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Water problems and opportunities in the hydrological sciences in China

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Abstract This paper first summarizes the characteristics and distribution of water resources in China and then addresses the three major types of water problems from both historical and geographical perspectives. Major water problems, i.e. floods, droughts and water shortages, and water pollution, have tremendous impacts on the economic development and social well being in China. Analyses of water problems in the context of natural causes and human influences lead to the discussion of the role of the hydrological sciences in sustainable management of water resources, with an example of the preliminary findings of a study of water resources renewability in the Yellow River basin. Finally, challenges and opportunities for hydrologists are highlighted to present a brief summary and prospect on the development of the hydrological sciences in China.

Key words water problems; hydrological sciences; renewability of water resources; China

Problèmes liés à l’eau et opportunités pour les sciences hydrologiques en Chine

Résumé Cet article résume les caractéristiques et la distribution des ressources en eau en Chine et identifie les trois types majeurs de problèmes liés à l’eau, sur la base de considérations historiques et géographiques. Les problèmes majeurs liés à l’eau, en l’occurrence les crues, les étiages, les manques d’eau et la pollution, ont des effets énormes sur le développement économique et le bien-être social en Chine. L’analyse des problèmes d’eau en termes de causes naturelles et d’influences humaines mène à une discussion sur le rôle des sciences hydrologiques dans la gestion durable des ressources en eau. Nous nous appuyons en particulier sur l’exemple des premiers résultats d’une étude du renouvellement des ressources en eau dans le bassin versant du fleuve jaune. Finalement, nous mettons en évidence les défis et les opportunités qui se présentent aux hydrologues, ce qui permet d’identifier les perspectives d’avenir des sciences hydrologiques en Chine.

Mots clefs problèmes d’eau; sciences hydrologiques; renouvelement des ressources en eau; Chine

INTRODUCTION

Over the past two decades, China has increasingly attracted the world’s attention for a number of reasons. Since the implementation of its “reform and open door” policy in the late 1970s, China has achieved great economic success at a rapid and stable pace

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and meanwhile experienced enormous social transformation. As the largest developing country, China has a vast area of 9.6 million km^2 and relatively abundant natural resources. However, with the largest population in the world of nearly 1.3 billion, China is in a position of severely lacking many natural resources in terms of per capita availability. As its economy and population continue to grow, China will have to face greater and greater pressures on resources and the environment in the 21st century. Researchers and policy makers in China and from around the world have found more and more challenges and opportunities in studies of a wide range of sustainable development issues in the country.

Water is a highly precious resource in China and even becomes a limiting factor that plays a critical role in socio-economic development in many parts of the country. Since the Ministry of Water Resources completed a nationwide assessment of water resources in 1986 (MWR, 1987, 1992), a number of volumes have appeared in the Chinese language and have become major references in a variety of issues related to water resources from a national perspective. Qian (1991) edited a volume that addresses almost all aspects of water resources problems in China. As a result of research efforts for preparing China's Agenda 21, the United Centre for Water Research of the Chinese Academy of Science published a volume on water problems and strategies in China (Liu & He, 1996). Later, Zhang (1997) edited a volume specifically on the causes, characteristics, occurrence and trends of the flood and drought hazards in China; Zhang (1999) published an up-to-date treatment of the supply and demand analyses of water resources in China. Most recently, the Chinese Academy of Engineering completed a two-year effort and produced a series of nine volumes on strategic studies of water resources for sustainable development in China (Qian & Zhang, 2001). This series addresses a wide variety of important issues including the national assessment of water resources, analysis and forecasting of water supply and demand relationship, flood prevention and hazard mitigation, agricultural water demands and water saving for effective farming, sustainable development and utilization of urban water resources, pollution prevention and control for river, lake and ocean waters. It discusses ecosystem restoration and water resources protection and utilization, rational allocation of water resources in northern China and south-to-north water transfers, as well as water resources development and utilization in western China.

While the majority of the literature on water resources in China is in Chinese, a few publications are available in English and therefore accessible to the international readership. The English version of the *Water Resources Assessment for China* is the only comprehensive volume published so far (MWR, 1992). A number of articles on water resources in China are scattered in scholarly and professional journals published in English. For example, Chen (1985) discussed the characteristics of water resources and the situation of water resources development, conservation and management in China. In their work on the role of water as an indispensable resource for sustainable development, Zhang *et al.* (1992) analysed the reasons for shortages of water as a major challenge and discussed the opportunities for water resources development in China. Zhang & Zhang (1995) presented an analysis of five types of water issues and proposed a framework for sustainable development and management of water resources in China. More recently, Chen & Xia (1999) addressed water resources management problems in China, with an emphasis on the barriers to achieving sustainability, and proposed a number of solutions to deal with the challenges.

This paper aims to contribute an update and illustration to the English literature on these water problems and how hydrologists advance and apply their science to strengthen water resources management in China. A summary of the characteristics and distribution of water resources will be presented first to form the basis for understanding the natural causes of and human influences on water problems in China. Three types of water problems, i.e. floods, droughts and water shortages, and water pollution, will be addressed from historical and geographical perspectives. After a discussion of the role of hydrological sciences, the challenges and opportunities for hydrologists in the development of scientific disciplines and engineering practices for water resources management in China will be highlighted.

