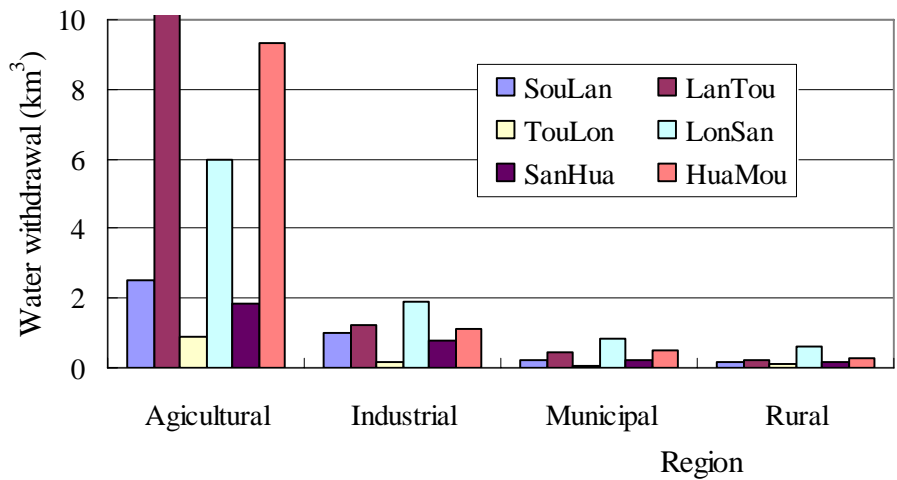
The irrigated area in the Yellow River basin was 3.78 million ha in 1980, and it increased to 4.1 million ha in 1993. But the water use for irrigation in the study area decreased slightly from 30.6 in 1980 to 29.9 km<sup>3</sup> in 1993. In 2001, the Yellow River provides 37.1 km<sup>3</sup> of irrigation water for the cultivated land inside and outside of the basin, in which 29.8 km<sup>3</sup> of water resources were consumed (YRCC, 2003). Figure 20 shows the amount of agricultural water use in different regions, and shows that the region from Lanzhou to Toudaoguai consumed the most water for agriculture with the share of 44.6 percent. The region from Huayuankou to the river mouth has the second highest share at 16.2 percent. However, the region from Toudaoguai to Longmen withdrew quite little water for agriculture and only accounts for 2.4 percent of the total amount of agricultural water in 2001. As in the other basin of China, surface water is the major sources for agriculture, and groundwater accounted for only about 20.9 percent of the total agricultural water in 2001.

Competition between agricultural and other sectors over the limited water resources in the Yellow River basin is likely to intensify in the future. The water use for irrigation in the study area will be expected to remain more than 50 percent of the total water use. Increasing the efficiency of agricultural water use, therefore, has the highest priority as it has a great potential in contributing to solve the water scarcity in the Yellow River basin. Improving the water use efficiency by cutting down losses of conveyance, evaporation and over-exploitation, on the one hand, and improving the agricultural yield per unit flow of water and unit area of land, on the other hand, will be a major challenge in the agricultural water resources management in the Yellow River basin.

