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Assessment Report
of Climate Change Impact and Water Resources
of the Yellow River Basin

Yellow River Conservancy Commission
December, 2008

黄河流域
气候变化影响及水资源评估报告

（讨论稿）

水利部黄河水利委员会国际合作与科技局

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Part I Assessment Report

1 Impact of Climate Change on China

1.1 Climatic Elements

Overall, in china climate in recent 100 years is warming under the global warming background. Over the last 100 years, mean temperature in Chinese Mainland has risen significantly, with mean annual increment around 0.6 to 0.8 (Qin Dahe, 2005). Its change trend is in consistent with the overall trend of global climate, slightly higher than global or North Hemisphere warming trend. From the geographical point of view, temperature increment in North China and Northeast China is largest, up to 0.4 to 0.8 per 10 years, while that in the upper reach of Yangtze River and Southwest China declines slightly. There is no apparent cool-warm trend in most southern regions (Wang Shaowu, 1998). From the seasonal point of view, winter warming is greatest, for example, warming winter in China since 1985 has been appeared to be common. In recent 40 to 50 years, the lowest and mean temperatures in China both see a rising trend, especially in winter in northern regions. Meanwhile, frequency of cold wave and day number for low temperature both drop.

In 1951 to 1990, China mean maximum temperature rose slightly, minimum temperature rose markedly, daily range declined greatly, both extreme and mean minimum temperatures remained rising, especially in winter in north regions. Cold wave activity wore off. On an average, national frost days in the last 50 years dropped greatly down to about 2.4 days per 10 years. In the meantime, frequency for either thermal day or warming night increased, but that for cold day decreased, especially a sharp decrease for cold night (Zhai Panmao, 2003). Precipitation variation over the last 50 years shows that mean annual precipitation drops by 2.9mm per 10 years, but that in recent 10 years (1990 to 2000) increases slightly. For example, precipitation in most of North China, East Part of Northwest China, and Northeast China reduces significantly to about 20 to 40mm per 10 years. Precipitation in South China and Southwest China increases significantly to about 20 to 60 mm per 10 years. Precipitation in the west part of Northwest China also increases to some extent. Annual precipitation days in 1951 to 1995 remained decline, but precipitation intensity remained in upward trend (Qin Dahe, 2002, Wang Shaowu, 2000). As a whole, China total precipitation change is not evident, rain day region reduces, which means that precipitation process will have an intensified trend, leading to the increase of drought and flooding accidents, and especially in 1990, extreme precipitation proportion trended to rise. Annual precipitation in North China trends to decline, both extreme precipitation value and precipitation intensity trend to weakness, but proportion of extreme precipitation in gross precipitation still remains rising. According to data in recent 100 years, both drought and flooding changes are featured with apparent stages and abrupt change. China climate in the 20th century obviously trended to dryness. Two climate abrupt changes from dampness to dryness occurred respectively in the 1920s and 1960s. Yellow River basin has continued and aggravated dry spell since 1965.

Ding Yihui et al.(2006), by using domestically developed global air-sea coupled model (such as the NCC / IAP T63), by reference to IPCC which gives future greenhouse gas emission and concentration scenarios, integrating simulation results yielded from multiple models adopted by IPCC, had an pre-estimation of Climate Change trend in the next 20 to 100a in global scope, east Asia and China. His study showed that over the next 20~100a, Chinese surface temperature will increase significantly, an upward trend also in precipitation (Table 1.1). In 21st century, Chinese surface temperature will continue to rise, where warming increment in the North is more than in the South, and warming increment in winter and spring is more than in summer and autumn. Compared with the average value of climate, the average temperature in China will increase by 1.3~ .1 in 2020, 1.5~2,8 in 2030, 2.3~3.3 in 2050. It is estimated that the national average annual precipitation in 2020 will increase by 2% to 3% , 5% to 7% in 2050. The number of Precipitation days will see a significant increase in the North, but remain unchanged in the South. It is large in space-time variability of precipitation change, and different models give significant different results.

Table 1.1 Future Change of the surface temperature and precipitation over China (compared with average data of year 1961-1990)

Elements	2020	2030	2050	2100
Temperature change（ ）	1.3-2.1	1.5-2.8	2.3-3.3	3.9-6.0
Precipitation Change （%）	2-3		5-7	11-17

Some other Chinese scientists selected some of simulation results out of domestic and global climate models to further calculate China's Climate Change (Zhao Zongci, Xu Ying, 2002; Xu Ying, 2002; Zhao Zongci, 2003; Ding Yihui, Xu Ying, 2003) (Xu Ying, 2002; Ding Yihui, Xu Ying, 2003). The calculation results show that China warming over the past century may be affected by human activities, especially in the last 50 years. It is forecasted that future temperature in China is likely to warm by 1.5 ~2.8 ℃ till 2030, 2.3~3.3 ℃ till 2050, 3.9~6.0 ℃ till 2100. Of four scenarios, scenario A2 has a greatest increase in temperature. In given Scenario A2 and B2 based on global model, it is estimated that in different time of 21st century, the greatest warming are to be seen in the northeast, northwest and North China, up to 4~ 5 ℃ by 2100 (see table 1.2, 1.3). A number of model and emission scenarios show that in the 21st century China will continue to warm due to the increase of human emissions, and warming rate (3~5 ℃ / 100 years) is more evident than in the 20th century, especially in the north and in winter. Nationally, climate may become wet, especially in the Northeast and Northwest, but it is likely to be dry in Central China. As a result of increasing human emissions, winter monsoon in the East Asia may continue to weaken, but summer monsoon may intensify. It is forecasted that intensified summer monsoon may only reflect the impact posed by intensified water cycle under climate change background, which leads to an increased precipitation.

Table 1.2 Change of average temperature of every 30 years in the 21 century

forecasted by the Global Climate Model with the scenario of SRES-A2

Zone	Whole China	Northeast China	North China	Central China	East China	South China	Southwest	Northwest
2020	1.2	1.5	1.4	1.0	1.0	0.7	1.0	1.4
2050	2.6	3.5	2.9	2.4	2.4	1.9	2.2	3.0
2070	4.4	5.5	4.8	4.1	3.9	3.3	4.0	5.0
2100	5.6	6.9	6.1	5.1	5.0	4.1	5.0	6.3

Table 1.3 Change of average temperature of every 30 years in the 21 century forecasted by the Global Climate Model with the scenario of SRES-B2

Zone	Whole China	Northeast China	North China	Central China	East China	South China	Southwest	Northwest
2020	1.3	1.9	1.5	1.1	1.1	0.8	1.0	1.6
2050	2.5	3.2	2.7	2.2	2.2	1.8	2.1	2.9
2070	3.5	4.5	3.9	3.2	3.2	2.6	3.1	4.0
2100	4.0	4.9	4.2	3.6	3.5	3.0	3.6	4.4

1.2 Runoff of Rivers

Water Resources Information Center, Ministry of Water Resources (1996) , after studying Chinese typical river basins based on 4 GCM scenarios, believes that under future climate change scenario, the runoff in Songhuajiang River is much more likely to go up, that in Liaohe River is likely to either go up or down, that in Beijing-Tianjin-Tangshan Regions, the upper and middle reaches of the Yellow River and Huaihe River are much more likely to go down, that in Hanjiang River remains unchanged, that in Dongjiang River is likely to have a little loss, but annual runoff will has a larger rise. In North China, if the temperature rises by 2 ℃, annual runoff in Qinglong River, Tanghe River and Shahe River is likely to reduce roughly by 10% to 20%, that in Baihe River will has a 40% reduction. If rainfall is reduced by 10%, runoff in four small-and medium-sized rivers above mentioned will reduce by 15%~ 25%. The study of tropical areas shows that under identical climate amplitude of variation, both tropical and temperate regions have different responses, if the temperature rises by 2 ℃ and rainfall reduces by 10%, runoff in North China will reduce by 40% to 60%, while that in Wanquan River of Hainan Province will reduce by 25.6% (Fu Guobin, 1991). In some studies of climate change scenarios (2030) based on GCM simulation model, they applied hydrologic balance model and water resources integrated estimation model to study the potential impact of climate warming on annual and monthly runoffs, evaporation as well as water supply and demand balance. The result shows that climate warming posing a significant impact on water resources is expected to occur in Huang-Huai-Hai River Basin. Being the main source of water resources, annual water amount greatly relies its increase or decrease on variations of run-off and evaporation in flood season. Therefore, under future climate change scenarios (2030), the region's shortage of water will accelerate significantly. Concretely speaking, the shortage of water resources in Beijing-Tianjin-Tanggu of the Haihe River Basin will go up from current $1.6\times10^8m^3$ to $14.3\times10^8m^3$, that in Huaihe River from current $4.4\times10^8m^3$ to $35.4\times10^8m^3$, and that in the Yellow River Basin from $1.9\times10^8m^3$ to $121.2\times 0^8m^3$ (Wang Futong, 2002). Qu Jinhua (2007), by using HD and MPI models, reveals the impact of climate change on

China natural annual runoff in 2030. By 2030, natural runoff in most of river basins will see an increase, of which Liaohe River, Hekou Town to Sanmenxia section of the Yellow River, Dongting Lake water system, all coastal rivers in the west of Guangdong, all rivers in the east and south of Fujian and Minjiang River will see an increase by 11.64% to 14.64%, in addition to a likely aggravating flooding. In particular, runoffs in Liaohe River and Minjiang River from June to August of flood season are likely to rise by 9.3% and 18.9% respectively, the Maximum runoff of the latter may rise by 23% (Figure 1.1).

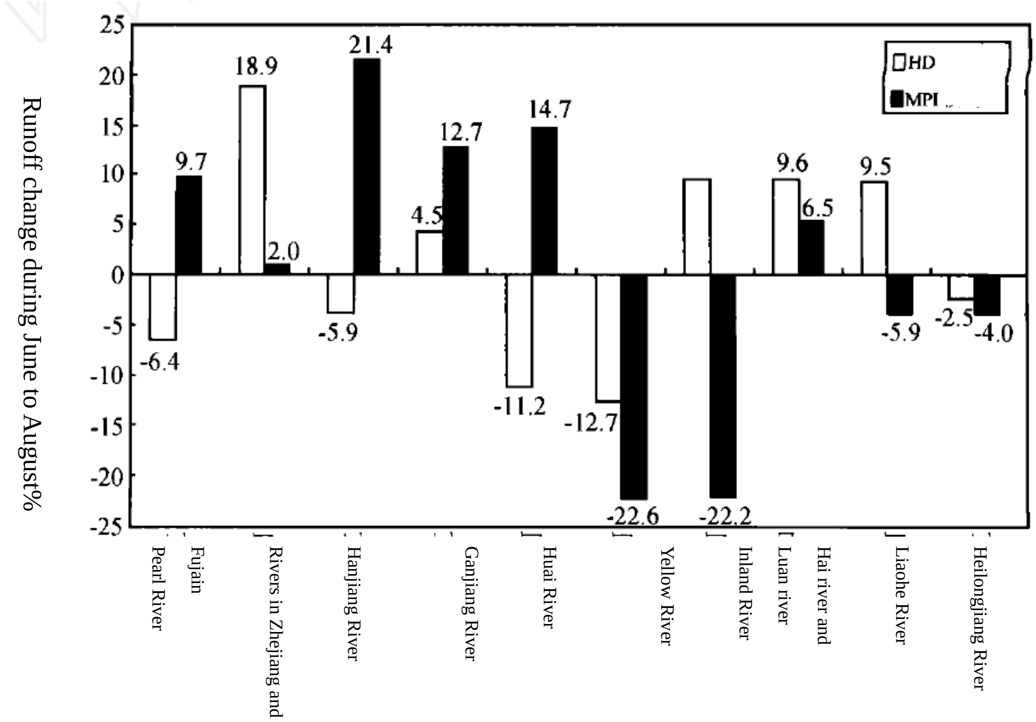


Figure 1.1 Runoff Variation Forecast in June to August of China Rivers

1.3 Evaporation

On the basis of future climate change model, average temperature in the Yellow River and its north area over the next 30 years is likely to increase by 2.0 ℃ (HD model) or 2.38 ℃ (MPI model), that in its south area increase by 1.8 ℃ (HD model) or 1.5 ℃ (MPI model). By 2030, China's average annual evaporation will increase by 3% to 15.1% (Table 1.4), in which that in the Yellow River and the continental rivers might increase by around 15% (MPI model), higher than increase rate of summer evaporation (Wang Shourong, 2003). Another study reveals that summer evaporation in northeast China in 2020 to 2049 is expected to increase by 4.3 to 5.4% and that in 2071 to 2100 will have a significant increase of as much as 12.3 to 14.4% (Qu Jinhua, 2007)

Table 1.4 Evaporation Variation Forecast of Rivers in China by 2030

River	All rivers in Zhujiang, Zejiang and Fujian	Hanjiang River	Ganjiang River	Huaihe River	Yellow River	Haihe River	Luanhe River	continental river	Liaohe River	Heilongjiang River
HD	4.0	3.0	3.8	3.5	5.6	13.0	12.5	6.0	6.6	8.6
MPI	3.1	3.0	3.1	3.3	4.8	14.8	5.1	15.1	6.0	11.5

1.4 Sea Level

Tian Guangsheng (1999), by using sea-level change forecast model, has a forecast of future seal level rise of five coastal regions in China, with results presented in table 1.5. By reference to sea-level rise scenarios published by IPCC in 1995 (in light of IS92a scenario), the simulation estimation indicates that the relative sea level along China coast will rise by as much as 4 16 cm in 2030, more optimistic by 6~14 cm; that in 2050 will rise by 9~26cm, more optimistic by 12~23 cm (Table 1.6) (Wang Futang, 2002)

Table 1.5 Prediction of Future Sea Level for Five Coastal Regions in China

Unit: cm

Region	Year		
	2030	2050	2100
Costal regions in Liaoning, Tianjin	13.1	22.5	69.0
Costal regions in Shandong Peninsula	1.1	5.7	40.2
Costal regions in Jiangsu and the east of Guangdong	15.5	25.4	73.9
Costal regions at Zhujaing River Estuary,	7.6	14.8	1.8
Costal regions in the west of Guangxi	15.3	25.5	74.2

Table 1.6 Estimated Rise of Seal Level in Five Coastal Regions in China under

Future Climate Change Scenario (2030 and 2050)

	2030			2050		
	Lower estimation	intermediate estimation	Higher estimation	Lower estimation	intermediate estimation	Higher estimation
Coastal regions in Liaoning and Tianjing	9.5	11.4	13.1	16.2	19.6	22.5
Costal regions in Shandong Peninsula	-2.5	–0.6	1.1	-0.6	2.8	5.7
Costal regions in Jiangsu and the east of Guangdong	5.5	11.5	13.5	19	22.5	25.4
Costal regions in Pearl River Delta	4	5.9	7.6	8.5	11.9	14.8
Costal regions in west Guangdong and in Guangxi	11.6	13.6	15.3	19.2	22.7	25.5

1.5 Moisture Contents of Soil

According to NCARGCM output (Zhang, 1993), China's annual average soil moisture content generally increases by 0~1%, but in the south of Yangtze River, central China and southern China, that has a larger increase ranging between 1% to 3 %; in the Yunnan-Guizhou Plateau, southern Sichuan Basin, western Guangxi, Shaanxi, Ningxia, eastern Gansu, eastern Hebei and coastal areas of Bohai Sea, that has a reduction ranging between 0% to 2%.

1.6 Grain Safety and Natural Vegetation

By 2050, except for Qinghai-Tibet Plateau, the north of northeast China where elevation is high, almost all other places will have a great change in cropping systems (Table 1.7). Currently, most areas with two cropping per year will be superseded by three cropping per year through different combination. The existing two-cropping areas will be moving north to the central region of current one cropping area. A great change for three cropping system is that its northern boundary will move north from the current Yangtze River to the Yellow River. Therefore, it can be said that climate warming will be beneficial to China's agricultural production (Wang Siu-tong, 2002) due to the diversification of cropping systems and the increase of multiple cropping index.

Tian Guangsheng (1999), based on China's future climate change scenarios in 2030, uses China forest productivity model to predict forest productivity and production. The result shows that changes rate of forest productivity increases from southeast to northwest. That is, the southeast has a small change in productivity, about 1%~2%, while the Northwest about 6%~8%, even to 10%. Another study reveals that by 2050, various vegetations will be moving north significantly, tropical rainforest in the south will expand, and boreal forest in northeast area and Tibet mountain vegetation in southwest area will be reduced. Northwest China (Xinjiang etc.) is much more likely to change from current temperate desert or grassland into a warm temperate or subtropical desert (Wang Siu-tong, 2002), see Table 1.8.

Table 1.7 Likely Change of Distribution Area for Planting System of Different Crops under 2005 Climate Change Scenario Simulated by Synthetical GCM Model

	Current Climate (1951～1980)	2050	Likely Change of Climate
One cropping system	62.3	39.2	–23.1
Two cropping system	24.2	24.9	+0.7
Three cropping system	13.5	35.9	+22.4

Table 1.8 Likely Change of Distribution Area for Distinct Natural Vegetation Type under 2005 Climate Change Scenario Simulated by Synthetical GCM Model

Distinct Natural Vegetation Type	Current Climate (1951～1980)	Climate in 2050	Likely Change（%）
boreal forest	2	0	-2
needle oil and broad leaf forests at temperate zone	7	6	-1
deciduous broad-leaved forest at warm temperate zone	11	11	0
broad leaved evergreen forest at subtropical zone	21	21	0
monsoon rain forest at Torrid Zone	1	7	+6
temperate grassland	16	11	-5
temperate zone desert	14	10	-4
Tibet mountain vegetation	28	20	-8
Undefined categories	0	14	+14

2 Impact of Climate Change on the Yellow River

2.1 Runoff

In the entire river basin, if calculated in light of 1919~1975 series of hydrological data, average natural runoff of the Yellow River for is 58 billion m^3. If calculated in light of 1956~2000 series of hydrological data, average natural runoff (Huayuankou Hydrological Station) is 53.28 billion m^3, reduced by 8%, Change trend of Natural runoff is in roughly consistent with precipitation change trend, overall in a declining trend (Figure 2.1), reduction of runoff is greater than precipitation.