WATER RESOURCES IN CHINA

As the most populous country, China faces many resource problems and challenges, among them water is a critical issue. The characteristics and distribution of water resources in China, as discussed in many of the publications mentioned above, can be summarized as follows:

First, as a vast country, China has relatively abundant water resources and is ranked sixth in the world after Brazil, the Russian Federation, Canada, the United States and Indonesia in terms of absolute amount of annual runoff. However, given its large population of nearly 1.3 billion, China has a very low per capita amount (about one quarter of the world average) of water resources and, is therefore one of the

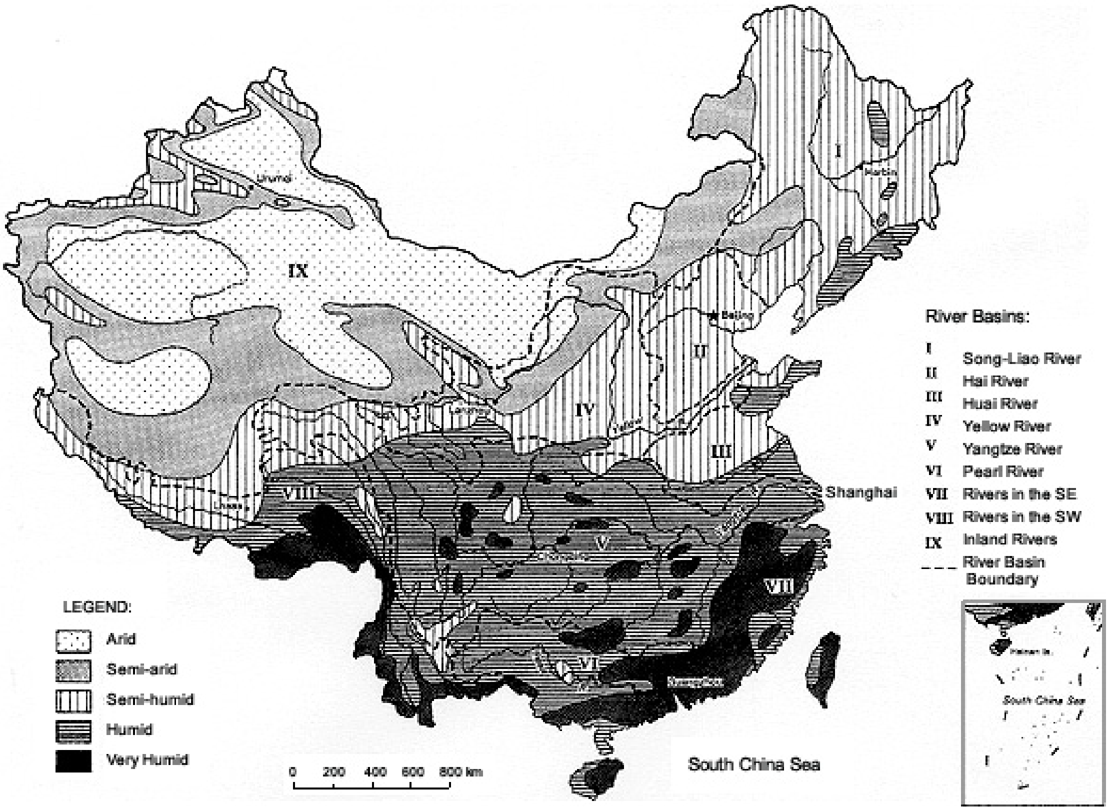

Fig. 1 Major river basins, water resources regions and availability of water resources in China.

countries with the most severe shortage of water in the world. In China, there are numerous rivers with a total length of 0.42 million km, of which about 1500 rivers drain a basin area of over 1000 km^2 each. Figure 1 shows the seven major river basins and nine water resources regions in China.

Second, due to the dominance of the monsoon climate, the temporal and spatial distribution of water resources is highly uneven. Very distinctive wet (April–September) and dry (October–March) seasons lead naturally to extreme seasonal variations in streamflow, as illustrated by the fact that around 60% of the streamflow occurs from April to July in southern rivers and in northern China over 80% usually occurs in the four months from June to September. Interannual variations of streamflow are also highly significant. Ratios of the maximum to the minimum annual runoff are usually greater than five and even reach 10–20 for northern rivers, and fall within 2–3 in the south. This is obviously the most critical factor causing recurring floods and droughts (sometimes in sequential years) in river basins across the country. Spatially, as one moves from the south and east coast inland, moisture transported primarily by the summer monsoon gradually decreases, leading to a fairly consistent southeast-to-northwest gradient of water availability from very humid to arid (Fig. 1). The great contrasts between several hydroclimatic indicators for the different regions are clearly shown in Table 1. Also presented is the percentage area of each region, indicating that nearly half (47.5%) of China's territory is classified as semiarid and arid.

Table 1 Availability of water in different regions and area of each region in China. Adapted from Lou (1998).

Region	Precipitation (mm)	Runoff (mm)	Aridity index*	Area (%)
Very humid	>1600	>1000	<0.5	7.8
Humid	800–1600	300–1000	0.5–1.0	26.1
Semi-humid	400–800	50–300	1–3	18.6
Semiarid	200–400	10–50	3–7	20.9
Arid	<200	<10	>7	26.6

* Annual potential evaporation divided by annual precipitation.