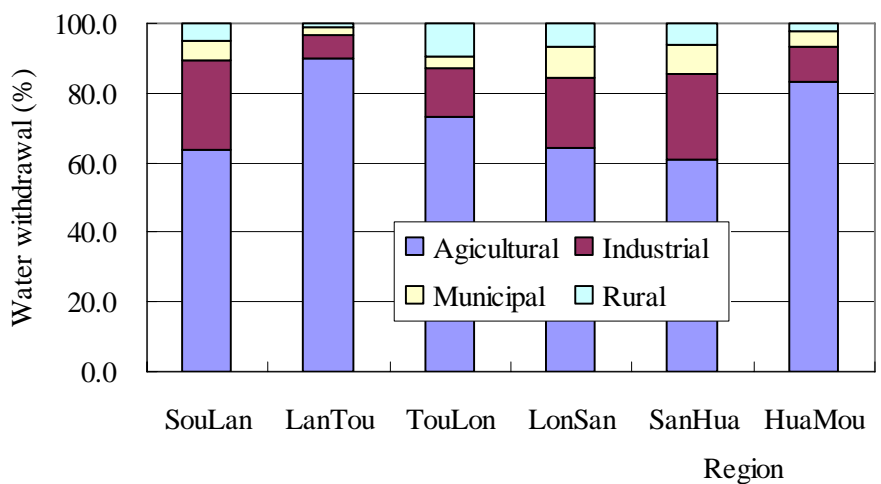


**Figure 20.** Agricultural water uses in different regions in 2001

In many parts of the world, the constraint on agricultural development is limited to the availability of irrigation water. This problem is particularly aggravated in arid and semiarid regions due to the fact that quantity and quality of the irrigation water supply are strongly associated with the variability of surface water resources (Mohan and Jothiprakash, 2003). The Yellow River basin where nearly 21 percent of the irrigation water is supplied by groundwater aquifer, without doubt, will also face the same problem in the future. Figure 21 shows the amount of water withdrawal (including surface water and groundwater) for different sectors in 2001 (YRCC, 2003). It can be seen that all regions have the largest shares for agricultural water uses. The largest one was found in the region from Lanzhou to Toudaoguai with 89.8 percent of the water was used by agricultural sector. The second highest share was found in the region from Huayuankou to the river mouth at 83 percent. Even the smallest one, found in the region from Sanmenxia to Huayuankou, reached 60.7 percent. The largest share of industrial water use among four sectors in six regions was found from the river source to Lanzhou at 25.6 percent, and the second largest one was in the region from Sanmenxia to Huayuankou at 25 percent, as given in Figure 22. The largest share of domestic water withdrawal for municipal and rural uses was found in the region from Longmen to Sanmenxia with the share of 15.6 percent, and the second largest share was found in the region from Sanmenxia to Huayuankou at 14.4 percent.



**Figure 21.** Amounts of water withdrawn by different sectors in 2001



**Figure 22.** Ratio of water withdrawn by different sectors in 2001

#### 4.4 In-stream Ecosystem Demand

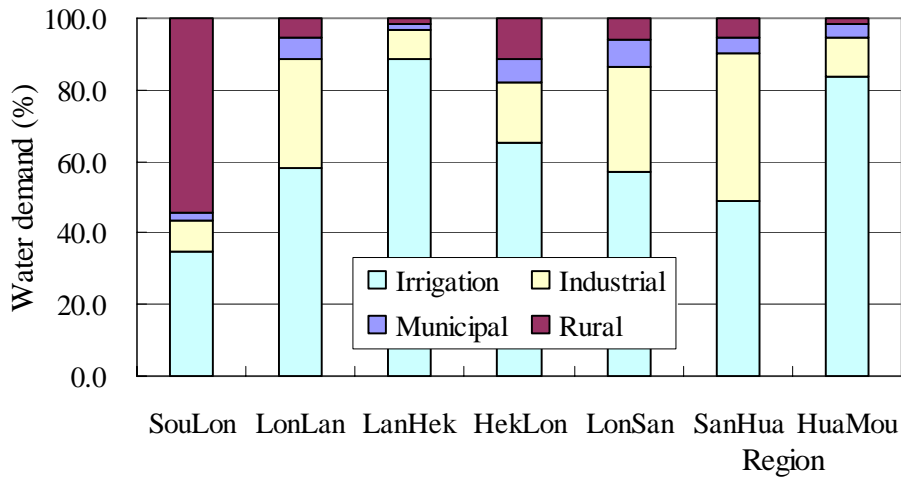
Traditionally, the ecosystem itself is rarely considered as a water user, although the healthy existence of the ecosystem clearly depends on adequate fresh water (Postel et al., 1998). Correcting this oversight is particularly important in the Yellow River basin, because the surface streamflow was over-allocated and there was little surplus left to sustain ecological functions. The reservoir operation has also been detrimental to aquatic ecosystems somewhere in the basin. Allocating water to the river system itself will be beneficial for the restoration of the ecosystem in the study area. The Yellow River is also unique in the world in that a significant amount of the discharge has to be allocated for sediment flushing. Some aspects of these issues have been partly neglected in the past