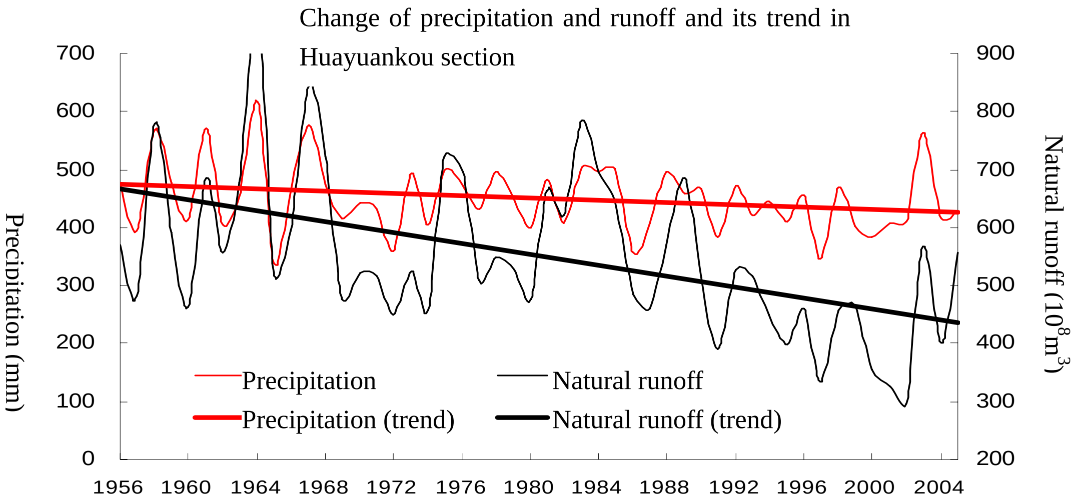


Figure 2.1 Change of precipitation and Natural Runoff in the Yellow River

Liu Changming (2003) believes that, as for control section of Lanzhou, surface runoff has an obvious reduction trend, but elements change in other water cycle is not very obvious. As for control section of Huayuankou, the natural runoff, surface runoff and underground runoff all have an obvious decrease trend, while precipitation, evaporation, interflow and soil moisture all trend to decrease. Based on WEP-L model, Wang Hao(2005) believes that, driven by "natural-artificial" dual mode, total average water resources of the Yellow River during 1980-2000 reduces by 3.1% in comparison with that during 1956-1979, of which surface water resources falls by 6.9%, but unrepeated groundwater resources increases by 21.4%. Huang Qiang (2002), based on annual runoff data of the Yellow River, adopts wavelet analysis approach to explore runoff evolution since the 1920s in the Yellow River and its driving force under binary model. He believes that, overall runoff change in the Yellow River basin may be classified as three stages as increase, slow decrease and rapid decrease. Among them, overall change of river runoff since the 1950s trends to a slower decrease. Ma Zhuguo (2005), based on runoff and climate data of upper, middle and lower reaches of the Yellow River, has an analysis of relationship between multi year annual runoff change law and climate change, and he believes that the runoff of the Yellow River has a significant change among years, the salient features of runoff from the 20th century began to decrease from the 1980s, but did not reach the lowest in history, the trend of declining runoff in the upper reach is more significant than the lower reach.

（2）Causes

From the perspective of climate change, Liu Changming (2004), based on historical materials about droughts and floods as collected by meteorological department in 1977 and *China Drought Chronology* published by China Institute of Water Resources and Hydropower Research, by reference to the *Yellow River Hydrological Yearbook*, has a comprehensive analysis and reveals the dry-wet characteristics of the Yellow River in 1470–1980. He believes that, since the late 15th century, the water flow change of the Yellow River has been dominated by negative anomaly, namely, the number of dry years is more than that of wet years. Shao Xiaomei (2007), based on meteorological information in 1961 to 2001 as collected by China Meteorological Administration, by the aid of GIS technology, uses Penman-monteith model as recommended in 1998 by Food and Agriculture Organization (FAO) to have an analysis of spatiotemporal distribution pattern with regard to climate moisture gain and loss of the Yellow River. She believes that the Yellow River being drought and lack of water is a universal phenomenon; overall spatial change regarding gain and loss quantity of climate moisture behaves in that the gain and loss quantity is gradually increased from south to north, from east to west, that in most parts of it ranges between 200~600 mm. Ma Zhuguo (2005) believes that the runoff change trend is basically in consistent with climate change trend, which indicates that multi-year, runoff change is mainly controlled by climate; In addition, dryness of basin surface is an essential reason for the reduction of runoff, temperature rising more accelerates the dryness of basin surface. Based on remote sensing data from 1982 to 1999, Yang Shengtian (2002) believes that climate in the Yellow River between the 1980s and the early 1990 is relatively humid, but relatively dry in the mid and late1990s.

From the perspective of renewable water resources, Li Chunhui (2005), using T0PSIS method for estimation, believes that main water-source areas such as above Longyangxia, Huangshui River, Taohe River and Weihe River are an area where it has strongest or stronger renewable water resources, but Beiluohe River is weakest, and the rest belongs to a neuter or weaker area.

From the perspective of using water resources, Wang Hao (2005) believes that the impact of water utilization on the evolution of water resources mainly behaves as follows: (1) changing the composition of water resources defined with a narrow sense. As water utilization captures river water and reduces river drainage of groundwater, which results in a significant reduction of river runoff and a significant increase of non-repetition groundwater resource. Although total water resources in the narrow sense is not much changed, but the change of water resources composition may produce a series of eco-environmental consequences, including issues such as the maintenance of river ecosystems and negative ecological environment due to over exploitation of groundwater; (2) increasing the use of effective precipitation mainly because water utilization causes the decline of groundwater level, thickening of vadose zone, which increases effective soil water resources and is conducive to the use of rainfall in situ. Tian Jinghuan et al.(2005) believes that a tributary of the large and medium-sized reservoirs built along the Yellow River Basin has accelerated runoff losses of rivers, and sees a loss of 770 million m^3 in water resources due to newly-increased surface evaporation. Zhang Xuecheng (2005), on the basis of annual series analysis with regard to surface water depletion of the Yellow River in 1956~2000, believes that annual average surface water depletion of the whole basin is 24.9 billion m^3 (of which diversion water outside the basin is 7,909,000,000 m^3, accounting for 31.8 percent of total river basin), that in 1980 to 2000 is 29.66 billion m^3(of which diversion water outside the basin is 10,830,000,000 m^3, accounting for 36.5 percent of the total). Overall inter-annual change regarding surface water depletion in the Yellow River Basin is: water use level in the 1950s and 1960s was relatively low, but in the 1970s rose steadily, in the1980s up to the peak, and in the 1990s trends to be stable. In the entire Yellow River, water depletion proportions in agricultural irrigation, industrial and living, rural industry, rural people and livestock under existing conditions are 90.8%, 7.5%, 0.4%, 1.3% respectively.

From the perspective of vegetation, increase trend of both vegetation area and coverage in the Yellow River is obvious. Gao Ge (2006) , after the analysis of annual average potential evapotranspiration in 1980 to 2000 and in 1956 to 1979, believes that, as for most areas in China, evapotranspiration rate in 1980 to 2000 was less than the previous period, but that in the Yellow River Basin increased. By reference to historical information, farming area in the Yellow River has been doubled over the last 3000 years, as shown in Figure 2.2. Li Yuchen(2006) believes that, vegetation in 1980 to 2000 was generally in upward trend, vegetation average NDVI increased by 11.69 percent during growing season, and it was in most obvious upward trend in spring and autumn. Based on NOAA / AVHRR NDVI data from 1982 to 1999, Yang Shengtian (2002) believes that vegetation cover in the Yellow River basin is generally in the upward trend. Moreover, the vegetation poses an important impact on runoff. Liu Changming (2004) believes that forest poses an important impact on annual runoff volume, especially significantly in reducing annual runoff and reducing annual surface (flood) runoff. However, the forest may lead to a slight increase of underground runoff. Wei Xiaohua et al. (2005) , with a view to water natural attribute, explores the consistency and complexity with regard to the relationship between forest change and runoff from aspects such as the impact of forest on runoff, interference threshold of forest in response and hydrological restoration. The consistency of relationship between forest change and runoff is mainly manifested in annual runoff which is represented by longer time scale. She believes that deforestation can result in the increase of annual runoff, if deforestation in the wasteland, can result in decrease of annual runoff. Wang Hao et al (2005) believes that the underlying surface change posing impacts on the evolution of water resources is mainly manifested in: (1) gross water resources in the narrow sense decreased by two billion m^3, of which surface water decreased by 4.1 billion m^3, non-repetition groundwater increased by 2.1 billion m^3. This is mainly because with the implementation of artificial measures, such as soil and water conservation, field training, terrace construction, it was not conducive to the contribution of surface water, and thus accelerated vertical infiltration capacity; (2) utilization of effective precipitation increased by 11.39 billion m^3, in which not only it utilized runoff water resources locally impounded, but also increased invalid inferflow and surface flow interception; (3) Gross water resources in broad sense increased by 9.4 billion m^3. Under the actions above-mentioned, water resources in river basin in the broad sense may have an increase to some extent.

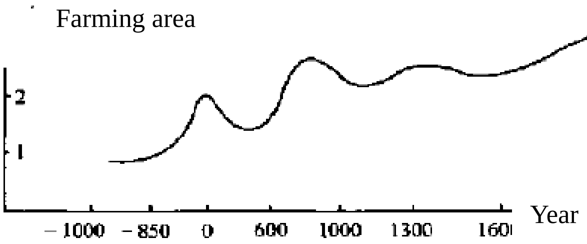


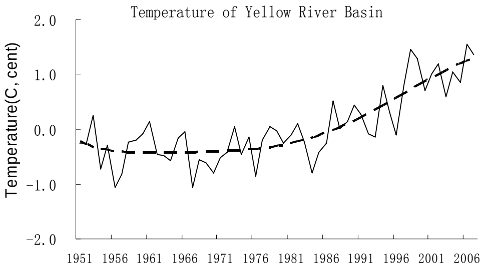
Figure 2.2 Area Change Trend of Agricultural Farming Region

Note: Only roughly illustrating the increase/decrease trend of agricultural farming region area due to the limitation by inadequate data and calculation approach.

From the perspective of soil and water conservation, Chen Hao et al. (2002) believes that since the 1970s, the role of rainfall in reducing water and sediment has continued to be weakened; with the improvement of water and soil conservation measures, the proportion of human activities' reducing water and sediment has continued to rise. In the 1970s, average water and sediment reductions due to climate fluctuation and human activities were 53.4%, 28.6% respectively, and in the 1980s were 46.6% and 71.4%.

2.2 Temperature

Temperature fluctuations in the Yellow River among multiyear is in upward trend, which is in consistent with global warming (Figure 2.3) (Jia Yangwen, the Third International Yellow River Forum). From 1961 to 2000, annual average temperature in the Yellow River rose by as much as 0.6 (Qiu Xinfa), of which warm trend in winter was very obvious, but that in summer was weakest.



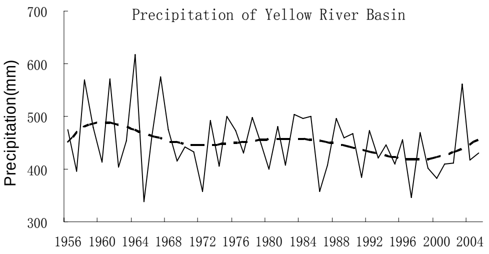


Fig. 2.3 average temperature change in the Yellow River

Fig. 2.4 precipitation change in the Yellow River

On an annual average, it was cool prior to the mid-1980s, but warm mostly after that; especially after the late 1990s, the warm weather continued to accelerate. The warmest year in the analyzed period is 1998. In winter, it was cool after the 1980s, down to a lowest temperature after 1968; in summer, cool and warm occurred alternatively prior to the 1970s, but cool dominated from the mid 1970s to the late 1980s; the climate continued to warm after the 1990s (Ren Guoyu, Climate Change and Water Resources in China). Lasting warm in the Yellow River began in the 1990s, after entry into the 21st century this trend is particularly significant.

Because of differences of geographical location, temperatures responsive to global warming in different regions within the basin are not the same. Among them, the biggest change occurs in river source area (Table 2.1). Over the last 40 years, average temperature in the upper Yellow River has risen by 0.32 , higher than global and Chinese average temperature rise rate (Lan yongchao, 2006); and that in areas above Tangnaihai in the 1990s is around 0.5 higher than annual average value(Shi Yupin et al. *Advances in Science and Technology of Water Resources*, 2005), the largest temperature increase occurred in Zeku area where average temperature increased by 0.58 , with average growth rate of 0.14 / 10a (Lan Yongchao et al. 2006)

Table 2.1 Temperature Fluctuation of Water Inflow in the Yellow River

Time	1956-1959	1960-1969	1970-1979	1980-1989	1990-2000
Entire river basin	6.2	6.1	6.2	6.2	6.9
Above Longyangxia	-1.5	-2.5	-2.4	-2.2	-1.9
Longyangxia to Lanzhou	1.7	1.3	1.4	1.5	2.3
Lanzhou to Hekou Town	6.6	6.8	6.9	7.1	8.0
Hekou Town-Longmen	8.2	8.3	8.3	8.3	9.3
Longmen to Sanmenxia	9.6	9.7	9.7	9.7	10.4
Sanmenxia to Huayuankou	12.6	12.9	12.9	12.7	12.5
Below Huayuankou	12.2	12.6	12.5	12.5	12.1

2.3 Precipitation

Annual average rainfall in the Yellow River is 447mm (1956~2000 series), precipitation from southeast to northwest gradually reduced (Figure 2.5). Multi year rainfall variation in the Yellow River is large; the less rainfall becomes, the larger the variation is. Both the uneven distribution of seasonal rainfall and large inter-annual variation lead to frequent floods and droughts.

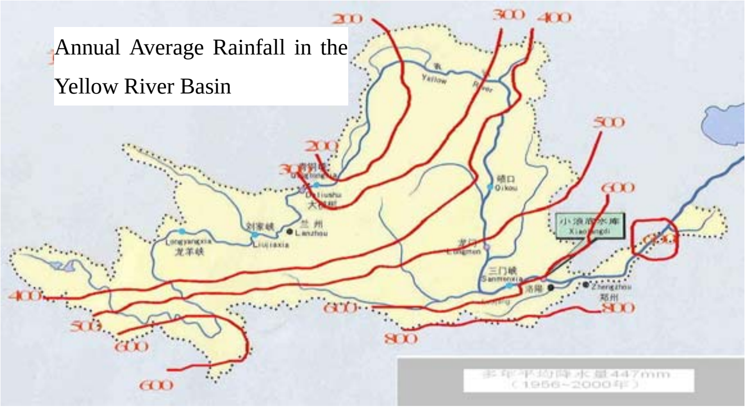


Figure 2.5 Isoline of Annual Average Rainfall in the Yellow River

Rainfall fluctuations in the Yellow River as a whole are in downward trend (Figure 2.4), with least precipitation in the 1990s, but a slight increase since 21st century. From the prospective of inter-annual variation, the largest temperature change occurred in the 1980s and the 1990s, especially in the 1990s up to 0.7 (relative to the 1980s) (Qiu, Xinfa, Natural Resources Journal, 2003; Jia Yangwen, Third Yellow River International Forum, 2007). Annual average temperature in areas above Tangnaihai in the 1990s was about 0.5 higher than usual average value, and 0.7~ 0.8 higher than the previous period; Meanwhile, annual average rainfall was not only less than annual average value, but significantly less than the previous period, especially in Maqu region down to 15.8% (Shi Yupin, *Advances in Science and Technology of Water Resources*, 2005).

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Both annual rainfall and seasonal rainfall in the Yellow River fluctuate in downward trend (Table 2.2). From an annual average, the rainfall before the 1970s was more and in greater amplitude, but in 1964 down to the least; however, after that was in less amplitude. Rainfall in the mid and late 1970s was more, but in less amplitude. Rainfall since the 1990s has become less. Based on MK check of regional annual average rainfall standardized sequence in 1956-2002, it shows that rainfall in the Yellow Rive since the 1970s has continued to decrease (Ren Guoyu, Climate Change and Water Resources in China, p69). Pang Aiping (2008), based on data monthly monitored in 827 monitoring stations in 1951-1998 which focuses on the spatial movement of typical precipitation isoline 200, 400 and 800mm, believes that Loess Plateau along the Yellow River trends toward dry significantly, the typical rainfall isoline moves south. After the analysis of spatial change with regard to rainfall during flood and non-flood seasons over 1980–1998, it is found that the largest decrease of precipitation occurred in Loess Plateau and the lower reach of the Yellow River, but in the source of the Yellow River, Yiluo River, source and lower reach of Fenhe River trends upward. Meanwhile, change trend between rainfall in flood season and rainfall in non-flood season is not full consistent in space sense.