Third, the highly uneven spatial distribution of water resources does not match with the distribution of population and the agricultural land. As shown in Table 2, large portions of the population and farmland are located in northern China, where a small fraction of the water resources is available. This geographic mismatch is particularly severe in the Yellow River, the Huai River and the Hai River basins (Regions II, III and IV, covering about 15% of the country), where only 7.5% of the nation's water resources are shared by 34.7% of the population and 32.1% of the gross domestic product (GDP) is produced on 39.3% of the agricultural land (Zhang, 1999). By contrast, southern, especially southwestern, China possesses larger portions of water resources but relatively low population and little farmland.

The above summary of the characteristics and distribution of water resources in China is essential to analysing and understanding water problems and challenges in this populous and fast developing country. The low per capita availability of water, together with the highly uneven temporal and spatial distribution of runoff, has numerous implications for water resources development and management in China.

Table 2 Distribution (%) of water resources, population, farmland and gross domestic product (GDP) in China. Adapted from Zhang (1999).

Region	Water	Population	Farmland	GDP
Nation	100	100	100	100
Song-Liao River	6.9	9.7	20.2	11.3
Hai River	1.5	10.0	11.2	11.3
Huai River	3.4	16.2	15.2	13.7
Yellow River	2.6	8.5	12.9	7.1
Yangtze River	34.2	34.3	23.8	32.7
Pearl River	16.7	12.1	6.7	13.8
Rivers in the southeast	9.2	5.5	2.5	7.5
Rivers in the southwest	20.8	1.6	1.8	0.8
Inland rivers	4.6	2.1	5.7	1.8
Comparison between the north and the south:				
North*	19.0	46.5	65.3	45.2
South†	81.0	53.5	34.7	54.8

Note: data of 1993 as a percentage of the national total.

* Regions I, II, III, IV and IX.

† Regions V, VI, VII and VIII.

Most importantly, water is generally in short supply nationwide and the problem is particularly severe in the north and northwest. While water shortage problems often cause enormous hazards (especially for agriculture) in drought years, too much water may come in a very short period of time in other years, bringing about flooding disasters and tremendous economic losses and loss of life. The spatial mismatch between water resources and the population and agricultural land, together with frequent flooding and drought hazards, have resulted in an enormous need of building a water resources infrastructure extensively around the country. Besides the *quantity* aspect of water resources, water *quality* has become an increasingly important issue in China. As a result of rapid economic development and population growth, water pollution and degradation of aquatic ecosystems have caused massive damage to the functions and integrity of water resources. In summary, water problems and challenges in China include three major types: too much water—floods, too little water—droughts, and too dirty water—water pollution.

Legislation and government regulation have played a vital role in managing water resources and dealing with water problems in China. The fundamental and comprehensive water-related legislation in China is the Water Act which was promulgated in January 1988 after a long process of drafting and consultation for nearly ten years. Other major laws include the Water Pollution Prevention and Control Act of 1984 and the Flood Prevention Act of 1997. Since the People's Republic of China was founded in 1949, the country's administrative systems have undergone a series of changes and modifications as political and societal transformations and reforms have occurred over the years. Water management agencies are not an exception. Traditionally, the tasks of development, utilization, protection and management of water resources were split and handled by different government bodies including the Ministries of Water Resources, Hydropower, Urban and Rural Construction, Public Health, Transportation, Agriculture, and Geology and Mineral Resources. This situation is reflected in the saying "ruling waters by nine dragons". In recent years, water management tasks have been centralized under the Ministry of Water Resources, while other government agencies also have certain responsibilities for regulation and coordination, e.g. the State Environmental Protection Administration for the water environment and the Ministry of Public Health for drinking water quality. Besides the Ministry of Water Resources at the national level, there are now two major administrative systems in charge of water issues in China. One comprises the seven integrated basin management commissions, directly under the administration of the Ministry of Water Resources, for the Yangtze River, the Yellow River (also in charge of all inland rivers in the northwestern territory), the Huai River, the Hai River, the Pearl River, the Songhua and Liao River, and Lake Tai. The other is composed of the water conservancy departments and bureaux in charge of managing local and regional water resources at provincial, municipal and county levels. Many other government agencies concerned (e.g. those of Meteorology, Forestry, Energy, Land Management, etc.) play supporting and complementary roles for managing water resources across the nation.

FLOOD AND DROUGHT HAZARDS

China has a very long history of fighting against floods and droughts—major natural hazards recurring frequently. According to historical records, during the period of 2155 years from 206 BC to 1949 AD, large-scale droughts and severe floods occurred 1056 times and 1092 times, respectively. Compared to major drought and flood events recurring every two years on the average, hazards on a smaller scale have been witnessed more frequently. Floods and droughts of varying intensities occur around the country almost every year (Zhang, 1999).

The variability of the monsoon climate, topography and river drainage, sedimentation and human activities are the main factors affecting the occurrence and severity of floods. Rainstorms brought by summer monsoons and tropical cyclones or typhoons are usually the weather phenomena that cause floods in the low lands. Presently, one third of agricultural land and two thirds of cities are under the threat of floods and most flood control works can only protect against the floods with recurrence intervals of 10–20 years. Hence, economic losses caused by floods are enormous almost every year, e.g. the monetary figure was 800 billion Renminbi yuan (Chinese currency: US$1 roughly equals to 8.4 yuan) from 1993 to 1997, or about one fifth of the state revenue for the same period (Zhang, 1999).