practices of water resources management and the ecological water requirements are not explicitly included in the previous sectoral water allocation in the Yellow River basin. It is estimated that a 15 km<sup>3</sup> of water is needed for sediment flushing, and 5 km<sup>3</sup> of water need to be maintained for biodiversity protection and sustenance of grasslands, wetlands, and fisheries at the mouth of the river. The ecological water requirement for the study area is then estimated to be over 20 km<sup>3</sup> annually (Zhu et al., 2004). This figure is about one-third of the historical runoff and nearly half of the average annual runoff over the dry decade of the 1990s.

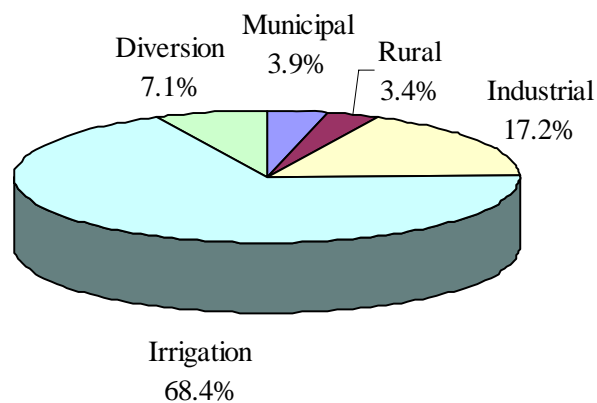
## **5. Projected Water Demand and Water Resources System Assessment**

In most regions of the middle stream and downstream reaches of the Yellow River basin, the groundwater resources are gradually being depleted, and the ability to successfully meet the demands of water for increased population without jeopardizing the ecoenvironmental systems will become increasingly difficult in the future. Several projects to divert water to the areas outside of the Yellow River basin are being implemented or are in planning. These projects have or will have a substantial impact on the streamflow regime of the Yellow River. Rapid urbanization in these areas will need to increase water supplies by transferring water from agricultural sector and by importing water into the area. Once surface water rights were completely appropriated, the transfer of water rights from agriculture to municipal and industrial uses will become one of the important selections to satisfy new demand on water (Crifasi, 2002). For the planning horizons in 2010, the future water demand is identified for domestic, irrigation, and industrial sectors. In order to estimate the domestic demand, population projections were used for low, medium, and high population growth rates and three different per capita demands were proposed (MWR, 1999).

Due to the space limitation, only the medium scenario is presented in this paper. Figure 23 shows the shares of the water demand for different sectors in various regions (Chang et al., 1998). Although the percentage of irrigation water has to be decreased in the future, several regions such as these from Lanzhou to Hekouzhen and from Huayuankou to the river mouth will still need much water for agricultural sector, both accounts for 88.4 percent and 84 percent. The smallest share is found in the headwater area from the river source to Longyangxia at 34.7 percent. Figure 24 further shows the shares of different sectors at the basin scale. The agriculture has the greatest share at 68.4 percent. The industry has the second greatest share at 17.2 percent, and the domestic sector will need 7.3 percent of the total water withdrawal, and another 7.1 percent of the water will be used by in-stream ecosystem and diverted to the regions outside of the Yellow River basin.