In short, the source area and the upper reach of the Yellow River has reduced to some extent since the 1990s, temperature rose significantly, which leads to a sharp drop of runoff and increase of drying-up days. So, the water inflow is the primary cause to affect water resources in North China (Huang Ronghui, Climate Change and

Environment, 2006)

Table 2.2 Temperature Change for Main Reaches of the Yellow River

(Unit: mm)

Reaches	1956-1959	1960-1969	1970-1979	1980-1989	1990-2000
Entire river basin	477.0	471.3	446.1	445.4	422.7
Above Longyangxia	460.4	494.2	482.0	507.2	468.8
Longyangxia to Lanzhou	476.3	491.6	487.3	480.4	459.7
Lanzhou to Hekou Town	288.9	277.3	269.5	243.3	262.2
Hekou Town-Longmen	510.6	463.6	427.9	415.6	397.3
Longmen to Sanmenxia	585.4	578.4	532.7	553.6	492.3
Sanmenxia to Huayuankou	738.5	685.0	639.9	671.7	606.1
Below Huayuankou	697.2	680.3	645.7	564.4	660.0

2.4 Evaporation

In the Yellow River, arid and semi-arid climate dominates, rainfall is little and seriously uneven in spatiotemporal distribution, in addition to robust evaporation. Annual evaporation may reach around 1100mm. The greatest evaporation areas are detected in the upper reach of the Yellow River in Gansu, Ningxia and Inner Mongolia, central and western regions are the largest domestic evaporation in the region, and the biggest annual evaporation is more than 2500mm.

Surface evaporation of the Yellow River changes greatly, depending on temperature, terrain, geographic location. Above Lanzhou is dominated by forests of Qinghai Plateau and the Shishan Mountain, with average surface evaporation of 790mm. From Lanzhou to Hekou Town, the climate is arid with little rainfall, dominated by desert and steppe, average surface evaporation being of 1360mm. From Longmen to Sanmenxia, the area is large, across nine longitudes from east to west, both underlying surface and climatic condition experience great change, with average surface evaporation of 1000mm. From Sanmenxia to Huayuankou, average surface evaporation is 1060mm. Below Huayuankou is the alluvial plain of the Yellow River, with surface evaporation of 990mm. inter-annual climatic conditions of the Yellow River changes little, so does inter-annual surface evaporation. The ratio of maximum surface evaporation to the minimum ranges from 1.4 to 2.2, most at around 1.5; Cv value ranges from 0.08 to 0.14, most at around 0.11 (see Table 2.3) (Zhang Xuecheng, *Investigation And Assessment of Yellow River Water Resources,* 2006).

Table 2.3 Characteristic Value Statistics Regarding Evaporation From Water Surface of Long Series Representative Station

Unit: mm

Station	Annual average value	Cv	Maximum	Year	Minimum	Year	Maximum /minimum	Note
Minhe	968	0.14	1352.5	1965	841.8	1992	1.6	
Huzhu	802	0.09	963.6	1956	657.1	1964	1.5	
Dangyangqiao	1863	0.19	2724.3	1983	1213.1	1967	2.2	φ20 Series
Taiyuan	1580	0.08	2080.0	1955	1427.5	1964	1.5	φ20Series
Linfen	1800	0.11	2274.8	1960	1466.6	1964	1.6	φ20Series
Shenmu	921	0.12	1096.7	1999	721.8	1996	1.5	
Zhaoshiyao	951	0.11	1100.8	1987	718.5	1992	1.5	
Linjia Village	769	0.10	942.8	1997	669.7	1993	1.4	
Jiaokou River	942	0.12	1124.8	1997	730.3	1983	1.5	
Linkou	721	0.13	865.7	1981	580.0	1993	1.5	

Many observing and studies show that pan evaporation of the Yellow River in recent 40 years trends downward (Figure 2.6), sharply drop in spring and summer (Xu Zongxue, Hydrology, 2005). Local climate change of the Yellow River is not fully synchronized with the whole river basin, for example, the Yellow River upstream and downstream pan evaporation trend downward, but the middle reaches is flat or of a slight upward (Qiu Xinfa, Natural Resources Journal, 2003). Guo Jun (Water Science Progress, 2005) believes that the evaporation of Huang-Huai-Hai Basin over the last 50 years has dropped significantly, which is likely directly caused by the reduction of both sunshine time and solar radiation, in addition to the reduction of both, average wind speed and daily temperature range also plays an important role.

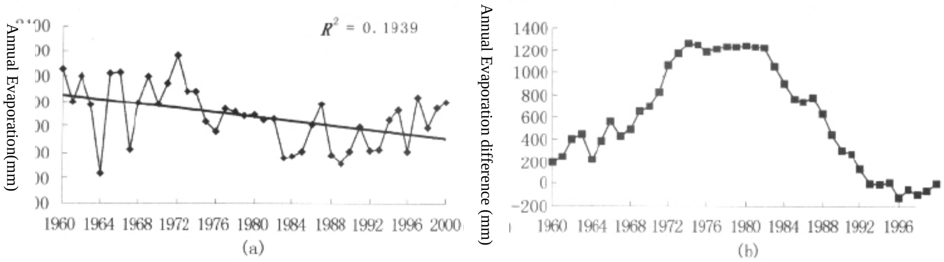

Figure 2.6 Characteristic Change Curve for Pan Evaporation of the Yellow River in 1960~2000

Contrary to pan evaporation, actual evaporation of the Yellow River increases with years. Li Lin (Weather, 2000) believes that the increase of sunshine hours, temperature and saturation deficit in the upper reach of the Yellow River accelerates the increase of grassland evapotranspiration, subsequently, both increased evapotranspiration and decreased precipitation directly result in the reduction of water flow in the upper reach and the expansion of grassland desertification. Sun Rui (Natural Resources Journal, 2003) in his study reveals that multiyear average evapotranspiration of the Yellow River changes greatly, the maximum of it is in the southeast, and then followed by that above Lanzhou, and the minimum occurred in Ningxia-Inner Mongolia section and E'erduosi Plateau. Xu zongxue (Hydrology, 2005) believes that annual average evaporation of the Yellow River features in gradually reduced distribution from the northeast to the southwest. The reduction of water surface evaporation is concerned with sunshine and solar radiation as temperature rises. Mai Miao (Weather, 2006) in her study concludes that, sunshine percentage throughout the river basin trends downward significantly, and annual average sunshine percentage in the 1990s dropped by 2.49 percent in comparison with that of the 1960s; Evident sunshine percentage drop is seen mainly in the summer and winter, few in spring and autumn.

Many studies show that pan evaporation trends downward, but the actual evaporation increases significantly; space characteristics of evaporation change varies greatly, the reasons may be related to selected information. According to some analysis (Liu Changming, *Advance in Water Science,* 2004), the decline in pan evaporation is mainly resulted by the decline of global radiation. Actual land surface evaporation of the Yellow River increasing significantly is caused by the increasing irrigation water consumption. Despite the weakening of solar radiation, but in more arid areas, water supply conditions are an essential factor to decide land surface evaporation.

2.5 Groundwater

Annual average groundwater resources volume of the Yellow River in 1980~ 2000 is 37.76 billion m^3, of which groundwater resources volume whose total salinity is no more than 1g/L is 35.23 billion m^3, accounting for 93%, while that whose total salinity ranges from 1g/L to 2g/L is 2.53 billion m^3, accounting for 7%. Among groundwater resources of the Yellow River, groundwater resources volume in Hilly Areas is 26.5 billion m^3, in plain area 15.46 billion m^3. The re-computation quantity between Hilly and plain areas is 4,200,000,000 m^3 (Pan Qimin, 2007).

2.6 Sediment

Annual average sediment of the Yellow River is about 1.6 billion t, and annual average sediment load 37.6kg/m^3, in addition to a highest sediment load of 920 kg/m^3 that ranks the first in the world. The sediment source of the Yellow River is relatively concentrated, featuring "different sources of water and sediment ". Source area of the Yellow River (above Tangnaihai) have an area accounting for only 15% of the whole river basin, containing very little sediment, but annual average runoff accounts for 1/ 3 of the total, and it is an important water-creating area for the Yellow River and so called "water tower of the Yellow River". The sediment mainly comes from the middle reach of the Yellow River (Hekou Town to Huayuankou), accounting for more than 90% of the total. The coarse sandy soil region covering an area of 78,600 km^2 in the middle reach of the Yellow River plays a critical role in heavy in soil and water loss, The area may yield sediment as much as 900 million t.

The outstanding issue for the Yellow River sediment is related to the uncoordinated relationship between water and sediment (Li Guoying, major issues and countermeasures of the Yellow River, 2001). The uncoordinated relationship results in sedimentation, raises riverbed, aggravates "Secondary Suspended River", drops flood control capacity of water resources project, bring more vulnerability to climate change and triggers floods. Since 1986, sediment load has fallen by nearly 40%, which benefits from recent few heavy rains on the one hand, and comprehensive management measures regarding water resources and soil conservation in the upper and middle reaches on the other. However, comprehensive management measures under heavy rain plays a weak role, so the decline of sediment load is not stable. In this reason, in usual years the water inflow reduces greatly, but in years with high-intensity heavy rain, high-sediment flood may occur which results in high sediment load, so polarization trend exists. (Zhang Xuecheng, Water Resources Assessment of the Yellow River, 2006)

It should be noted that, in spite of enhanced impact of human activities in Loess Plateau area, and some regions even bigger the impact of climate change on water and sediment. However, the characteristics in the middle reach of the Yellow River, such as scarce rainfall and sparse vegetation, show that its water resource is sensitive to climate change, especially to precipitation change, so the study regarding the impact of climate change on water and sediment is very important.

2.7 Extreme Hydrological Value

Storm flood of the Yellow River mainly comes from the middle reach to Hekouzhen and the reach above Lanzhou. Among them, storm flood from uncontrolled section of Sanmenxia-Huayuankou section is the most serious and one of the focuses of study on climate change. Since the 1980s, storm flood in the upper and middle reaches has dropped significantly in magnitude and frequency (Figure 2.7). Since the 21st century, few floods above $5000m^3/s$ have occurred. If the flood at Huayuankou whose peak flow is greater than bankfull flow is regarded as a floodplain flood in the lower reaches, it has occurred for 9 times since the 1950s, nearly once a year; but it only occurred for 3 times in 15 years from 1986 to 2000. From 2002 to the water and sediment regulation in this year, the largest peak flow in the lower reaches is only $4200m^3/s$. Both Climate change and the regulation of water conservancy projects may affect the flood frequency and intensity

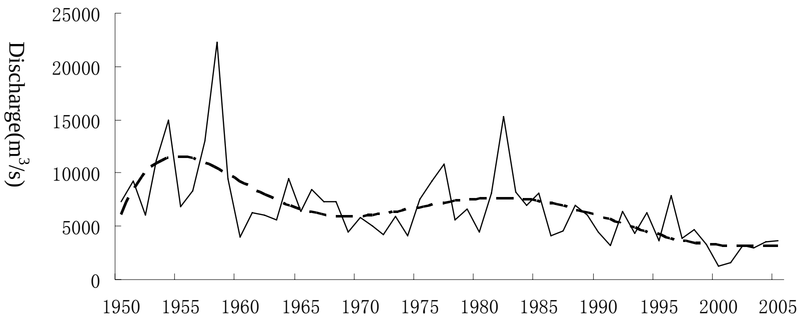

Figure 2.7 Annual Maximum Peak Flow Change at Huayuankou Station

Both drought and water shortage are main issues of the Yellow River. By reference to observed data, the Yellow River has continued to dry since 1965, aggravated and expanded since the 1990s. The reduction of water inflow as resulted from climate change plays an important role in the drought of the river basin.

There is a large Latitude difference along the Yellow River. The ice flood exclusively occurring in the Yellow River can not be found in other rivers. Ice status in Ningxia-Inner Mongolia section and the lower reaches is most serious, easily swamped. Since the 1990s, winter temperature in the Yellow River is significantly high, and ice status in Ningxia-Inner Mongolia section has new features, behaving in: number of freezing-up day is reduced, freezing-up date and breaking-up date is instable, which aggravates the difficulty in forecasting; "hanging river on the ground "develops, water level during breaking-up continues to rise (Figure 2.8), which aggravates embankment protection pressure. During ice flood period in 2007~ 2008, water level of Sanhuhekou at Ningxia-Inner Mongolia section reached as much as 1021.22m, 0.41m above the highest historical water level, which resulted in a breach occurring in Inner Mongolia Hangjinqi section.

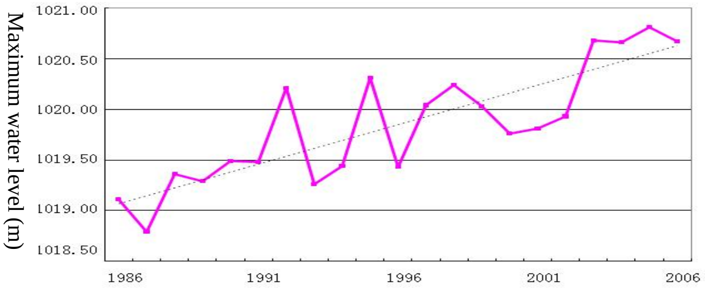

Figure 2.8 Maximum Water Level Variation at Sanhuhekou during Breaking-up Period Since 1986

3 Impact of Climate Change on the Upper and Lower Yellow River

At present, there are many studies regarding Water Resources variation of the Yellow River which are based on observed data. From a prospective of regional division, the studies mainly relate to the source area, upper, middle and lower reaches, partial studies, however, from a prospective of the whole river. Based on analysis of collected literature and information, main study views in light of different river sections are presented as follows:

3.1 Source Area and Upper Reach

Source area of the Yellow River is called as “water tower" of the Yellow River, which is located in alpine region, few affected by human activities, particularly sensitive to climate change, therefore, relatively more studies focus on runoff changes at source area of the Yellow River. Compared to the source area, the upper reach of the Yellow River is more affected by human activities, which results in more data accumulation, therefore, some scholars in study combines the upper reach and source area, in a word, studies relating to both the source area and the upper reaches are:

(1) Analysis of runoff change and reasons

Most scholars believe that runoff in source area and the upper reach of the Yellow River has been substantially reduced since the 1990s, Annual Runoff Distribution turns from dual peak in 1950s-1980s to single peak since the 1990s, see Figure 3.1 and Figure 3.2.Zhang Shifeng, et al (2004) believes that hydrological cycle rule of the Yellow River source changed greatly in the 1990s, and that in river source areas features were: in case of little change but a slight increase in rainfall, the runoff drops significantly, and more concentrated in the flood season. Liu Xiaoyan, et al (2005) proves this point through an analysis of runoff changes at Tangnaihai hydrological station, based on her conclusion and analysis of study progress on runoff change in source areas. Guo Changgang, et al (2007), by using meteorological, hydrological information of Maduo hydrological station in the source area of the Yellow River and those along the Yellow River in 1955~2005, has an analysis of the evolution with regard to surface water resources, climate and permafrost in the region. He believes that it is frequent for wet-dry transforming of flow in the Yellow River source, the flow trends downward since the 1990s in the source area, and annual flow distribution behaves as single-peak type. Li Lin, et al (2004), by using hydrological data of Tangnaihai Hydrological Station and meteorological data in 1961-2002, studies the impact of climate change on the upper reach of the Yellow River and on surface water resources. The results show that annual flow in the upper reach of the Yellow River trends downward by years, more sharply since the 1990s.