The largest river in China, the Yangtze, has experienced many severe floods in the course of history. According to Lou & Le (1996), 23 severe floods occurred in the Yangtze River basin in the period of 153 years from 1840 to 1992, i.e. once every seven years on average. Major floods in the whole basin (especially in the middle and lower reaches) occurred on 11 occasions, i.e. 1848, 1849, 1870, 1924, 1926, 1931, 1935, 1948, 1949, 1954, and 1991. The 1954 Yangtze flood has been considered as the most disastrous in modern history. Due to the abnormal atmospheric circulation, the rain belt lingered persistently in the Yangtze–Huai River basin in the summer of 1954, leading to as many as nine long heavy rain storms covering large areas in June and July. The severity and destructive power of this biggest flood can be illustrated as follows. At the Hankou gauge of Wuhan City, the peak discharge and stage reached 76 100 $m^3 s^{-1}$ and

29.73 m (1.45 m above the historical highest water level), respectively. Flood stages at other control stations in the middle and lower reaches also surpassed the historical levels by 0.18–1.66 m. This exceptionally serious flood struck 123 counties and cities and inundated 3.17 million ha of land, forcing 188.8 million people to suffer and taking over 30 000 lives.

Since 1991, several serious floods have occurred in the Yangtze River basin. The 1998 great flood of the Yangtze was another extremely serious basin-wide disaster after the 1954 flood. From mid-July to late August 1998, a series of torrential rains fell in the middle reaches of the Yangtze River basin, leading to eight flood peaks coming one after another. The discharges and levels nearly reached those of the 1954 flood. A comparison of the maximum discharge of 1998 major floods, recorded from the upstream control station to the downstream station, with that of the 1954 great floods is shown in Fig. 2. Besides the Yangtze River basin, several other regions, including the Nen and Songhua rivers in the northeast, the Pearl River in the southern Guangdong Province and the Ming River in the southeastern Fujian Province were also seriously hit by historically rare floods. Nationwide in 1998, 29 provinces were affected to varying extents by flood hazards, which caused the inundation of 21.2 million ha of land and brought suffering to 223 million people at an estimated direct economic loss of 166.6 billion Renminbi yuan. Historical data indicate that big floods in China are very much comparable to the most serious floods of similar scales elsewhere in the world, which clearly demonstrates the severity and damage of flood hazards in China.

In contrast to floods bringing too much water, droughts and water shortages are another major type of hazard caused by hydrological extremes. Water shortages are a

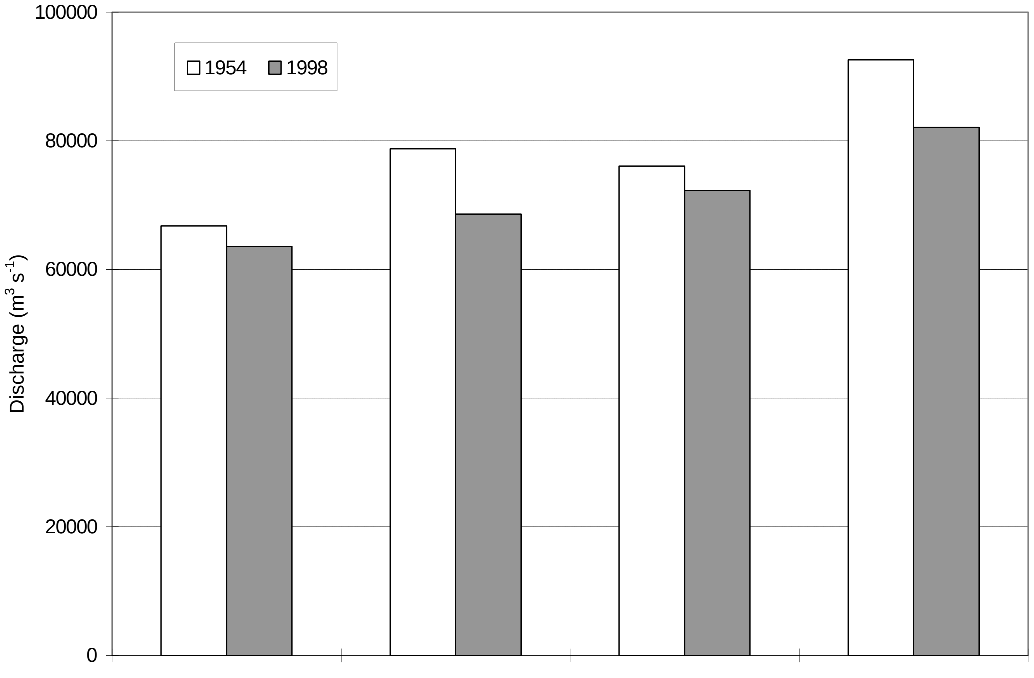

Fig. 2 Comparison of the maximum discharge of 1998 floods with that of the 1954 floods in the Yangtze River, China.

persistent and widespread problem, causing serious natural hazards mainly for the following three reasons. First, as discussed earlier, China is seriously deficient in water resources on a per capita basis nationwide and the water shortage is particularly distressing in the north and northwest. Second, interannual and seasonal variations of precipitation often cause floods in some years, but droughts in other years. Third, compared to regions at similar latitudes in the western side of the Euro-Asian continent where precipitation falls evenly throughout the year, in China the rainfall is highly concentrated in the summer and early autumn months. This has important implications for agriculture. The temporal coincidence of precipitation and warm temperature is beneficial to the growth of crops. However, it is also a disadvantage because drought problems arise every year in winter, and especially in spring, during and immediately after sowing, when water is in great demand for irrigation.