**Figure 23.** Shares of water demand over various regions for different sectors in 2010



**Figure 24.** Share of water demand for different sectors projected for 2010

When water shortage is assessed, available water resources must be estimated firstly. Depending on the occurrence probability, dry year ( $p=95\%$ ), medium dry year ( $p=75\%$ ), and average year ( $p=50\%$ ) are usually used to estimate the amount of water resources. Due to the space limitation, only the result for an average year will be given in this paper. Figure 25 gives a clear picture of the “low-scenario” water demand for an average year in the Yellow River basin in 2010 (Chang et al., 1998). The highest water demand is found in the region from Huayuankou to the river mouth, and the lowest water demand is at the headwater from river source to Longyangxia. There is a great difference between the water availability and water demand (Figure 13). The comparison of demand and availability shows a significant imbalance and indicates that demand should not be increased somewhere unless more water is made available through improved



management options. Figure 26 shows the amount of water shortage in different regions in the Yellow River basin.

The discrepancy between availability and demand of water will result in a 2.0 to 5.0 km<sup>3</sup> water shortage by the year 2010 (Chang et al., 1998; MWR, 1999). The major region in water deficiency will be from Longmen to Sanmenxia including the Fen River and Wei River basins, the center of economics in Shanxi and Shaanxi provinces. The region from river source to Lanzhou has enormous water availability with very low water demand. The unstable river-dependent water supply against demand from Lanzhou to Hekouzhen and from Huayuankou to the river mouth creates a need for storage space to trap the water, and new storage schemes need to be considered for this part of basin. These regions provide less than the amount of needed water, thus discouraging the increase of demand for water. A relatively larger volume of water availability from Sanmenxia to Huayuankou can accommodate increase in water demand in the near future, but attention is strongly required to manage the water demands in dry years/seasons.



**Figure 25.** Spatial distribution of the water demand in the study area in 2010



**Figure 26.** Spatial distribution of the water shortage in the study area in 2010

## 6. Discussion and Recommendation

A major challenge for water resources management in this century is to satisfy the growing demands for water while protecting the aquatic ecosystems upon which the humankind and economic development depend. The shortage of water in the Yellow River basin together with the Hai River and Huai River basins has posed a great challenge for the water authorities on both local and national levels in China. In the arid Yellow River basin with rapidly growing populations and economics, the challenge appears daunting. Water shortage in the study area has occurred for many years. Water diversion from outside the basin, like the South-North Water Transfer project, is quite necessary. Although the water shortage in the Yellow River basin will only be resolved from the construction of the West Route in the near future, both East and Middle Route will definitely decrease the burden of the Yellow River for transferring water to North China.

In addition, more effective and integrated water resources management considering both floods and droughts is urgently needed. In order to reduce the threat from the shortage of water resources in the Yellow River basin, conventional supply-oriented water resources management practices should be replaced with more effective demand-oriented management, particularly within the agricultural and industrial sectors. The additional water demand from the expanded population cannot be avoided but need to be minimized to an extent by adopting measures for a more effective and rational use and allocation of the limited water resources. The vision for water resources planning, development, operation, and management should be the development of policies and strategies that promote water conservation practice in the future. Adaptation strategies should be paid close attention in order to develop robust water resource systems and techniques, e.g., supply adaptation such as installing canal linings, changing location of

water intakes, using closed conduits instead of open channels, integrating separate reservoirs into a single system, using artificial recharge to reduce evaporation, and alternative management of existing water supply systems such as changing operation rules, using conjunctive surface/groundwater supply, changing priority of releases, and physically integrating reservoir operation systems.

The escalating water demands have been mainly satisfied by the construction of new reservoirs to date. Many dams have been built and more are being planned in the middle stream of the Yellow River. The rate of reservoir development in the Yellow River basin is higher than most of the major rivers in China, and the rate of water utilization is already very high. Most of the suitable sites for dams have already been used. At the same time, water demands continue to increase with ongoing growth of population, urbanization, and modernization processes. The study area is a typical basin where the increased demands for limited water resources are complicated by difficulties to manage a vulnerable ecosystem. The major challenges also include the high erosion rate of the Loess Plateau, the high sedimentation loads in the middle stream and downstream, the high flood risk in the downstream plains, and the increasing water pollution. Since the 1970s, less precipitation, soil conservation practices, and sediment trapping reservoirs have decreased the sediment loads. Recently, water shortage and water pollution have received more attention in the Yellow River basin.