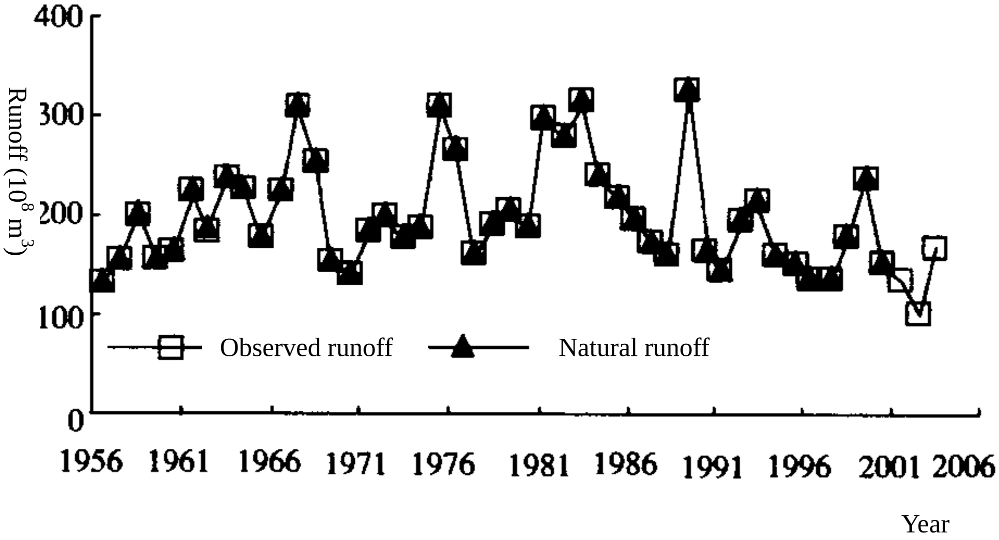

Figure 3.1 Runoff Change of Tangnaihai Hydrological Station of the Yellow River

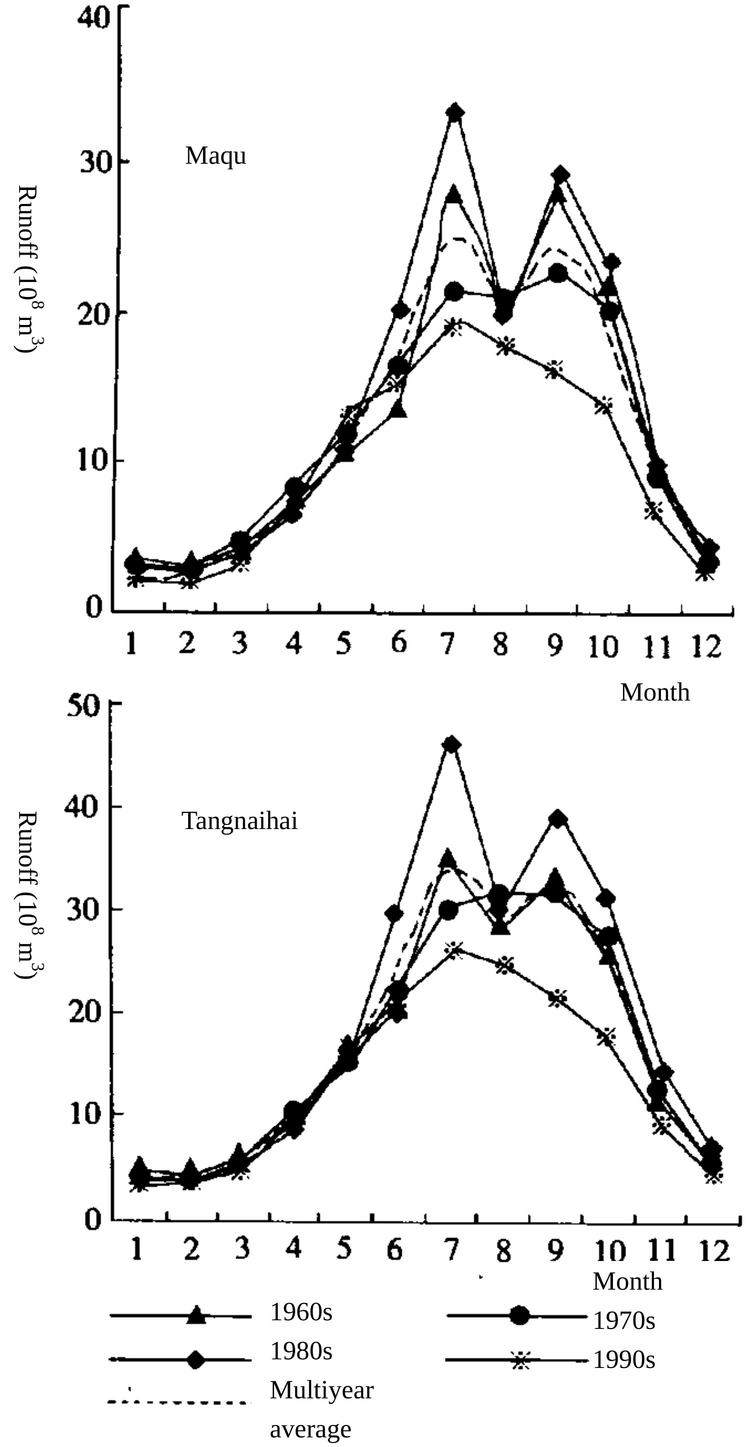

Figure 3.2 Annual Flow Distributions in Source Area of the Yellow River

In domestic studies, it has not been agreed on reasons resulting in the reduction in runoff, but most people believe that rainfall trends to decrease. Liu Xiaoyan et al. (2005) believes that precipitation mainly triggers runoff change; rainfall change in different regions, seasonal rainfall change and precipitation intensity change may lead to the reduction of runoff; underlying surface of source area experiencing change may affect the relationship between rainfall and runoff, but it is still difficult to identify the extent which both climate change and human activities pose impact on underlying surface change. Xie Weichan et al. (2007), through an spectral analysis method, believes that in the late 1980s, runoff reduction in source area of the Yangtze River and the Yellow River runoff is mainly triggered by the reduction of rainfall of those areas. Chang Guogang et al. (2007) believes that rainfall in source area poses significant impact on flow, featuring certain continuity; Temperature rising significantly in source area of the Yellow River has a much more impact on the reduction of flow replenishment resulted from increased basin evaporation than the replenishment of snow and ice melt water resulted from it. Zhou Degang et al. (2006), through an analysis of climate change characteristics in source area of the Yellow River source from 1960 to 2000, estimates the evaporation, analyzes changes in vegetation and permafrost and explores the causes resulting in the significant runoff reduction after the 1920s. He believes that the reduction in runoff of the Yellow River source area is directly caused by the reduction in precipitation; the weakening of precipitation intensity after the 1990s may also be an important cause. Shi Fucheng et al. (2005), through an analysis of the relationship between precipitation and runoff in source area as well as another analysis regarding the comparison between flood-season runoff and annual runoff of Weihe River, Yiluo River and Qinhe River in the middle reaches in 2003, believes that smaller runoff should relate to many factors such as lasting small rainfall, few storms which are above certain scale, increased temperature and increased evaporation. Lan Yongchao et al. (2006) analyzes the change course and characteristics regarding water cycle factors such as rainfall, temperature and runoff over several decades in the upper Yellow River. He believes that water contribution volume in the upper Yellow River trends to decrease gradually due to the impact of rainfall reduction and temperature rise in main water contribution area.

Zhang Shifeng, et al (2004), however, believes that the reduction of runoff is mainly triggered by the increase in evaporation; Since the runoff in source area has a favorable correlation to runoff of all hydrological stations in the upper reach, the reduction of runoff in source area may lead to a drop of water inflow in the upper reach, further affecting water supply and demand of the whole river basin. Lan Yongchao, et al (2006), by using observational data regarding rainfall and runoff of relevant stations, has an analysis of wet-dry change characteristics of runoff during flood season in the upper reach and its circulation background. He believes that either wet section or dry section in the upper reach (above Tangnaihai) occurs alternatively, dry duration is generally longer than wet duration. A complete wet-dry cycle is around 18 a. The wet-dry runoff in the upper reaches relates closely to the abnormity of atmospheric circulation.

Annual average runoff in the Yellow River source area is 20.5 billion m^3. Average natural runoff of Tangnaihai station in the 1990s was 17.6 billion m^3, a reduction of 15 percent below annual average value. The Yellow River source area is the main contributing region of the Yellow River, nearly 40% of the total runoff comes from the Yellow River source area, so it is also known as the "water tower". The Yellow River source area is located in alpine region where there is little impact of human activities and it is particularly sensitive to climate change, so many studies focus on the runoff of the Yellow River source area. Some studies suggest that climate change plays an essential role to trigger the reduction of natural runoff in the Yellow River source area [LAN Yongchao, 2006]. Although since the 1990s precipitation in the Yellow River source area has decreased by 5%, but precipitation intensity has decreased significantly, soil infiltration has increased, which leads to the decline of flow contribution; the significant rise in temperature in the Yellow River source area over the past 50 years has caused at least 4% runoff loss (Wang SW 2002; Ding YH 2002, Li. 2002). The precipitation in the upper reach since the 1990s has decreased to some extent. Huang Ronghui, et al (Climate Change and Environment, 2006) in his study believes that a marked increase in temperature gives rise to a sharp reduction of runoff in the Yellow River source area and the upper reach, and the increase of drying-up days. The water inflow quantity from the upper reach is an essential factor to affect the water resources in north China.

（2）Glacier Permafrost and Wetland

Glacier permafrost is a reserve for Yellow river water resources. The majority of scholars believe that the permafrost in source area has an evident degradation trend. Chang Guogang et al. (2007) believes that permafrost in the Yellow River source area behaves in a significant degradation trend, permafrost thickness is generally in a positive correlation to flow, its increasingly reduction weakens its role as a natural impermeable layer. Based on the data analysis regarding Normalized Difference Vegetation Index (NDVI), Zhou Degang et al. (2006) believes that the vegetation in the late 1990s was in degradation trend, a clear degradation trend in permafrost can be seen since the 1980s, the degradation of vegetation permafrost may result in a drop of water level at frozen crust, an increase of soil water leakage to a lower layer and a reduction of runoff. Cao Wen-bing et al. (2006) believes that overall permafrost degradation trend in the Yellow River source area behaves as follows: continuous permafrost zone for many years is turned to a discontinuous permafrost distribution zone, the status of rich in frozen soil is gradually turned to a status where both dry permafrost and seasonal thawing depth increase, and the elevation of permafrost lower bound rises. Pan Jinghu et al. (2005), through an analysis of land use in the Yellow River source area from 1986 to 2000 and temporal and spatial variation characteristics regarding landscape structure, reveals that woodlands, wetlands, grasslands and glaciers area in the source area shrinks, but construction land, cultivated land and unused land area all increase significantly, and the comprehensive land use drops.

（3）Glacier and Snow Cover

Retreat of glaciers is an evidence of global warming. According to statistics, 82% glaciers in Western China are rapidly shrinking. Glaciers in the Yellow River source area are mainly distributed in Animaqing Mountains and Bayankala Mountain. The former is located in the East Kunlun Mountains of Qinghai-Tibet Plateau, serving as an important glaciers zone, its mountain ranges in 34°20' N to 35° N, 99°10' E to 100° E , totaling 58 modern glaciers distributed, covering an area of around 125km^2.

Analysis of temperature, precipitation data in the source area in recent 50 years indicates that temperature in source area continues to rise, precipitation decreases significantly, climate generally trend toward warming. Such a change results in accelerating the melting of glaciers, broad degradation of permafrost, water reduction in lake and marshland, and degradation of grassland. Glacier area in the source area in

1966-2000 years reduced by 17% (Liu Yin et al.), and annual reduction ration is ten times over that in hundreds of years before 1996; glacier water loss amounts to 2.39 billion m^3, equivalent to around 10% of annual average runoff at Lanzhou section. Due to the impact of climate change, permafrost degradation, damage by wild rat and heavy grazing, the grassland ecosystem experiences a significant change, for example, coverage in overall decreases, “Black Beach" and land desertification expands rapidly. Main stream in the source area since the 1990s has stepped into a strong dry season, water resources volume has decreased to some extent, which exacerbates shortage extent of water resources in the middle and lower reaches of the Yellow River.

Table 3.1 Glacier Area Change in different period for typical glacial action region in the Yellow River (Liu Shiyin et al.2002)

Time	Glacial area （km^2）	Area change (km^2)	Change ratio of area（%）
Last Glacial Maximum	391.6		
Maximum of the Little Ice Age	147.8	-243.8	-62
1966	125.5	-17.5	-15.1
2000	103.8	-22.74	-17.3

3.2 Middle Reach

The middle reach of the Yellow River is an most important sediment source area where ecological environment is fragile, human activities are strong, so the study on runoff change should focus on the coordination between water and sediment

（1）Water and Sediment Change

Similar to the reduction trend regarding water inflow in the upper reach, water and sediment in the middle reach is generally in reduction trend. Annual analysis shows that precipitation, runoff and sediment transport is relatively concentrated. XU Jiongxin (2004) in his study believes that runoff renewable indicators in the interval from Hekouzhen to Longmen are in reduction trend. Rao Suqqiu et al. (2001) have an analysis on changes characteristics of water and sediment in the middle reach generally. She believes that since the 1950s water and sediment in the middle reach has decreased year by year, most significantly in the 1980s and 1990s. 1990s is the decade during which gross runoff in the upper and middle reaches was the least, but sediment transport were higher than that in the 1980s. Yin Guokang (1998) believes that annual precipitation, runoff and especially sediment transport in the coarse sand area are very concentrated. Erosion-yielded sediment in four months during flood season accounts for more than 97% of the whole year, while sediment yield is often concentrated in several heavy rainfalls. Through an statistical analysis of measured data for 75 floods occurring at Hekouzhen-Longmen section during nearly 40 years from 1950 to 1999, Gao Guofu, et al. (2002), believes that, differing to spatial and temporal distribution in the upper reach, that at Hekouzhen-Longmen reach is concentrated in 7-8 months, of which 67% of them concentrated in July 15 to August 15, commonly known as "Qi Xia Ba Shang" in Chinese (last tend days of July and first ten days of August) .

（2）Reasons

From the perspective of climate, Yu Shuqiu (1996) applies T test method to have an analysis of rank order regarding droughts and floods in the middle reach of the Yellow River in summers (May to September) from 1470 to 1991 (5 September) . The results show that: there are two sharp changes in regional climate with about 100-year scale, one is before and after the 1750s (drought to flood), another is in the early 1860s (flood to normal). Wang Yunzhang et al (2004), by using drought-flood grade in the river basin and partial tree-ring data, reconstructs drought index sequence in the middle reach since 1575, analyzes the historical law and change trend regarding drought. He believes that: drought change by stage significantly, for example, it has experienced roughly six drought phases and 5 non-drought phases in recent 429 years. The probability for special drought, heavy drought at drought phase is respectively 3.3 times and 2.1 times over at non-drought phase, while probability for flood and non-drought at non-drought phase is respectively 6.5 times and 1.8 times over at drought phase; drought change also has a significant cyclical characteristic, the main cycle lengths are 5,7,22.5,32,55,69 and 123 years. Wang Canggao (2004), based on drought index series in each quarter in the middle reach of the Yellow River, analyzes drought frequency and change characteristics. He believes that the probability of drought occurring in the middle reach is high, the probability at which a drought occurs or not in early summer and autumn is roughly 7:3, and 6:4 in midsummer; special drought occurring in three consecutive quarters can be seen in 1997 since 1995, no flood occurring in three consecutive quarters but in two consecutive quarters is found. Drought probability increases with age, for example, probability of special and heavy droughts in summers from 1986 to 2002 is three times over previous periods, autumn drought index has maintaining at a high level, and autumn floods does not occur fundamentally.

From the perspective of vegetation cover, Liu Changming (2004), based on hydrological station information regarding rivers with different forest covers and flowing by Ziwuling and Huanglong Mountain in Loess Plateau, establishes equations regarding the relation between forest rate and annual runoff in small and medium-sized river basins, uses inverse problem calculation to seek the quantitative relationship between river runoff and forest cover. He believes that in a given river where measures as returning farmland to forests and enclosure are implemented, if future forest rate will get close or up to 100%, the annual runoff will be reduced by 30%~53%. XU Jiongxin (2004) in his study believes that the implementation of water and soil conservation measures has accelerated evaporation and transpiration, temperature rise has accelerated evaporation, thus leading to the drop of runoff renewable indicator at Hekouzheng-Longmen reach.

In the middle reach of the Yellow River, especially in the Loess Plateau are the most important Yellow River source area, about 80% sediment created from the region. Since the 1980s, the human activities have become strong (Zhang Shengli et al. 1996; Chen Jiangnan, 2004); ecological environment has become fragile. Therefore, the study of the middle reach of the Yellow River shall mainly focus on how to assess the impact of climate change and human activities on runoff and sediment. A large-scale water and soil conservation has been carried out in the middle reach of the Yellow River, water and sediment inflow at Hekouzheng-Loangmen reach has been reduced since the 1970s, and reduced drastically since the 1980s. Compared to annual average value from 1950 to 1969, runoff of Hekouzheng-Loangmen reach in the 1980s reduced by as much as $36.15\times10^{8}m^{3}$, and sediment load reduced by $6.2325\times 10^{8}t$. Water and sediment change in the middle reach is caused jointly by climatic variations and human activities. So it is essential to identify the roles of climate change and human activities in the reduction of water and sediment. Study on water and sediment change in the middle reach mainly focuses on Hydrological approach and water resources conservation approach. Chen Hao, et al. (Geographical Studies, 2002), based on this, develop an elements approach regarding geographical environment to analyze water and sediment change and causes. He believes that the runoff and sediment load relate closely to the impact of geographical environmental factors. Since the 1970s, the role of rainfall by which water and sediment are reduced has been weaken continuously; with the improvement of water and soil conservation measures, the proportion of water and sediment erosion reduced by human activities continues to rise. In the 1970s, average water and sediment reductions due to climate fluctuation and human activities were 53.4%, 28.6% respectively, and in the 1980s were 46.6% and 71.4%. Wang Guoqing, et al., has an analysis of the impact of climate change and human activities on the runoff in the middle reach of the Yellow River. The results show that from 1970 to 2000 human activity played a primary factor in reducing runoff, the impact of climate change and human activities on the runoff accounts for 38.5% and 61.5% of the total reduction respectively.

3.3 Lower Reach

Related studies (Liuguo Xu, 2002) shows that in Pre-Qin period, a large number of branches was formed at alluvial plain in the lower reach of the Yellow River, and also in the forefront low-lying land in the alluvial fan and between rivers, natural lakes were well developed, according to statistics in Pre-Qin Dynasty, there were about 40 lakes of different sizes. It can be certain that there are many omissions in the documentation and it is geographically uneven. In Han and Tang Dynasties, natural factors that affected the distribution of lakes changed slighty. Natural lakes in Pre-Qin Dynasty remained basically at that period. In “Shui Jing Zhu," more than 500 lakes are recorded, of which over 190 lakes are located in the Huang-Huai-Hai Plain. After Tang and Song dynasties, lakes in the Huang-Huai-Hai Plain experienced a significant change, and a large number of lakes were silted to flat land. Large-sized lakes recorded in "Shui Jing Zhu", such as Dalu Lake in Hebei Province, Daye Lake and Heze Lake in Shandong Province, Putian Lake and Huang Lake in Henan Province, have now completely disappeared, some only remains a very small portion.