Droughts and water shortages have caused enormous problems to socio-economic development in China and have become one of the most crucial limiting factors in some regions. Agriculture is a vital component in the nation's economy and about 70% of the population live in rural areas. As a large agricultural country with rapid economic growth and industrialization, China still uses around 80% of its total water consumption for agriculture, but a large portion of irrigation water is wasted due to inefficiency and poor management. Hence, water shortage problems are extremely detrimental to the country's agricultural production and droughts are the most damaging natural calamities for agriculture.

Nearly half of China's 96.35 million ha of agricultural land do not have any irrigation works. With minimal drought-relief capabilities, these lands essentially depend on the weather and climate for agricultural production. In the past four decades, an average of 20.85 million ha of farmland (about 17% of the country's sown area) were afflicted by droughts each year, of which 8.67 million ha experienced severe productivity losses. The areas of agricultural land affected by droughts was over 30 million ha in exceptionally dry years such as 1959, 1960, 1972, 1978 and 1988 (Zhang, 1999).

Water shortages also seriously affect other sectors in China. More than half of China's cities (about 600) face urban water supply problems due to either lack of water source or poor water quality. Some of these cities have actually experienced water crises in dry seasons. The total amount of water shortages for domestic and industrial supplies is about 6 billion m^3 a year, affecting urban residents seriously and causing 120 billion yuan in lost industrial output (SPC, 1995). The causes of water shortages in China can be summarized as: (a) scarcity of water for geographical reasons, such as in the northern and northwestern parts of the country, (b) lack of engineering works and water supply systems which primarily applies to the mountainous region in the southwest, and (c) water quality constraints which are the critical factor, often exclusively, controlling the suitability of water uses in southern China, where sufficient amounts of water are normally available.

In recent decades, water shortage problems have been worsening in the Yellow River basin due to droughts and growing population pressures. The drying up of the middle and lower reaches of the Yellow River has attracted wide national and international attention. Wu *et al.* (1998) described the characteristics and variations of the dry episodes and found that decrease in runoff, increase in water use and massive waste of water are all responsible for reducing streamflow to zero for extended periods

Table 3 Statistics of zero-flow events at the Lijin station of the Yellow River. Adapted from Wu *et al.* (1998).

Years	No. of years during which zero flow occurred	Total no. of days during which zero flow occurred	Max no. of days with zero flow in a year	Max reach length with zero flow in a year (km)	Earliest date of zero flow in a year
1972–1979	6	86	21	316	23 April
1980–1989	7	105	36	662	4 April
1990–1997	7	717	226	700	7 February
1972–1997	20	908	226*	700*	7 February*

*The maximum values and the earliest date were recorded in the year 1997.

of time in some years. Since its first occurrence at the Lijin hydrological station in the lower reaches in 1972, zero flow in the mainstream was recorded on 908 days in 20 of the 26 years from 1972 to 1997 (Table 3). On average, dry events occurred in three of every four years and on average 45.4 days in each year. As shown in Table 3, over the years dry events in the Yellow River have become more and more serious as the number of zero-flow days, number of episodes and length of reaches affected have gradually increased and dry episodes have started earlier in the year. Also shown in Table 3 are the extreme records of 1997 when the worst situation occurred.

WATER POLLUTION AND ECOSYSTEM DEGRADATION

While countries and regions around the world face different water quantity problems, water quality has become a key issue, or sometimes even a limiting factor, that is common globally in water resources management. China is no exception, especially as water pollution has increasingly resulted from the rapidly growing economy and the rising population. In China's Surface Water Quality Criteria (Reference Code: GB3838-88), ambient water quality is divided into five categories based on an acidity level (pH) and maximum concentrations for 28 major pollutants. Grades I, II, and III permit direct human contact and use as raw water for potable water systems. Grade IV is restricted to industrial use and recreational uses other than swimming. Grade V is restricted to irrigation. Exceeding the pH or any of the concentration standards for a given grade disqualifies the measured water body from being designated as that grade.

Based on the national water quality standards, the water quality status of the nation's rivers, lakes and other bodies of water has been evaluated using monitoring data acquired by the State Environmental Protection Administration (SEPA) or the Ministry of Water Resources (MWR). Findings indicate that, generally, river water quality is better in the upper reaches than in the lower reaches, mainstreams have better water quality than tributaries, and urban streams are among the most polluted because they receive large amounts of untreated industrial and municipal wastewater (MWR, 1997; World Bank, 1997; Zhang, 1999). Another nationwide pattern of water quality distribution is that rivers in the south are generally cleaner than those in the north, because southern rivers generally have larger assimilative capacities due to the relatively more abundant runoff. Rivers and streams in economically more advanced regions in the east have poorer water quality than those in the less developed central and western territories. On the basis of drainage basins, the most severely polluted

Table 4 Water quality categories of rivers, lakes and reservoirs in China (data from Zhang, 1999).