The increased water needs throughout the basin are difficult to satisfy due to the high variability of precipitation in both spatial and temporal scales. Serious water scarcity frequently occurred. How to efficiently allocate the limited freshwater resources within the competitive sectors is a major challenge that is likely to receive increased attention in China in the future. Improvements in water allocation would enhance the aggregate benefits with the limited water supply. Water policies such as water pricing and allocation programs should encourage improvements in water resources management to reflect the water scarcity conditions. Meeting the needs of the present without compromising the needs of future generations will require a major economic, social, administrative, scientific, and political shift in the direction of sustainable development.

Opportunities still exist in the Yellow River basin to increase the efficiency of water use and allocation in ways that boost water productivity, output per unit of water, while at the same time providing sufficient freshwater for environmental restoration. Conservation, increased efficiency, recycling, and reuse are among the most cost-effective ways of meeting new water needs including ecosystem requirements (Postel et al., 1998; Al-Salihi and Himmo, 2003). For example, the potential for increasing the efficiency of water use in just one sector of the basin, the irrigation districts from Lanzhou to Hekouzhen, seems substantial. Most of the cultivated lands in this region are irrigated by flooding method, which are prone to substantial evaporation losses in arid climates. Only a few of the irrigated districts are watered by drip irrigation. With proper incentives such as taxes on freshwater over-depletion, improved irrigation efficiency would result in significant water savings. Pricing and policy reforms that promote investments in efficiency, conservation, reuse, and recycling are critical to moving toward sustainable water management, as well as to providing freshwater for rehabilitation and

protection of the fragile ecosystem. The demand-oriented water resources management, including different measures to improve water use efficiency on the distributive and consumptive level, such as changing the cropping pattern less consumable and more profitable crops as well as increasing the efficiency of the irrigation system within the agricultural sector, will make great contribution for the sustainable water resources development and management in the Yellow River basin.

## **7. Conclusion**

One important aspect to increase the water supply reliability in the Yellow River basin is the conjunctive use of surface water and groundwater resources. Integration of recharge and extraction of groundwater with surface water storage and utilization in a coordinated manner can substantially increase basin-wide water-use efficiency and reliability. Rational utilization of the surface water resources should be given priority. New water supply schemes should be investigated to store the excess water in wet seasons to increase the reliability of water supply in dry seasons. Promoting the conciliation of water rights during droughts on the basis of mutual concession will be another possibility to solve water scarcity. Because agriculture is a major water user in the Yellow River basin and the water use for irrigation is mostly consumptive, reducing the sensitivity of the agriculture to droughts, improving dry land management, diversifying agriculture crops, and selecting crop cultivation with strong tolerance to drought should be encouraged. In order to cope with drought effectively, the Yellow River basin should establish a system such as water bank so that the temporary water transfer between users can be made effectively during droughts.

Integrated water resources management is a complex and difficult task in the Yellow River basin, which is unique for its sediment issue. Keeping a good balance between the freshwater needed to flush sediment, the water resources required to augment the water supply within and outside the basin, and that needed to conserve the threatened ecosystems downstream presents a major challenge, which should be ranked as the number one basin-wide water resources management problem in the world.

## **Acknowledgements**

This study has been jointly financed by the National Key Study Project on Yellow River “973” (No.G19990436-01), Ministry of Sciences and Technology of China, and the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Corporation (JST) under the project “Sustainable development and management for water resources in Yellow River basin.” Part of the data has been provided by authors’ cooperators from China Institute of Water Resources and Hydropower Research (IWHR), Yellow River Conservancy Commission (YRCC), and the Ministry of Water Resources (MWR), People’s Republic of China. The opinions expressed here are those of the authors and not those of other individuals or organizations.

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