At present, runoff change in the lower reach of the Yellow River relates closely to water inflow from the upper reach, middle reach and major branches. Liu Changming (2004), based on data regarding annual average rainfall and natural runoff depth in drainage basin above Huanyuankou, believes that since the 1960s, water cycle elements have trended downward. As for annual runoff coefficient above Huayuankou, 1968 is regarded as the boundary to divide data during 1952-2001 into two stages, at which runoff coefficients are 0.185 and 0.168 respectively. He also believes that under the impact of climate change and land-used cover change, the runoff coefficient decreased by around 9%, resulting in annual runoff reduction of around 5.6 billion m^3

Yellow River flow entering into the sea is calculated by using the runoff measured at Lijin hydrological station to deduct industrial and agricultural water below Lijin. Annual flow entering into the sea in 1956 to 2000 is 31.32 billion m^3, of which, in 1956~1979 is 40.98 billion m^3, in 1980~2000 is 20.27 billion m^3 (nearly 50% below that in 1956~1979). Yellow River flow entering into the sea generally trends downward, which is caused by the continuous reduction of natural water inflow on the one hand, and continuous increase of national- economy water on the other.

Drying up in the lower reach of the Yellow River began in 1972, accelerated since the 1990s. In 28 years from 1972 to 1999, drying up in the lower reach occurred accumulatively for 22 years, on average, 4 times per 5 years, 1092 days accumulated; in addition, 50 days a year. In 1997, the runoff measured at Huayuankou was a dry year only next to that in 1928, with drying up duration of 226 days and length of 704km, which created a historical record of the Yellow River (Guan Huan, 2001; Zhang Xuecheng, 2006).

Ecological environment status in the Yellow River Basin relates closely to water resources. With the sharp drop in natural runoff, water demand by rapid socio-economic development in the Yellow River continues to rise, the contradiction between them have become increasingly sharp. Meanwhile, substantial water for ecological environment is diverted; water flow entering into the sea drops sharply (Figure 3.3). Reduction of the flow and even drying up may result in seriously shrunk channels in the lower Yellow River and rapid development of secondary Suspended river, which not only increases the possibility of "burst" and "break" of embankments, but leads to the shrinkage of wetlands, deterioration of water quality and damage with biodiversity. According to statistics in the 1990s, due to the drying up in the lower Yellow River, estuary vegetation area have decreased by almost half, fishes reduced by nearly 40%, birds reduced by 30%. Since 21st century, water allocation, water-sediment regulation have alleviated to some extent the environmental issues in the lower reaches and at estuary regions, however, functional drying up as well as ecological environment issues at river basin level are far from being addressed.

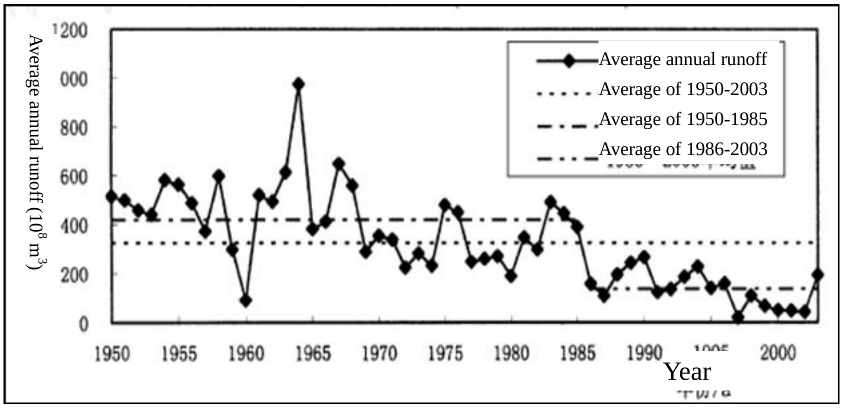

Figure 3.3 Annual Average Runoff Change at Yellow River Entrance

4 Study on Impact Mechanism

4.1 Analysis of Causes

Study on the Mechanism regarding the impact of climate change on Yellow River Water Resources mainly focuses on basic law of climate change, causes analysis of drought and flood events, identification of the impact of climate change and human activities on water resources and so on.

There are many studies relating to the drought and flood events and their causes. Wang Yunchang, et al. (Yellow River, 2004) , based on drought and flood grade and partial tree-ring data, reconstructs drought index sequence in the middle Yellow River since 1575, analyzes the historical law and change trend with regard to drought. Ma Zhuguo, et al. (Journal of Geography Science, 2003), uses monthly precipitation and average temperature in 1951-2000 to construct surface humid index reflecting surface wet and dry status in North China. He believes that over the last 10 years, extreme drought frequency in North China has increased significantly, a rare period in which high-intensity wide-range extreme droughts occurs frequently in the past century, at the same time, the frequency of extreme wet relatively decreases; a frequent occurrence area of extreme drought is always corresponding to a significant warming area, whether the increasing frequency of extreme drought relates to regional warming requires a further study. Ye Duzheng et al. (Ye Duzheng, Huang Ronghui, et al. Study on Drought and Flood Laws and Causes in the Yangtze River and the Yellow River. 1996), based on his analysis of drought and flood change in the Yellow River over a hundred years, points out that since 1965 the Yellow River has experienced continuous drought, and since the 1990s, the drought has been accelerated. He also reveals the main circulation factors affecting the drought and flood in the Yellow River and their corresponding relationships. According to historical data and tree-ring, Liu Xiaodong et al. (2002), reconstructs precipitation sequences over 400 years, studies the probable change of rainfall in the Yellow River under global warming, points out that higher (lower)global average temperature corresponds to some extent to lower (higher) annual precipitation in the middle reach of the Yellow River.

Many important results have been yielded through the study on physical climate causes of large-scale precipitation occurring in the upper Yellow River under global warming. Through an analysis of atmospheric physics field change resulted from abnormal sea surface temperature, it reveals many important facts that the ocean-atmosphere system poses impacts on spatial and temporal distribution of precipitation in China, explores the impact of winter and summer monsoon on the precipitation in flood season in Qinghai Plateau and Northwest China (Zhang Cunjie, Plateau Meteorology, 2002). Some studies suggest that global warming gives rise to the weakness of summer monsoon in Northwest China, decline of southerly winds and increase of northerly winds in August, in addition to a drying trend. Affected by it, main contribution area of the upper Yellow River (Jimai-Maqu reach) continues to decrease in precipitation, which is one of major causes resulting in lasting drop of natural water inflow of the upper Yellow River over 10 years(Zhang Guangzhou et al. Journal of Xinjiang Meteorology, 2000). The precipitation change in the upper

Yellow River behaves in periodicity, mainly affected by celestial bodies movement and sunspot strength changes, change cycle of subtropical high ridge location, and amplitude variation cycle of polar migration (Yang Jianping, Journal of Desert Research, 2005)

In studies of the impact of climate change in the Yellow River on water resources, it reveals that it is affected jointly by climate change and human activities. Xia Jun et al. (Journal of Geography Science, 2003), based on system theory method, has analysis of regulation of water resources volume in Yellow River trunks, and believes that serious drying up is mainly triggered by human factors; Since the 1950s, the trend composition change regarding natural annual runoff sequence well corresponds to the development and utilization of land and water resources that are one of the main causes to advance the evolution of river runoff (Jiang Xiaohui et al. Natural Resources Journal, 2003). Liu Changming (Advance in Water Science, 2004) points out that rainfall over 50 years in the Yellow River above Lanzhou have decreased by 5%~ 10%, correspondingly, runoff decreased by 15% to 20%. The extent at which runoff decreases is greater than that of precipitation, which is likely caused by underlying surface changes; under the impacts of climate change and land-cover change, runoff coefficient reduced by about 9%, resulting in annual runoff reducing around 5.6 billion m^3; Wang Xiqin et al (Journal of Natural Resources, 2006) believes that since the 1980s the impact of human factors has gradually increased, because human activities leads to the reduction of surface runoff. Zheng Hongxing et al. (Advance in Geographic Science, 2003), however, holds another view that a large change in annual runoff distribution in the 1990s occurred, especially in the reduction of flood runoff, to which climate change is a major cause; in river source area, especially in some drought and alpine regions where it is not easy to carry out the construction of ecological protection, the vegetation coverage trends downward (downward rate about 0-3.0% a year).

4.2 Simulation Technology

The Large-scale AOGCMs is now most credible for future climate prediction. The study on future climate simulation prediction in the Yellow River is dominated by prediction results based on climate model, but also some subjecting to comprehensive analysis and conclusions. It is generally believed that in the next few decades, or even in 100 years, global warming will continue to rise, precipitation may increase in a slight extent, meteorological droughts and floods may increase to some extent.

Climate change assessment model based on climate models and hydrological models can also be applied in the study of impact of climate change in the Yellow River. Xu Ying et al. (Zhao Zongci, Xu Ying, 2002; Xu Ying, 2002; Zhao Zongci, et al. 2003; Ding Yihui, Xu Ying, 2003) (Xu Ying, 2002; Ding Yihui, Xu Ying, 2003), by using seven global model simulation results provided by IPCC, further calculate the change regarding temperature and precipitation in 10 major river basins of China in 21st century, of which temperature and precipitation in the Yellow River is generally in upward trend (Table 4.1~4.2), but before 2050, precipitation will increase only by around 5%, temperature will rise by nearly 3 , which may lead to the reduction of the Yellow River water resources. Of course, it requires more deep study due to big uncertainty existing in applying global climate model in regional scale simulation.

Table 4.1 Prediction of Annual Average Temperature in the Yellow River in 21st Century Based on Global Model（Unit：　）

	2020	2050	2070	2100
SRES-A2	1.3	2.8	4.7	5.9
SRES-B2	1.5	2.7	3.7	4.1

Table 4.2 Prediction of Annual Average Rainfall Change in the Yellow River in 21st Century Based on Global Model（Unit：　）

（Unit：%）

	2020	2050	2070	2100
SRES-A2	-1	4	9	12
SRES-B2	0	5	8	11

Xu Yinlong et al. (Advance in Climate Change Study, 2005), use regional climate model system (PRECIS: Providing Regional Climates for Impact Studies) to have a downscaling calculation of SRES A2 B2 as provided by IPCC scenarios. The results show that it is more in North China and Northwest China by the end of 21st century, so warming trend is very clear. Zhang Yong et al. (Journal of Natural Disasters, 2006), having a study by the aid of SRES B2 scenario of PRECIS nested one-way global coupled ocean-atmosphere model HadCM3, points out that heavy rain and storm events in the Yellow River in 2080 trends upward, and the distribution of annual average largest precipitation events is fundamentally in consistent with heavy rain events.

Shi Yafeng et al. (Quaternary Research, 2003), through a comprehensive analysis of climate change in Northwest China, believes that the east of Northwest China including the upper Yellow River is potentially in warming and wetting trend, but it is difficult to identify specific time. Some scholars believe that, in the next few decades, runoff in the upper Yellow River is generally in downward trend (Liu Changming, Journal of Natural Resources, 2003). Some scholars, however, also believe that as global warming gives rise to the strengthening of water cycle, the increase of marine and terrestrial evaporation, the increase of atmospheric moisture content, as a result, precipitation in general increases. Zhang Feng, et al. (Science in China (E series), 2004) believes that Northwest China in the 21st century will continue to warm, water cycle will evolve as the increase of evaporation and the further decrease of runoff.

4.3 Responsive Mechanism

Many scholars carried out studies on water resources system in response to climate change. In give multiple GCMs model and hydrological models, it is predicted that in 2030 runoff in the Yellow River on the whole decrease, and water shortage in the basin caused by climate change is -1.9~12,120,000,000 m^3(Liu

Chunzhen, 1997). Based on GCMs results of IPCC DDC 13 series and large-scale hydro-simulation results, in the next 100 years, warming trend in Yellow River source region is expected to be in consistent with global warming. Temperature will continue to rise, evaporation will be enhanced apparently; in spite of the increase of precipitation, future climate change in sum is expected to cause the reduction of water resources to some extent; meanwhile, inter-annual distribution of water flow is expected to be more and more uneven, drought and flood will become increasingly aggravated. (Hao Zhenchun et al. Glaciology and Geocryology, 2006). Bao Weimin et al. (2000) , based on HadCM3 climate model, in combination with large-scale basin model with regard to freeze-up, snow melt and run-off variable coefficients, believes that runoff above Anningdu in the upper Yellow River in 2030 will increase, its water flow will be affected significantly by area ratio above snow line. Zheng Hongxing (2000), based on "greenhouse gases plus sulfide aerosol" program, applies CGCM1, ECHAM4 and HadCM2 models as well as BP neural net algorism for prediction. The results show that the precipitation in the Yellow River above Lanzhou in the next 100 years will be reduced by 20%, and average temperature in 2020, 2050 and 2080 will rise by 2 to 3, 3 to 5 and 5~8 ; under different climate scenarios, runoff change differs greatly in different time and different intervals, but overall, runoff is expected to decrease.

In short, studies on the impact of future climate change in the Yellow River have developed to some extent, but great uncertainty exists; in addition, less studies, with incomplete study approach, focus on the impact of future climate change on extreme events, most of which use the increase/decrease of average precipitation to predict future trend regarding droughts and floods. It is generally believed that that future temperature will rise significantly, precipitation increase slightly, the increase of precipitation being consumed by the increase of evaporation will result in the reduction of runoff, if so, water resources crisis in the Yellow River will be more serious.

5 Trend Analysis

5.1 Trends in Climate Change

Xu Ying et al., by using seven global model simulation results as provided by IPCC, further calculates the change regarding temperature and precipitation in 10 major river basins of China in 21st century. It is found that temperature and precipitation in the Yellow River is generally in upward trend. Before 2050, precipitation will increase only by around 5%, and temperature will rise by nearly 3 , which may lead to the reduction of Yellow River water resources.

5.2 Change Trend of Water Resources

Many studies focus on the impact of future climate change on Yellow River water resources, but great uncertainty exists. Shi Yafeng et al. (Quaternary Research, 2003), through a comprehensive analysis of climate change in Northwest China, believes that in the west and middle of Northwest China since 1987, both precipitation and river runoff have increased significantly, climate have turned evidently from warming dry to warming wet.

Signs of mild transformation in some areas exist, for example, in the east of Northwest China including the upper Yellow River in the next ten years will be always in either drier period or low flow period, but which may have been in the bottom, so it has a potential to trend toward warm and wet; however it is difficult to identify a specific time. Some scholars believes that, in the next few decades, the runoff in the upper Yellow River will be generally in downward trend under global warming (Liu Changming, Journal of Natural Resources, 2003). Some scholars, however, also believes that as global warming gives rise to the strengthening of water cycle, the increase of marine and terrestrial evaporation, the increase of atmospheric moisture content, as a result, the precipitation in general will increase.

Many scholars have carried out the research of water system in response to climate change. Some scholars adopt GCMs model and hydrological model to predict that runoff of the Yellow River in 2030 will decrease, besides, they reach a conclusion that water deficit as a result of climate change will be 1,900,000,000~12,120,000,000 m^3(Liu Chunzhen, 1997). Xia Jun et al. (Xia Jun, et al. Journal of Wuhan University (Engineering Science), 2005; Ye Aizhong, Journal of Wuhan University (Engineering Science), 2006), focusing on the issue regarding the impacts of climate change in the Yellow River Basin on water resources volume, combines systematology with physical mechanism to establish a distributed time-variant gain model, which to some extent solves the problem of hydrology in the regions without data. The model also proves in the Yellow River that climate factors influences greatly the course of hydrology, and increase in precipitation by 10% exerted greater influence on runoff than the impacts of decrease by 10%. Wang Guoqing et al. (Meteorology Journal of Henan, 2000) analyzes the response of hydrology in the upstream of the Yellow River to climate change based on the supposed climate program and monthly water balance model, and gets a conclusion that the change in precipitation has a great impact on the hydrology of the upper reach, while change in temperature exerts a relatively small impact; Changes of runoff and soil moisture in response to climate change in flood season is greater than that in non-flood season; in terms of regional distribution, the middle reach is more sensitive than the upper reach to climate change (Wang Guoqing et al, the Journal of Applied Meteorology, 2002). Hao Zhenchun et al.(2006, Journal of Glaciology and Geocryology), by using climate models results and a large scale distributed hydrologic model, assesses water resources of the Yellow River source region in future. According to 13 series of GCMs results yielded from IPCC DDC, in the next 100 years, the trend in the Yellow River source region will be coherent to global warming, temperatures in the future will continue to increase, evaporation will significantly increases even with the increase in precipitation, the future climate change to a certain extent will cause the reduction in the volume of water resources as a whole; in addition, the inter-annual distribution will be more and more uneven, the threat of severe droughts and floods will become severe. Zhang Guanghui (Geographic Research, 2006), based on the HadCM3 climate models, analyzes the average natural runoff changes of the Yellow River for years in different climate change scenarios: under the A2 scenario from 2006 to 2035, 2036 ~ 2065, 2066 ~ 2095, the average natural runoff changes will be respectively 5.0%, 11. 7%, 8.1%, under B2 scenarios, those will be 7.2%, -3.1%, 2.6%. Most of the Seven models, including GFDL, GISS and others, in combination with the analysis of large scale basin model which took factors of frozen and snow, run-off variation into consideration, showed that in 2030 the runoff above Anningdu in the upper reach of the Yellow River will increase, which will be affected remarkably by area ratio above snow line (Bao Weimin et al. 2000). The study also shows that the runoff yield in the Hekouzhen-Longmen region of the Yellow River will decrease by 2.13% on average (China Climate Change Country Study, 2000). In the "greenhouse gases + sulfide aerosol " program, predicted outcomes, through the method of BP neural network algorithm, based on the use of CGCM1, ECHAM4 and HadCM2 model, are: in the next 100 years, precipitation in the region above Lanzhou in the Yellow River will be reduced by 20%, average temperature will rise in 2020, 2050 and 2080 by 2~3, 3~5 and 5~8 ;

River runoffs at different time and regions under different climate schemes are different, but overall, the runoff will decrease (Zheng Hongxing, 2001). Some scholars maintain that in the next few decades, under global warming, runoff in the upper reach of the Yellow River will take on a decrease trend; while other scholars believe that strengthening of the water cycle and increase in ocean and land evaporation and moisture content in the air caused by global warming may increase general precipitation (Wang Guoqing et al. 2002; Bao Weimin,2000; Lan Yongchao, 2004; Liu Changming, 2003). Through an analysis of environment and climate change in the Northwest, Shi Yafeng found that both rainfall and run-off in the west central region of the northwest increase significantly and climate has taken on a transition from warm dry type to warm and wet type since 1987.