Body of water	Length or number	Grade of water quality standards: I	II	III	IV	V	Beyond V
River*	98 614 km (100%)	6042 (6.1%)	25 773 (26.1%)	20 993 (21.3%)	27 171 (27.6%)	8 163 (8.3%)	10 472 (10.6%)
Lake†	50 (100%)	1 (0.1%)	9 (24.7%)	13 (23.6%)	7 (5.4%)	5 (26.6%)	15 (19.6%)
Reservoir‡	50 (100%)	0	33 (66%)	9 (18%)	2 (4%)	6 (12%)	0

* River length (percentage of length of river section for each water quality category in parentheses).

† Number of lakes assessed (percentage of lake surface area for each water quality category in parentheses).

‡ Number of reservoirs assessed (percentage for each water quality category in parentheses).

areas include the Hui River, the Yellow River, the Hai River, the Song-Liao River and the Lake Tai region in the lower Yangtze River basin (Zhang, 1999). These findings are clearly illustrated in the second National Quality Assessment of Water Resources which was conducted by the MWR in 1995. The assessment covered a total channel length of about 100 000 km on nearly 700 rivers and used water quality data from over 1800 monitoring stations around the country. As shown in Table 4, 46.5% of the assessed river sections did not meet Grade III standards and the length of these so-called "polluted" river sections had more than doubled since the MWR completed its first national water quality assessment in 1984 (Zhang, 1999).

Another water quality assessment by the SEPA in 1995 found that 34 of 66 urban river sections in the north and 18 of 69 in the south did not meet Grade V standards, rendering them waste sinks, and none of the 135 sections assessed was rated Grade I (World Bank, 1997). In rivers and streams, oxygen-demanding organic substances are the most common pollutants, while water pollution by toxic and accumulative synthetic chemicals as well as heavy metals is also very serious in many industrial areas.

Water quality problems of lakes and reservoirs are primarily associated with eutrophication caused by increasing concentrations of nitrogen and phosphorus (World Bank, 1997). Table 4 indicates that 51.6% (by surface area) of the 50 lakes assessed and 16% (by number) of the 50 reservoirs assessed were rated below Grade III standards, disqualifying these bodies of water as sources of urban water supply. From a regional perspective, organic pollution (measured mainly by chemical oxygen demand, i.e. COD, and ammonia concentration) is particularly serious in urban lakes in the south and in lakes on the northeastern plain, while salinization (excessively high mineral contents) is a relatively more common water quality problem for lakes in the northwestern arid regions (MWR, 1997). In recent years, tremendous efforts have been focused on water quality restoration for the three most seriously polluted lakes, i.e. Lake Tai in the Yangtze River Delta, Lake Cao in Anhui Province and Lake Dianchi in Yunan Province. As major sources of urban water supplies for many cities, reservoirs are generally well protected and therefore have better water quality. However, more attention must be given to the declining water quality of many small reservoirs (MWR, 1997).

In summary, as a result of rapid economic development and industrialization, as well as population growth, water bodies in China, with few exceptions, have been polluted to varying extents and water quality has deteriorated in the past two decades, with a significant portion falling below Grade III. Water pollution and degradation of aquatic ecosystems have drastically aggravated water shortages in the north, leading to crises in water uses for the agricultural, industrial and domestic sectors in many regions and cities. As mentioned above, since there are usually sufficient quantities of water in the south, water quality has often become the exclusive factor, which makes the water unusable. In recent years, China has made enormous efforts and massive investment to control water pollution and restore ecosystems. Water quality protection through enforced regulation and management, wastewater treatment and cleanup programmes have stabilized, or even reduced, pollution levels in some major rivers and lakes.

THE ROLE OF THE HYDROLOGICAL SCIENCES

Water problems have enormous influence on socio-economic development in China. Floods, droughts and water pollution are barriers to sustainable development and management of water resources. The hydrological sciences have played an increasingly vital role in the understanding of these problems and in finding solutions. Over the years, the Chinese government has made enormous efforts and investments in research and in the application of hydrological sciences, especially in recent years as the Yangtze floods and the drying up of the Yellow River have caused increasingly severe damages to the nation's economy.

While following international trends, the development of the hydrological sciences in China has demonstrated its own characteristics and uniqueness. Hydrologists face tremendous challenges and opportunities in studying flood and drought problems in China. Many scientific issues are involved, mainly including: (a) hydrological cycles and processes at a range of temporal and spatial scales, (b) influences of climate variability and change, (c) hydrological impacts of human activities, (d) engineering and non-engineering measures for flood control and drought prevention, and (e) the socio-economic dimensions in water resources management. Hydrologists in China have carried out, and will continue to carry out, numerous studies to investigate these issues and thus provide scientific evidence and solutions for dealing with water problems around the country. Not only traditional theories and methods, but also modern technologies, such as remote sensing and geographical information systems, have been used in hydrological research and engineering practices. It should be pointed out that China is still a developing country and has limited financial resources for research and development. Hence, efforts and funds at the central government level have been primarily targeted to key water problems of national significance. One good example is the state key project on the drying up in the Yellow River basin.