5.3 Change Trend of Evaporation

Compared with study on precipitation, runoff and temperature changes, there is less study on the evaporation of the Yellow River and there is big dispute on impact of climate change on evaporation. Li Lin et al. (2000) analyzes change trends of climatic factors in the upper Yellow River, including evapotranspiration, sunshine duration, temperature, air saturation deficit, focusing on the impact of these factors on evapotranspiration. The results show that evapotranspiration in the upper Yellow River has increased year by year. By analyzing hydrological change pattern in the Yellow River source region, Zhang Shifeng et al.(2004) believes that because of continuous growth of temperature in the northwest, the increase in evaporation will be the trend of water cycle in the 21st century. Shi Zhonghai (2006) establishes a simple and practical evaporation estimate formula of exponential type and analyzes the influence of temperature change on evaporation capacity of river basin: evaporation capacity in the Yellow River increases by 5.0% to 7.0% when temperature increases by 1 ; In terms of geographical distribution, change in the middle reach of the Yellow River is the biggest, followed by the upper reach and the lower reach. Increase in region from Hekouzhen to Sanmenxia City is most significant (Table 5.1). Based on the data of pan evaporation of D 20cm from 1961 to 2000 in 123 weather stations in the Yellow River and its surrounding, Qiu Qinfa (2003) analyzes the climate change trend of evaporation capacity of pan evaporation. His research proves that evaporation capacity of pan evaporation takes on a decline trend in the upper reach and the lower reach of the Yellow River, while the middle reach shows a slight upward trend. Zhang Zhaohui (2006) has a calculation of potential evaporation of the Yellow River at different stages in future (Table 12). Scenario A2 represents that population growth speeds up and economic development slows down. Scenario B2 indicates that technological progress is relatively slow, but technological innovation is stressed. The study believes that evaporation from 2006-2095 will increase.

Table 5.1 Evaporation Capacity Change When Temperature Changes By 1 %

station	Maduo	Lan Zhou	Min County	Xining	Zhongning	Yulin	Yanan	Taiyuan	Tianshui	Xian	Zhengzhou	Jinan
E change	5.24	5.78	5.66	5.88	5.59	6.78	6.59	6.66	6.31	5.44	5.02	5.18

Table 5.2 Annual Average Potential Evaporation under Different Scenarios for Each Sub-Region （mm）

Reach	**1961～1990**	**A2**		
		2006-2035	**2036-2065**	**2066-2099**
Source-Guide	668.8	706.0	765.0	874.3
Guide-Lanzhou	835.7	871.4	929.7	1026.6
Lanzhou-Toudaoguai	944.7	1003.2	1063.3	1167.4
Toudaoguai-Longmen	991.7	1036.5	1091.4	1200.5
Longmen-Huayuankou	1033.0	1081.5	1144.3	1270.3
Huayuankou-Lijin	1035.0	1154.4	1267.9	1536.5
Reach	**1961～1990**	**B2**		
		2006-2035	**2036-2065**	**2066-2099**
Source-Guide	668.8	732.1	765.4	810.6
Guide-Lanzhou	835.7	918.5	922.5	936.0
Lanzhou-Toudaoguai	944.7	1062.8	1067.5	1100.9
Toudaoguai-Longmen	991.7	1092.5	1098.5	1130.3
Longmen-Huayuankou	1033.0	1149.0	1161.3	1192.9
Huayuankou-Lijin	1035.0	1280.7	1297.6	1355.9

5.4 Change Trend of Sediment

Analysis on sediment change in the middle and upper reaches of the Yellow

River since 1950 conducted by Rao Suqiu et al.(Rao Suqiu et al. Sediment Research 2001) shows that sediment, on the whole, was reduced year by year in the middle and upper reaches of the Yellow River, especially in the 1980s and the 1990s. The total volume of runoff in the upper and middle reaches of the Yellow River in the 1990s was the least since 1950, but the volume of sediment load increased compared with that in the 1980s. In the next 10 years, silt in Sanmenxia region of the Yellow River will be going up. Ren MeiE (2006) believs that in the next 20-30 years, economy in the Yellow River basin will be prosperous. Water consumption for industries and cities along the Yellow River will increase significantly, most of which will be abstracted from the Yellow River, even if irrigation water from the Yellow River will not increase due to the progress of agricultural and irrigation technology. In addition, ecological construction in the development of the western region, such as returning farmland to forests and grasslands, will also need water, so there will be an increase of demand for water for ecological needs. But the loss of evaporation will increase. In recent years, tens of thousands of small reservoirs and warping dams have been built in small tributaries and valleys of the Loess Plateau, among which more than 600 reservoirs have the capacity of more than millions m^3. They not only control the sediment, but also increase water evaporation. In addition, 12 large reservoirs have been built in the main stream of the Yellow River and another 3 are under construction, which prolong retaining time of water in the land and also increase water evaporation loss. Ren MeiE believes that the amount of sediment from the Yellow River into the sea will be decreasing in the next 20-30 years. Liu Cheng et al. (2007) maintain that silt reduction in the Yellow River is not a result of precipitation changes but human activities. Zhao Junxia and others (2001) believes that silt reduction in the Weihe River is caused by both human activity and climate change. The impact of human activity accounts for 57.1% of the total amount of decreased sediment and rainfall 42.9%. By analyzing observed data about more than 21 tributaries with area of over 1000 km^2 from coarse sediment area of the middle reach of the Yellow River, Yin Guokang (1998) respectively establishes the rainfall, runoff and sediment statistical models with a higher accuracy, and also calculates and analyzes the changes in sediment load, revealing the relative weight of impact of climate fluctuations and man-made causes on changes in water sediment, among which climate fluctuation accounts for 48.9%, while the cause of human activity accounts for 51.1%. Xie Yuting and Xu Zhiwen (1993) make a study and forecast on impact of human activity and rainfall on run-off and sediment in Zuli River Basin: from 1990 to 2000, the average annual reduced water caused by human activities was 81,000,000 m^3, the sediment was 33,600,000t, respectively, accounting for 52.3%, 50.6% of water sediment load in the simulation base year; from 2000 to 2030, the average annual reduced water caused by human activities will be 1,120,000,000 m^3, the sediment be 46,900,000t, respectively, accounting for 72.3%, 70.6% of water sediment load in the simulation base year(1955-1969). During the entire forecast period, impact of precipitation on average annual precipitation accounts for about 10%, and human activity accounts for about 90%; for average annual decreased sand, impact of precipitation accounts for 20%, and the impact of human activity accounts for about 80% (Table 5.3). A study on Wuding River Basin conducted by Zhang Shengli shows that compared with the base period of 1956-1969, the average annual sediment load in the 1970s reduced by 101,510,000 t, accounting for 46.7% the average annual sediment load of the base period, among which, the reduced amount of sediment load due to human activities, such as soil and water conservation, water measures and so on, was 87,740,000 t, accounting for 40.4% of the base period and

86.4% of actual measured reduced sediment load, the reduced amount due to rainfall was only 13,770,000 t, accounting for only 13.6% of the actual measured reduced sediment load; In the 1980s, activities, such as soil and water conservation, water conservancy measures, accounted for 52.3% of the actual measured reduced sediment load, rainfall changes 47.7%; in the 1990s (1990-1993), human activity and rainfall respectively accounted for 55% and 45% of the actual measured reduced sediment load. Erosion and sediment changes in the Yellow River basin were caused by multi-factors. You Lianyuan believes that due to the impacts of increased global precipitation, the long-period change in water and sand (the impact of astronomical factors), global warming and human activities on the Yellow River, water volume will be reduced to 2.6508×10^{10}-3.0508×10^{10} m^3 in 2050; to the year before and after the water can be reduced to; sediment load will increase to 1.503×10^{9}t if no project is launched; in case of the development of and reservoirs and dams, sediment load will decrease to 8.70×10^{8}-7.85×10^{8}t (Table 5.4).

Table 5.3. The Proportion of Precipitation and Human Activities Impacts on Reduced Water and Sediment In Zuli River Basin in Forecast Period of The Base Year (1955-1969)

period(year)	average annual reduced P (10^8 m^3)	precipitation impact		water conservancy		average annual reduced sediment (ten thousand	precipitation impact		water conservancy	
		reduced water	account for %	reduced water	Account for %		reduced sediment	Percent	reduced sediment	Account for %
1990-2000	0.91	0.10	11.0	0.81	89.0	4180	820	19.6	3360	80.4
2001-2030	1.25	0.13	10.4	1.12	89.6	5650	960	17.0	4690	83.0
1990-2030	1.16	0.12	10.3	1.04	89.7	5260	920	17.5	4340	82.5

Table 5.4. Water and Sediment Assess Around 2050 in the Lower Reach of the Yellow River

water conservancy project	Water inflow （10^8 m^3					Sediment inflow（10^8 t）				
	present situation 1986-1990	global warming Increase or decrease in volume	Long-period change Increase or decrease in volume	Human activity Increase or decrease in	Synthesis	present situation 1986-1990	global warming Increase or decrease in volume	Long-period changes Increase or decrease in	Human activities	Synthesis
1	377.5	+11.2	+18.3	-101.2	265.08	11.90	+0.95	+0.22	+1.964	15.03
2	377.5	+11.2	+18.3	-	-	11.90	+0.95	+0.22	-4.3879	8.70
3	377.5	+11.2	+18.3	-141.2	305.08	11.90	+0.95	+0.22	-5.224	7.85

Note: Water conservation project 1, 2 and 3 respectively refer to: no new project is added, develop dam projects in the average pace of past 40 years, develop reservoirs and dams in the planned pace of the water conservation project

5.5 Extreme Events

Based on drought and flood grades and the relationship of annual ring of parts of trees with drought index in the Yellow River (Figure 5.1),Wang Yunzhang (2004) believes that in the next 30 years from 2004, excepting recent years and the mid 1920s when drought remained prevail, most of the rest of year will be marked by no-drought and flood. By establishing dayly random model, Xu Lirong (2001) proves that under the climate scenarios with double content of C02, various types of drought events in the basin will increase and the average frequency of drought will increase by almost 5.8% (Table 5.5). By the use of Providing Regional Climates for Impact Studies (PRECIS), Xu Yinlong et al. (Xu Yinlong, Advances in Climate Change Research, 2005) made a downscaling calculation under SRES A2 B2 scenarios provided by IPCC, reveling that extreme high-temperature and precipitation events will increase by the end of the 21st century in China, but extreme low-temperature events will decrease. Meanwhile, temperature in summer will grow significantly while precipitation in summer will increase a little in the North and Northwest of China and the trend of warming will be obvious. Zhang Yong et al. (Zhang Yong, Journal of Natural Disasters, 2006) uses SRES B2 scenario of PRECIS nested one-way global coupled ocean-atmosphere model HadCM3 for study, the results show that annual average heavy rain and rainstorm will take on an increase trend in the period of 2080 along the Yellow River; distribution of annual average maximum daily precipitation is basically same with that of heavy rain events.

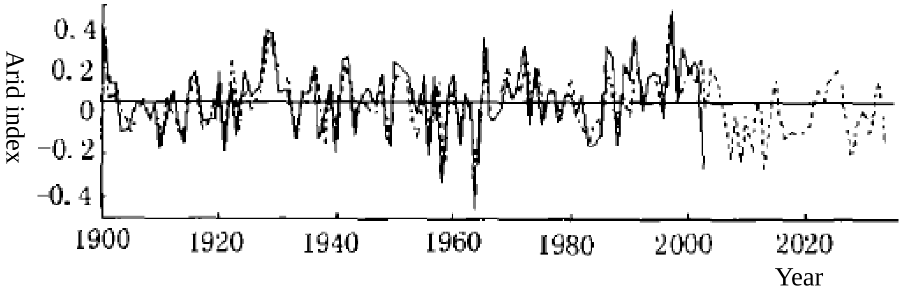

Figure 5.1 Index of Aridity in Summer Half Year since 1990 in the Middle Yellow River and Extrapolated Curve in the Next 30 Years

Table 5.5 Changes in Frequency of Drought

month	Contemporary Climate	2*CO2
4	57	58
5	50	61
6	63	75
7	59	63
8	56	60
9	59	62

6 Analysis and Conclusion

Based on views of most domestic scholars, it is concluded that:

（1）Since the 1990s, runoff of the Yellow River source region has reduced substantially and double-peak of annual distribution of runoff in the 1950s-1980s has been replaced with single peak since the 1990s. There has not been an agreement on reasons for the reduction in runoff in domestic, but most people think it is mainly because of reduction in rainfall.

（2）Water and sediment in the middle reach of the Yellow River have shown a reduction trend and annual analysis indicates that rainfall, runoff and sediment load are concentrated. The reason is that drought changes significantly at different stages and probability of occurrence of drought is high in the middle reach of the Yellow River.

（3）Both number and area of lakes in the lower reach of the Yellow River reduce significantly and changes in runoff in the lower reach of the Yellow River has a close relation to water delivery from the upper and middle reaches and key tributaries. On the whole, the reduction trend of runoff in the lower reaches is obvious.

For the whole basin, surface run-off has reduced significantly in Lanzhou control section, and natural runoff, surface runoff and groundwater runoff have reduced remarkably in Huayuankou control section, and the trend of runoff reduction in the lower reaches is more obvious than in the upper. Both climatic factors and increased water consumption due to human activities may be responsible for it.

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Analysis of origin of coarse sediment in Yellow River middle reaches

Floods in the middle reaches of Yellow River in the past 522 years mutation

Landscape critical phenomena of sediment yield in the middle reaches of the Yellow River basin

Analysis of sediment transporattion module change in the coarse area of the Yellow River middle reaches

Analysis of reason of water and sediment change in the coarse area of the Yellow River middle reaches

Analysis of mutation characteristics of water and sediment distribution in the coarse area of the Yellow River middle reaches

The impact of governance of Yellow River middle reaches area on Yellow River water resources

Analysis of cause of sediment flow curve of river water level changes in the Yellow River middle reaches

Analysis of rainstorm and flood in Fugu, Yellow River middle reaches on 2003-7-30

Analysis of hydrological characteristics in the interval of Fugu and Wubao in the Yellow River middle reaches

Evolution patterns of the Yellow River middle reaches droughts and its development trend analysis

Preliminary analysis of the characteristics of drought in Middle reaches of Yellow River

Discussion on Calculation Method of middle reaches of Yellow River drought index

Analysis of middle reaches of Yellow River to Longmen range of different strata of river contribute to the coarse

Comparative analysis of sediment yield of interval of Helong six rivers in the middle reaches of the Yellow River

Analysis of characteristics of the middle reaches of the Yellow River flood and flood resources

Analysis of flow characteristics and changes of the Yellow River middle reaches of the Loess Plateau

Impact of middle reaches of Yellow River basin environmental elements to water and sediment variation

Yellow River middle reaches characteristics of sediment yield and rainfall relations

Characteristics, problems, and remediation measures of middle reaches of Yellow River regional geo-environment

Type of summer drought in middle reaches of Yellow River and its circulation analysis

Frenquency of relation between water and sand in the Yellow River middle reaches

Impact of middle reaches of Yellow River basin bald tail river management on the evolution of river erosion and deposition

Reflections and countermeasures of tributary of the Yellow River middle reaches of the Kuye River devascularization

Characteristics analysis of middle reaches of the Yellow River rainstrom which casues flood

Probabilistic model extreme temperatures in Huanghuai region

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Review on benefit assessment of water and soil conservation meatures in Gushanchuan river basin

Plateau climate warming and drying trend and adaptive responses

Plateau major river sediment and sediment yield dynamic simulation

Small watershed in loess hilly and experimental research on the ecological water

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Huangshui River basin characteristics of climate change and its impact

Kriging Interpolation Based on the Yellow River Basin precipitation pattern of spatial and temporal distribution

MODIS data based on land-cover change and climate sensitivity factor analysis

Analysis of changes in sediment particle size of the Yellow River based on silt dam construction

Speed up the construction of the Loess Plateau silt dam

A suggested idea to solve the issue of Yellow River sediment problem-second talk about "on the next entry, sub-management of the Yellow River"

Dynamic analysis of land desertification of desert loess boundary belt over the past ten years

Analysis of change of the Yellow River upper reaches water cycle over the past fifty years

Inter-annual trend study on China's six major river basin runoff changes over the past fifty years

China's major rivers into the sea sediment changes over the past fifty years

The trend of the drought of 500 years of drought statistics

Impact of liquidity of precipitation change and human activities on the Yellow River into the sea

Impact of the upper reaches of the Yellow River recent climate change on the water storage of Longyangxia

Analysis of climate change over the past ten years on water and sediment impact of the middle reaches of Yellow River

Impact of characteristics of climate change on water resources over the past 49 years in Jinzhong

Kuye River several issues worth exploring

Preliminary analysis of Kuye River water and sediment changes over the years

Research on Kuye River basin rain erosion and sediment yield

Preliminary analysis of Kuye River water and sediment characteristics

Analysis of Kuye River water and sediment characteristics change

Research on runoff change in the Yellow River source region

International comparative analysis watershed management agencies and its recommendations

Assess of the impact of the consequences River Valley flood disaster and flood control situation

Research on rainfall erosion and sediment yield process of the relationship between water and sediment delivery

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Impact of climate change on Yellow River source region water system

Impact of climate change on Yellow River runoff

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Research of progress of impact of climate change on the Yellow River upper reaches water resource system

Analysis of impact of climate change on natural runoff of the Yellow River upper reaches

Impact of climate change on Yellow River water resources

Impact of climate change on Yellow River water resources II

Impact of climate change on runoff of the Yellow River source region process

Impact of climate change on runoff of the Yellow River water resources

Analysis of impact of climate change on Huangshui runoff

Stimulation of impact of climate change on runoff

Impact of climate change on Qinghai ecological environment and countermeasures study

Impact of climate change on Qinghai ecological environment and countermeasures

Impact of climage change and human activities on the Yellow River over flow during historical period

Impact of climate change and human activities on the eastern part of environment in Hexi Corridor and countermeasures

Climate change and Chaobai River water balance stimulation under the influence of human activities

Assessment methods and tools of adaptive responses to climate change

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Climate change and a thought on Yellow River devascularization

Impact of climate change on Yellow River ecological environment

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Global warming, the Yellow River Basin under the conditions of possible changes in precipitation

Global climate warming and drying of the river north and south of the Qinling the impact of runoff and sediment study

第一部分

黄河流域气候变化影响及水资源评估报告

（讨论稿）

1　气候变化对中国的影响

1.1 气候要素

从总体上讲，近百年来，在全球变暖的大背景下，中国气候也在变暖，在过去100年内，中国大陆地区的平均温度已经明显升高，年平均气温增加约0.6～0.8℃（秦大河，2005），其变化趋势与全球气候变化的总趋势是一致的，比全球或北半球变暖趋势略高。从地域分布上看，华北和东北地区的增温幅度最大，达到0.4～0.8℃/10年，长江上游和西南地区气温略有下降。南方大部分地区没有明显的冷暖趋势（王绍武，1998）。从季节分布看，冬季增温最为明显，1985年以来，中国几乎大范围连年暖冬。最近40～50年中，中国极端最低和平均最低温度都出现了增高的趋势，尤其以北方冬季最为突出。同时，寒潮频率趋于降低，低温日数趋于减少。

1951～1990年，中国平均最高温度略有上升，最低温度显著增高，日较差显著变小；极端最低和平均最低温度都趋于增高，尤其以北方冬季更为突出；全国范围寒潮活动逐渐减弱。就全国平均而言，在过

去50年中，霜冻日数显著下降，大约2.4天/10年。与此同时，我国的热日和暖夜频率显著增加，而冷日频数减少，冷夜减少的趋势更为明显（翟盘茂，2003）。近50年中国降水变化表明，中国年平均降水量减少，大约2.9mm/10年，但最近10年（1991～2000年）略有增加。华北大部地区，西北东部和东北地区，降水明显减少，大约为20～40mm/10年。华南与西南地区降水明显增加，大约20～60mm/10年；西北地区西部降水也有增加。每年降水日数在1951～1995年期间有减少趋势，但降水强度有增加的趋势（秦大河，2002；王绍武，2000）。从总体上看，中国总降水量变化趋势并不显著，雨日区域减少，这意味着降水过程存在着强化的趋势，致使干旱和洪涝事件趋于增多，尤其是在90年代，极端降水比例趋于增大。华北地区年降水量趋于减少，极端降水值和降水强度均趋于减弱，但极端降水占总降水的比例仍有所增加。从近100年观测资料分析发现，长江、黄河流域旱涝变化具有明显的阶段性和跃变。20世纪我国气候有明显的变干趋势；在20年代和60年代中期发生了两次气候由湿变干的气候跃变。黄河流域从1965年起连续干旱，而且不断加剧。

丁一汇等（2006）利用我国研制的全球海气耦合模式(如NCC／IAP T63)，参考IPCC给出的未来温室气体排放与浓度情景，并综合IPCC采用的多个模式的模拟结果，对全球、东亚以及中国未来20～100 a的气候变化趋势进行了预估。研究表明，未来20～1O0 a中国地表气温升高明显，降水量也呈增加趋势（表1-1）。21世纪中国地表气温将继续上升，其中北方增暖大于南方，冬、春季增暖大于夏、秋季。

与气候平均值比较，2020年中国年平均气温将增加1．3～2．1℃，2030年增加1．5～2，8℃，2050年增加2．3～3．3℃。预计到2020年，全国平均年降水量将增加2％～3％，到2050年可能增加5％～7％。降水日数在北方显著增加，南方变化不大。降水变化时空变率较大，不同模式给出的结果差异明显。

表 1-1 未来中国年平均地表气温与降水变化(相对 1961-l990 年平均值)

要素	2020	2030	2050	2100
温度变化（℃）	1.3-2.1	1.5-2.8	2.3-3.3	3.9-6.0
降水变化（%）	2-3		5-7	11-17

另外一些中国科学家选用其中的一些国内外全球气候模式的模拟结果进一步计算了中国的气候变化（赵宗慈，徐影，2002；徐影，2002；赵宗慈等，2003；丁一汇，徐影，2003）（徐影，2002；丁一汇，徐影，2003）。 模拟结果表明，近百年中国的变暖可能受到人类活动的影响，尤以近50年更明显。预估未来中国气温变化，到2030年我国气温将可能变暖1.5～2.8℃，2050年变暖2.3～3.3℃，2100年变暖3.9～6.0℃。四种方案中，A2方案温度增加幅度最大。根据全球模式考虑最新排放的A2,B2方案，预估21世纪不同时期的气温变化，增温最大的是东北、西北和华北，到2100年模式平均增温幅度达到4～5℃（见表1-2、表1-3）。多个模式和排放方案计算表明，21世纪由于人类排放增加，中国将继续变暖，且变暖幅度（3～5℃/100年）较20世纪更为明显，尤以北方和冬季明显。全国大范围可能变湿，尤以东北和西北明显，我国中部部分地区则有可能变干。由于人类排放的增加，东亚冬季风将可能继续减弱，夏季风将可能加强。预估未来夏季风的增强可能仅仅反映了气候变化背景下水循环增强所造成的降水增加的

影响。

表 1-2 基于 GCM 和 SRES-A2 方案的 21 世纪三十年平均温度变化预测

时间	中国	东北	华北	华中	华东	华南	西南	西北
2020	1.2	1.5	1.4	1.0	1.0	0.7	1.0	1.4
2050	2.6	3.5	2.9	2.4	2.4	1.9	2.2	3.0
2070	4.4	5.5	4.8	4.1	3.9	3.3	4.0	5.0
2100	5.6	6.9	6.1	5.1	5.0	4.1	5.0	6.3

表 1-3 基于 GCM 和 SRES-B2 方案的 21 世纪三十年平均温度变化预测

时间	中国	东北	华北	华中	华东	华南	西南	西北
2020	1.3	1.9	1.5	1.1	1.1	0.8	1.0	1.6
2050	2.5	3.2	2.7	2.2	2.2	1.8	2.1	2.9
2070	3.5	4.5	3.9	3.2	3.2	2.6	3.1	4.0
2100	4.0	4.9	4.2	3.6	3.5	3.0	3.6	4.4

1.2 河川径流

我国水利部水利信息中心（1996）根据4个GCM情景研究了中国典型流域后认为:在未来气候变化情景下,松花江流域径流增加的可能性大,辽河流域径流既可能增加,也可能减少;京津唐、黄河上中游及淮河流域年径流减少的可能性大,汉江年径流变化不明显,东江流域径流减少量较小,而年径流量增加较大。在华北地区,若气温升高2℃,青龙河、唐河和沙河年径流量大致减少10%～20%,白河减少40%以上;降水减少10%时,上述4个中小流域的径流减少15%～25%。对热带地区研究表明,相同的气候变幅,热带和温带的响应不同,若温度升高2℃,降水减少10%时,华北地区河川径流减少40%～60%,而海南万泉河流域仅减少25.6%（傅国斌，1991）。有研究根据GCM 模式模拟的气候变化情景(2030年),应用月水分平衡模式和水资源综合评估模式研究了气候变暖对年和月径流、蒸发以及水资源供需平衡的潜在影响。研究结果表明,气候变暖对水资源最显著的影响将会发生在黄淮海流域。作

为水资源主要来源的年径流，其增加或减少在很大程度上取决于汛期径流和蒸发的变化。因此，在未来气候变化情景下(2030 年) ,这个地区水资源供需的短缺将会显著增加。具体而言,海河流域的京津塘地区水资源短缺将由当前的$1.6\times10^{8}\mathrm{m}^{3}$ 增加到$14.3\ \times10^{8}\mathrm{m}^{3}$，淮河流域的短缺将由当前的$4.4\ \times10^{8}$m3 增加到$35.4\times10^{8}\mathrm{m}^{3}$,而黄河流域的短缺将由$1.9\times10^{8}\mathrm{m}^{3}$ 增加到$121.2\times10^{8}\mathrm{m}^{3}$（王馥棠，2002）。曲金华（2007）用HD 和MPI 模式得出的气候变化对中国2030 年天然年径流量的影响。 到2030 年,全国大部分流域的天然径流为增加的趋势,其中辽河、黄河流域的河口镇～三门峡区间、洞庭湖水系、粤西沿海诸河、闽东及闽南诸河天然径流将可能增加11、64 %～14、64 % ,洪水灾害可能加剧。尤其是辽河流域和闽江流域汛期6～8 月份的径流可能增加9、3 %和18、9 % ，闽江流域的最大径流量可能增加23% (图1-1) 。

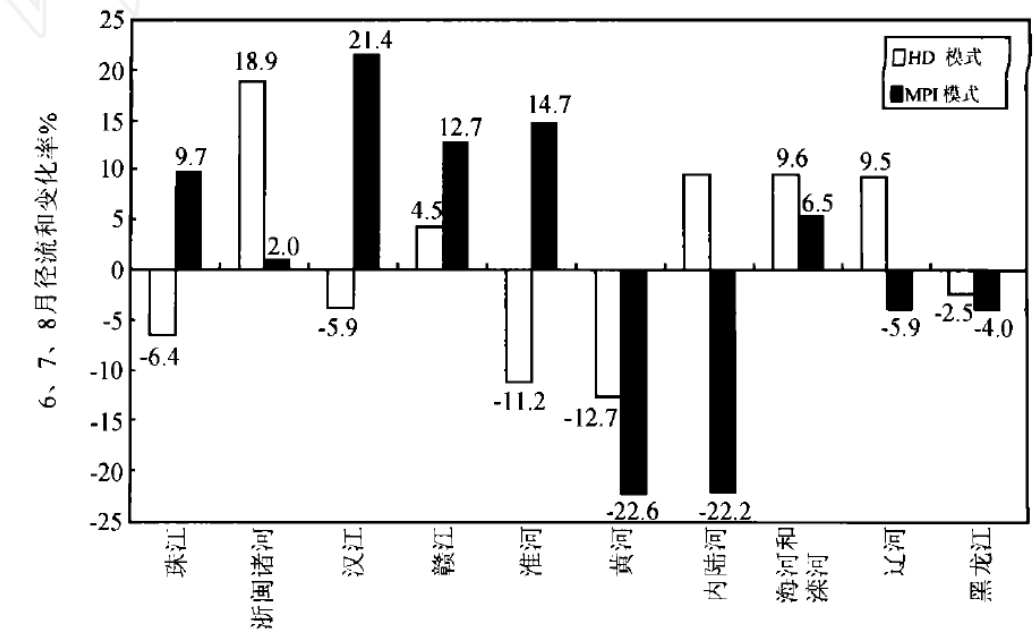


图 1-1 2030 年我国各流域 6～8 月径流量变化预

1.3 蒸发

根据未来气候变化模式，即未来30年黄河及其以北地区气温平均升高2.0 ℃ (HD 模式) 或2.38 ℃ (MPI 模式),黄河以南地区气候平均升高1.8 ℃ (HD 模式) 或1.5 ℃ (MPI 模式),在2030 年，中国年平均蒸发将增大3 %～15.1 % (表1-4) , 其中黄河及内陆河地区的蒸发量将可能增加15 %左右(MPI模式),超过降水增加的幅度（王守荣，2003）。另有学者研究，中国东北地区的夏季蒸发量在2020年～2049年增加4.3～5.4%，2071年～2100年增加幅度明显增大，达到12.3～14.4%（曲金华，2007）。

表 1-4　2030 年我国各流域蒸发变化预测

流域	珠江浙闽诸河	汉江	赣江	淮河	黄河	海河	滦河	内陆河	辽河黑	龙江
HD	4.0	3.0	3.8	3.5	5.6	13.0	12.5	6.0	6.6	8.6
MPI	3.1	3.0	3.1	3.3	4.8	14.8	5.1	15.1	6.0	11.5

1.4 海平面

田广生（1999）通过建立海平面变化预测模型对中国沿海5个区域未来海平面上升的进行了预测，预测结果见表1-5。根据IPCC 1995 年公布的海平面上升情景(按IS92a 情景) ,模拟估算表明，我国沿海相对海平面2030 年将上升4～16 cm , 最好的估计是6～14 cm ; 2050年上升9～26cm , 最好的估计是12～23 cm（表1-6）（王馥棠，2002）。

表 1-5　中国沿海 5 个区域未来海平面上升预测　单位：cm

区域	年份		
	2030	2050	2100
辽宁、天津沿海	13.1	22.5	69.0
山东半岛东南沿海	1.1	5.7	40.2

江苏、广东东部沿海	15.5	25.4	73.9
珠江口附近沿海	7.6	14.8	1.8
广西西部广西沿海	15.3	25.5	74.2

表 1-6 未来气候变化情景下(2030 和 2050 年) 我国 5 大沿海地区海平面的可能上升估计值

	2030年			2050年		
	低估计	最好估计	高估计	低估计	最好估计	高估计
辽宁-天津沿海地区	9.5	11.4	13.1	16.2	19.6	22.5
山东半岛东南沿海地区	-2.5	–0.6	1.1	-0.6	2.8	5.7
江苏-广东东部沿海地区	5.5	11.5	13.5	19	22.5	25.4
珠江三角洲沿海地区	4	5.9	7.6	8.5	11.9	14.8
广东西部-广西沿海地区	11.6	13.6	15.3	19.2	22.7	25.5

1.5 土壤水分

根据 NCARGCM 的输出（张翼，1993）,中国年平均土壤水分含量增加,一般在 0～1%左右,但在长江以南华东、华中地区和华南地区,增加幅度较大,为 1%～3%,年平均土壤水分含量减少出现于云贵高原、四川盆地南部和广西西部、陕西、宁夏两省和甘肃东部、冀东及渤海沿海地区,减幅一般在 0～2%之间。

1.6 粮食安全和自然植被

到2050 年,除了海拔很高的青藏高原地区和东北北部的部分地区以外,几乎其他所有地方的种植制度都将发生较大的变化(表1-7)，目前大部分两熟制地区将会被不同组合的三熟制所替代,而目前的两熟制地区将会北移到目前一熟制地区的中部。三熟制一个很明显的变化就是其北界将会由目前的长江流域北移到黄河流域。因此,在一定程度上可以说,由于种植制度的多样化和复种指数的增加,气候变暖对

我国的农业生产将是有利的（王馥棠，2002）。

田广生（1999）根据 2030 年中国未来气候变化情景，利用中国森林生产力模型预测森林生产率和产量，森林生产力的变化率从东南向西北递增。即东南部生产力变化较小，约 1%～2%，在西北地区生产力变化率在 6%～8%，甚至达到 10%。

另有研究认为，到2050年，各类植被将有明显的北移,南方的热带雨林范围将扩大,东北地区的寒温带针叶林和西南地区的西藏高山植被将缩小，中国西北地区(新疆等)可能从现在的温带荒漠或草原转变为暖温带或亚热带荒漠（王馥棠，2002），见表1-8。

表 1-7　由合成 GCM 模式模拟的 2050 年气候变化情景下我国不同作物种植制度分布面积的可能变化(%)

	当前气候(1951～1980年)	2050年	气候可能变化
一熟制	62.3	39.2	–23.1
两熟制	24.2	24.9	+0.7
三熟制	13.5	35.9	+22.4

表 1-8　由合成 GCM 模式模拟的 2050 年气候变化情景下我国特征性自然植被类型分布面积的可能变化

特征性自然植被类型	当前气候(1951～1980年)	2050年气候	可能变化（%）
寒温带针叶林	2	0	-2
温带针叶阔叶混交林	7	6	-1
暖温带落叶阔叶林	11	11	0
亚热带常绿阔叶林	21	21	0
热带-季风雨林	1	7	+6
温带草原	16	11	-5
温带荒漠	14	10	-4
西藏高山植被	28	20	-8
未定义类	0	14	+14

2　气候变化对黄河流域的影响

2.1 径流

整个流域而言，按 1919～1975 年系列水文数据计算，黄河多年平均天然径流量为 580 亿 m^3，1956～2000 年系列计算的天然径流量（花园口水文站）为 532.8 亿 m^3，减少了 8%。天然径流量变化趋势与降水变化趋势大体一致，总体上均呈减少的趋势（图 2-1），径流减幅大于降水。