The Yellow River is the cradle of the Chinese nation. Because it drains from an arid and semiarid region, the Yellow River has a relatively small mean annual runoff of 58 billion m^3—less than one sixth of the flow of the Yangtze River. Availability of water resources in the Yellow River basin on a per capita and per hectare basis is only one quarter and one sixth respectively of the national average. Since water shortage is already a serious problem, needless to say, the dry episodes discussed above have been extremely detrimental to socio-economic development and environmental quality in the Yellow River basin. Understanding the dynamics and complexities of water resources systems in the Yellow River basin is vital in dealing with the drying up problems and necessary for placing water management on a sustainable track. Hence, in 1999 the Chinese government started a state key research project entitled "Evolution of laws of water resources and sustaining mechanism of water renewability in the Yellow River basin". Over US$4 million have been allocated to this, one of the biggest hydrological research projects ever mounted in China. A systems approach is adopted to investigate the hydrological cycle and the influences of human activities in order to find out answers to a series of important questions, such as "What are the key factors controlling the renewable capacities of water resources in the Yellow River basin?"; "How do these factors function in water resources systems?" and "How to quantitatively evaluate the renewability of water resources and their variations given natural changes and human impacts?" The research findings will offer a scientific base for understanding the causes and characteristics of the dry streamflow events and for developing strategies and measures for sustainable water resources management. To evaluate the renewability of water resources, a novel evolution model must be built to investigate the hydrological cycle and other water issues in a nature-human system.

Renewability of water *quantity* can be characterized as replenishment and recovery of water resources from supply of precipitation after losses through evaporation, runoff and withdrawal. It is directly related to the periodicity of the hydrological cycle and replacement rates of water bodies. Water renewability is always limited by many factors, among which low precipitation total, given the regional climate, plays a decisive role. When water withdrawal exceeds the rates of replenishment and recovery, the renewability of water resources is partially reduced or even completely destroyed, causing damage to regional hydrological cycles and ecosystems. Maintenance and protection of water renewability can only be achieved when consumption of water is controlled within the limits of the mean annual amounts of water resources. Obviously, water renewability is closely related to water uses and yields in a basin within a certain period of time. Therefore, factors such as climate, topography, soils, vegetation and human activities that control water uses and yields, will affect water renewability in many ways.

Renewability of water *quality* describes the ability of water bodies to self-purify after being polluted by natural or manmade sources. Similarly, the concept indicates that water has an assimilative capacity and polluted water may recover either naturally, or with human assistance, through a variety of water quality processes. When the assimilative capacity is not exceeded for certain amounts of pollutants or sewage discharge, water quality is able to recover and, hence, the renewability of water quality is maintained. Otherwise, water quality will deteriorate and the renewability of water quality will be damaged.

Naturally and closely tied to hydrological and water resources systems, the renewability of water quantity and quality cannot be evaluated without a full understanding of the hydrological cycle. In essence, the renewability of water resources reflects the effect of the hydrological cycle and is thus controlled by all elements influencing the water balance at a range of temporal and spatial scales. The basin, defined by natural drainage boundaries, is scientifically and practically important as a system for studying the hydrological cycle and managing water resources. Analyses of the system components and their interactions, as shown in Fig. 3, help hydrologists to formulate the following fundamental rules and relationships:

1. Comprising natural and manmade components, the basin hydrological cycle is mainly controlled by atmosphere–soil–vegetation processes, the storage and flow of rivers, lakes and aquifers and the water supply–use–drainage of human society.

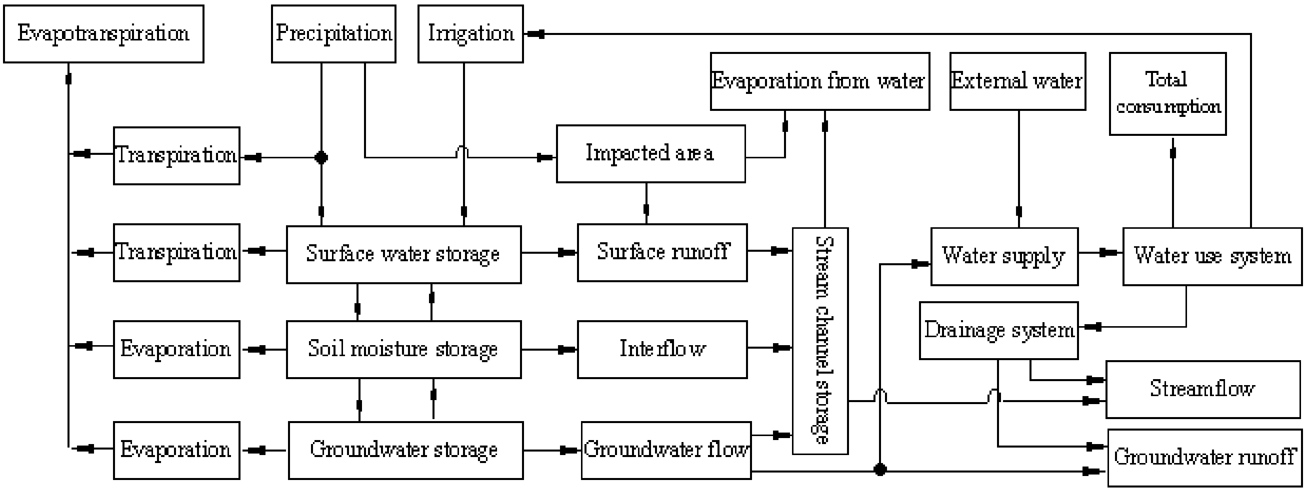

Fig. 3 Conceptual model of basin hydrology and water resources.

2. Water resources are available from sources within the basin and those derived from outside by inter-basin transfer.
3. Water resources consist of surface water and groundwater primarily derived from atmospheric precipitation.
4. Water resources are consumed through uses for agriculture, industry, domestic requirements and the maintenance of ecological and environmental quality.
5. Water gains (precipitation, water transferred from outside the basin) are always balanced with losses (evapotranspiration, total water consumption, surface water and groundwater runoff leaving the basin) when changes of basin storage are taken into account.

It is believed that distributed hydrological models, which account for the impacts of climate change and human activities, will be very useful for studying the renewability issues of water resources in the Yellow River basin.

DEVELOPMENT OF HYDROLOGICAL SCIENCES: OPPORTUNITIES AND PROSPECTS

Development of hydrological sciences is highly important to economic development and social well-being in China. As we enter the 21st century, hydrologists in China face many challenges and, meanwhile, have great opportunities to advance and excel in research and development. Advancement in science and technology is motivated by the needs of the society. Hydrology is not an exception and research efforts must be tied to the socio-economic development of the country. Across its vast territory, China experiences numerous water problems associated with tremendous complexities and variability. To reveal the causes and processes of floods and droughts in China, hydrologists must adopt a systems approach to studying the energy balance and water cycle at different time–space scales by using both field experimental and computer modelling techniques. Similarity and variability of hydrological regimes (low flows and floods) are important areas of study and research efforts on these topics will further discover the underlying causes and possible future changes of spatial heterogeneity and the temporal variations of water resources in China. Other focuses of hydrological research include climate change impacts on water resources, flood and drought forecasting and prevention measures, and the environmental assessment of water resources development projects (such as the Three Gorges Dam and the south-to-north water transfer).

Interdisciplinary studies of water problems offer excellent opportunities to advance theories and technologies in hydrological sciences in China. In the past two decades, a number of national key research projects funded by the sixth to ninth "Five-Year Plans" (1981–2000) were conducted for studying water problems, in particular sustainability issues in major water shortage areas in northern and northwestern China. Integrated water studies with multiple objectives for the economy, resources, the environment, ecology and management have made numerous important contributions to both decision making and the advancement of science and technology. It is worth mentioning that the importance of ecological issues in water studies (especially for arid and semiarid regions) has increasingly been recognized by hydrologists in China in recent years. Often with assistance of geoinformation technologies (mainly "3S"–GIS, remote sensing and GPS), many water experts have worked with ecologists and geographers to investigate important issues such as "ecological water demand" and "ecosystem restoration" within the framework of the emerging field of eco-hydrology. One excellent example is a recently completed ninth "Five-Year Plan" national key research project entitled "Rational Development and Utilization of Water Resources and Protection of the Ecological Environment in the Northwestern Regions". The project aimed to integrate social and economic development with ecosystem health protection to achieve rational allocation and effective utilization of the very limited water resources in the region. While progress has been made, the complexities and uncertainties of hydrological processes and systems will continue to produce enormous challenges to hydrologists. The success of these efforts will rely on many factors and inputs. Education and training of qualified water scientists and professionals is a vital task. In China, there are three types of educational institutions that offer hydrological and water science training at the undergraduate level and above. One type consists of the two specialized schools which are well known to many international colleagues: Wuhan University of Hydraulic and Electrical Engineering (recently merged with Wuhan University) and Hohai University in Nanjing. The other two types are the hydrology and water resources specialties in other universities, which are often part of departments of geography (e.g. Zhongshan University in Guangzhou and Nanjing University) and of civil or hydraulic engineering (e.g. Tsinghua University in Beijing and Sichuan United University in Chengdu). Hydrologists in China are encouraged to be more active in introducing our achievements in research to counterparts abroad and in pursuing international collaboration for studying the country's water problems.

CONCLUDING REMARKS

As the most populous and fast developing country, China faces many natural and anthropogenic problems in resource utilization and management. There are numerous water problems in China, which can be categorized into three major types—floods, droughts and water pollution. Due to natural causes and human influences, water problems are extremely complicated and highly variable (both temporally and spatially), given the enormous uncertainties associated with the hydrological cycle and climatic variations. Studying hydrological processes and the impacts of human activities is vital to the solution or prevention of water problems. The hydrological sciences have played, and will continue to play, an important role in developing and implementing strategies for sustainable management of water resources. One of the key sustainability issues is to fully recognize that water is a limited but potentially renewable resource and that the scientific assessment of the limited renewability of water resources will have tremendous technical and practical significance. As the economy and the population continue to grow, the importance and urgency of water problems will certainly increase in China. Hydrologists face both challenges and opportunities to advance scientific disciplines and engineering practices. The development of the hydrological sciences in China has been encouraging and is believed to promise more advances for the future.

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