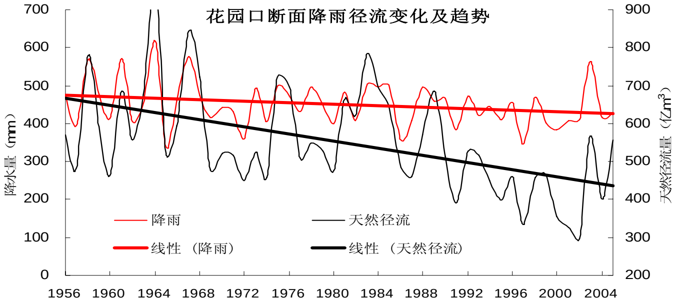


图 2-1 黄河流域降水和天然径流变化

刘昌明等（2003）认为，对于兰州控制断面而言，地表径流有明显的减少趋势，而其它水循环要素变化的趋势并不十分明显。对于花园口控制断面而言，天然径流、地表径流和地下径流减少趋势显著，而降水、蒸散发、壤中流和土壤水分通量也都呈减少趋势，但变化并不突出。根据 WEP-L 模型，王浩等（2005）认为，在“自然—人工”双驱动力作用下，黄河流域 1980-2000 年系列平均狭义水资源总量较 1956-1979 年系列减少 3.1%，其中地表水资源衰减 6.9%，但不重复的地下水资源增加了 21.4%。黄强等（2002）根据黄河年径流资料，

采用小波分析等方法，探讨二元模式下黄河 20 世纪 20 年代以来径流演变规律及其动因。认为，黄河河川径流的总体变化情况分为增大、缓慢减少和迅速减少 3 个阶段，河川径流的趋势成分呈现减少的趋势。其中，河川径流量总体变化情况自 20 世纪 50 年代以来呈缓慢减少趋势，80 年代末期到 90 年代，减少的趋势加剧，黄河实测年径流序列的趋势成分自 20 年代以来也是衰减的。马柱国（2005）基于黄河上、中和下游的径流及气候资料，对径流的年代际变化规律及与气候变化的关系分析认为，黄河流域的径流均存在显著的年代际变化趋势，径流的显著特征是从 20 世纪 80 年代开始的减少趋势，但并未达到历史的最低，径流减少的趋势在下游比上游更显著。

（2）原因

从气候变化的角度，刘昌明（2004）根据气象部门 1977 年收集整理的旱涝史料和中国水利水电科学研究院的《中国旱情年表》，同时参阅《黄河流域水文年鉴》，经过综合分析给出了 1470 - 1980 年黄河流域的丰枯特性。认为，15 世纪后期以来, 黄河流域水量变化明显的以负距平为主, 即枯水年出现的次数多于丰水年出现的次数。邵晓梅等（2007）以中国气象局整编的 1961～2001 年的气象资料为数据基础，采用联合国粮食及农业组织(FAO)1998 年推荐使用的 Penman-monteith 模型，并以 GIS 技术为手段进行黄河流域气候水分盈亏的时空分布格局分析。认为: 黄河流域干旱缺水是一种普遍现象，气候水分盈亏量在空间上总的变化规律表现为自南向北、自东向西气候水分亏缺量呈逐渐增大趋势，大部分地区全年气候水分亏缺量

介于 200～600 mm 之间。马柱国（2005）认为，流域径流变化趋势与气候变化趋势基本一致，说明在年代际尺度上，径流的变化主要受气候的控制；此外，近年来流域地表的干化是流域径流减少的原因，气温的升高更加剧了流域地表干化。基于 1982－1999 年的遥感数据，杨胜天（2002）认为，20 世纪 80 年代至 90 年代初黄河流域气候相对湿润，90 年代中后期相对干旱。

从水资源可再生的角度，李春晖等（2005）利用 T0PSIS 法进行评价，认为，主要产水区域如龙羊峡以上、湟水流域、洮河流域和渭河流域等都是水资源可再生性相对最强或较强的区域，北洛河流域是最弱的区域，其余属于中等或者较弱区域。

从水资源利用的角度，王浩等（2005）认为，人工取用水对于流域水资源演变影响主要表现在：（1）改变了狭义水资源的构成，人工取用水通过袭夺河水减少了地下水的河川排泄量，从而使得河川径流量有明显减少，不重复的地下水资源量有明显增加。虽然狭义水资源总量没有太大变化，但水资源构成变化带来一系列生态环境后果，包括河流生态系统的维护和地下水超采负面生态环境后效等问题；（2）有效降水利用量有所增加，主要是因为人工取用水造成地下水位下降，包气带增厚，增加了有效土壤水资源量，有利于降雨就地利用。田景环等（2005）认为，黄河流域干支流修建的大中型水库加大了河川径流量的损失，大中型水库因新增水面蒸发损失水资源量约 7.7 亿 m^3。张学成等（2005）根据 1956～2000 年黄河流域地表水耗损量逐年系列分析，认为，全流域多年平均地表水耗损量 249.0 亿 m^3 (其中

流域外调水 79.09 亿 m^3，占流域总量 31.8%)，1980-2000 年平均 296.6 亿 m^3 (其中流域外调水 108.3 亿 m^3，占流域总量 36.5%)。黄河流域地表水耗损量年际变化的总体情况是：20 世纪 50、60 年代用水水平相当，相对较低，70 年代稳步上升，80 年代达到顶峰，90 年代之后趋于稳定。整个黄河流域，农业灌溉、工业与生活、农村工业、农村人畜等方面耗损量占总耗损量比例，现状条件下分别为 90.8%、7.5%、0.4%、1.3%。

从植被的角度，首先，黄河流域植被面积与覆盖度增加趋势明显。高歌等（2006）通过 1980～2000 年和 1956～1979 年两时段多年平均年潜在蒸散量差值分析认为，我国大部地区 1980～2000 年时段较前一时段减少，而黄河流域等地则增多。从历史资料分析，黄河流域农耕区面积近 3000 年来增加了 2 倍，如图 2-2。李月臣等(2006)认为，18 年间研究区植被总体呈现增加趋势,植被平均 NDVI 生长季增加了 11.69 %。春、秋两季植被增加趋势最为明显。基于 1982 年～1999 年的 NOAA/AVHRR NDVI 数据，杨胜天（2002）认为，黄河流域植被覆盖状况总体一直处于上升趋势。再者，植被对径流有较为重要的影响。刘昌明（2004）认为，森林对年径流数量有重要的影响，对减少年径流量，特别是减少年地表(洪水) 径流量非常明显。但是，森林对年地下径流量却略有提高。魏晓华等（2005）从水的自然属性出发，从森林变化对径流的影响，径流响应的干扰临界值及水文恢复各方面，探讨森林变化与径流关系的一致性与复杂性。森林变化与径流关系的一致性主要表现在由较长时间尺度表达的年径流量上。认为，

采伐森林就会增加年径流量，而在荒地上造林就会减少年径流量。王浩等（2005）认为，下垫面变化对流域水资源演变影响主要表现在：（1）狭义水资源的总量减少了 20 亿 m^3，其中地表水减少了 41 亿 m^3，不重复地下水增加了 21 亿 m^3。这主要是因为随着水土保持、田间整治、梯田建设等各项人工措施实施，不利于地表水产流，而增加了垂向的下渗量；（2）有效降水利用量增加 113.9 亿 m^3，不仅利用了就地拦蓄下来的径流性水资源，而且还增加了原有一部分无效的土壤水和地表截流；（3）广义水资源总量增加 94 亿 m^3。在上述狭义水资源衰减、其他形式有效水分增加的作用下，流域广义水资源量仍有一定幅度增加。

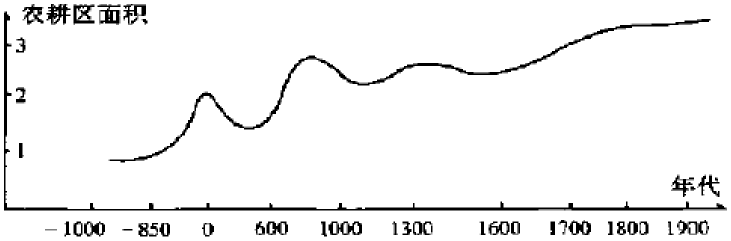


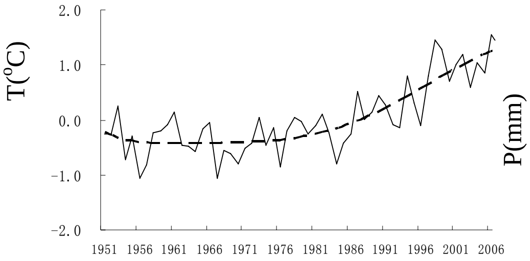
图 2-2　农耕区面积变化趋势（刘国旭，2002）

注:限于所收集资料的不充分和计算方法的选择，只能大致表示流域农耕区面积减少与增加的趋势。

从水土保持的角度，陈浩等（2002）认为，20 世纪 70 年代以来，降雨减水减沙作用不断减小，随着水土保持措施的提高，人类活动减水减沙所占比重不断增大。70 年代与 80 年代气候波动和人类活动影响的平均减水减沙作用分别为 53.4%、28.6%和 46.6 %、71.4 %。

2.2 气温

黄河流域气温在正常的年际和年代际波动中呈上升趋势，与全球增温一致（图 2-3）（贾仰文，第三届国际黄河论坛），在 1961～2000 年期间，黄河流域年平均温度升高了 0.6℃（邱新法），，其中，冬季增温趋势非常明显，夏季增温趋势最弱。



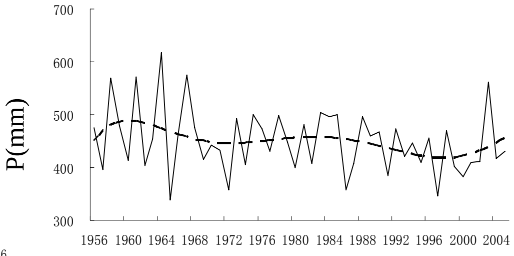


图2-3 黄河流域年平均气温变化

图2-4 黄河流域年降水变化

从年平均来看，1980 年代中期之前偏冷，之后则以偏暖为主，尤其 1990 年代中后期之后持续偏暖且幅度较大。1998 年是分析时段内最暖的一年。冬季，1980 年代以后以偏冷为主，1968 年以后气温达到最低值；夏季，1970 年代之前冷暖交替，1970 年代中期直到 1980 年代末偏冷年多以偏暖年，以偏冷为主，1990 年代以后持续偏暖（任国玉，气候变化与中国水资源）。黄河流域气温持续增温始于 20 世纪 90 年代，进入 21 世纪以后这种趋势尤为显著。

由于地理位置的差异，流域内不同区域温度对全球变暖的响应程度也不尽相同(表 2-1)。其中，河源区变化幅度最大（表 2-1），近 40 年来，黄河上游气温气温平均上升了 0.32℃，高于全球以及中国平均

气温上升速率（蓝永超等，2006），唐乃亥以上地区 20 世纪 90 年代(近期)各区年平均气温均较常年平均偏高 0.5℃左右（史玉品等，水利水电科技进展，2005），气温升幅最大的区域在泽库一带，该区平均气温上升 0.58℃，平均递增率为 0.14℃/10a（蓝永超等，2006）

表 2-1 黄河流域主要来水区间温度变化 (单位: ℃)

区间	1956-1959	1960-1969	1970-1979	1980-1989	1990-2000
全流域	6.2	6.1	6.2	6.2	6.9
龙羊峡以上	-1.5	-2.5	-2.4	-2.2	-1.9
龙羊峡-兰州	1.7	1.3	1.4	1.5	2.3
兰州-河口镇	6.6	6.8	6.9	7.1	8.0
河口镇-龙门	8.2	8.3	8.3	8.3	9.3
龙门-三门峡	9.6	9.7	9.7	9.7	10.4
三门峡-花园口	12.6	12.9	12.9	12.7	12.5
花园口以下	12.2	12.6	12.5	12.5	12.1

2.3 降水

黄河流域多年平均降水量为447mm（1956～2000年系列），降水自东南向西北逐渐减少（图2-5）。黄河流域降水量年际变化悬殊，降水量愈少，年际变化愈大。由于黄河流域降水量季节分布不均和年际变化大，导致黄河流域水旱灾害频繁。

图 2-5 黄河流域多年平均降水量等值线图

黄河流域降水总体呈波动下降趋势（图2-5），且以20世纪90年代降水最少，进入21世纪以来，降水略有增加[*]，降水总体呈现出波动下降的趋势。从年代际变化看，19世纪80和90年代气温变化幅度最大，尤其是90年代，流域气温增幅达到0.7℃（相对80年代）（邱新法等，自然资源学报，2003；贾仰文等，第三届黄河国际论坛，2007）。唐乃亥以上地区20世纪90年代(近期)各区年平均气温均较常年平均偏高0.5℃左右,而比前期升温达0.7～0.8℃;降水量不仅较多年均值偏少,更比前期显著减少,其中玛曲一带最大减幅达15.8%（史玉品等，水利水电科技进展，2005）。

黄河流域年降水量及各季节降水量均呈波动减少趋势（表2-2）。从年平均来看，1970年代之前降水以偏多为主，且幅度较大，1964年降水最少，之后降水变化幅度较小，1970年代中后期虽以降水偏多为主，但幅度较小，1990年代以来以降水偏少为主。对1956-2002年区域平均年降水量标准化序列进行MK检验发现，黄河流域降水1970年以来持续减少，1990年代以来减少尤为明显（任国玉，气候变化与中国水资源，p69）。庞爱萍等（庞爱萍等，2008）基于827个降水监测站1951-1998年的逐月监测数据，重点研究了1951-1998年期间典型降水等值线200、400和800mm的空间移动情况，结果表明：黄河流域黄土高原一带干旱化趋势十分明显，典型降水等值线南移。然后对1951-1979和1980--1998年前后2个时段黄河流域年、汛期和非汛期降水量空间变化分别进行分析，发现黄河流域降水减少幅度最

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[*] 50年代统计时段为1956~1960年系列，2000s统计时段为2001~2005年系列，以下同

大的区域在黄土高原大部和黄河下游，但是在黄河源头、伊洛河流域、汾河源头及其下游等则呈增加趋势，而且汛期降水量与非汛期降水量的变化趋势在空间上并不完全一致。

总之，黄河上游和源区降水从20世纪90年代有所减少，气温明显上升，导致了黄河源区和上游径流量锐减，黄河断流天数增多，黄河上游来水量的多少是影响华北地区水资源的重要原因黄荣辉等（气候变化与环境，2006）。

表2-2 黄河流域主要来水区间温度变化 (单位: mm)

区间	1956-1959	1960-1969	1970-1979	1980-1989	1990-2000
整个流域	477.0	471.3	446.1	445.4	422.7
龙羊峡以上	460.4	494.2	482.0	507.2	468.8
龙羊峡-兰州	476.3	491.6	487.3	480.4	459.7
兰州-河口镇	288.9	277.3	269.5	243.3	262.2
河口镇-龙门	510.6	463.6	427.9	415.6	397.3
龙门-三门峡	585.4	578.4	532.7	553.6	492.3
三门峡-花园口	738.5	685.0	639.9	671.7	606.1
花园口以下	697.2	680.3	645.7	564.4	660.0

2.4 蒸发

黄河流域以干旱半干旱气候为主，降水量少且时空分布严重不均，蒸发旺盛。年蒸发量达1100mm左右，黄河上游的甘肃、宁夏和内蒙古中西部地区属国内年蒸发最大的地区，最大年蒸发量可超过2500mm。

黄河流域水面蒸发量随气温、地形、地理位置等变化较大。兰州以上多系青海高原和石山林区，气温较低，平均水面蒸发量 790mm；兰州至河口镇区间，气候干燥、降雨量少，多沙漠干草原，平均水面

蒸发量 1360mm；河口镇至龙门区间，水面蒸发量变化不大，平均水面蒸发量 1090mm；龙门至三门峡区间面积大，范围广，从东到西，横跨 9 个经度，下垫面、气候条件变化较大，平均水面蒸发量 1000mm；三门峡到花园口区间平均水面蒸发量 1060mm；花园口以下黄河冲积平原水面蒸发量 990mm。黄河流域气候条件年际变化不大，水面蒸发的年际变化也不大，最大最小水面蒸发量比值在 1.4～2.2 之间，多数站在 1.5 左右；Cv 值在 0.08～0.14 之间，多数在 0.11 左右（见表 2-3）（张学成，黄河流域水资源调查评价，2006）。

表 2-3　长系列代表站水面蒸发量特征值统计　　单位：mm

站名	多年均值	Cv	最大值	发生年份	最小值	发生年份	最大/最小	备注
民和	968	0.14	1352.5	1965	841.8	1992	1.6	
互助	802	0.09	963.6	1956	657.1	1964	1.5	
挡阳桥	1863	0.19	2724.3	1983	1213.1	1967	2.2	φ20 系列
太原	1580	0.08	2080.0	1955	1427.5	1964	1.5	φ20 系列
临汾	1800	0.11	2274.8	1960	1466.6	1964	1.6	φ20 系列
神木	921	0.12	1096.7	1999	721.8	1996	1.5	
赵石窑	951	0.11	1100.8	1987	718.5	1992	1.5	
林家村	769	0.10	942.8	1997	669.7	1993	1.4	
交口河	942	0.12	1124.8	1997	730.3	1983	1.5	
灵口	721	0.13	865.7	1981	580.0	1993	1.5	

观测事实和研究均表明，黄河流域最近40年的蒸发皿蒸发呈下降趋势（图2-6）。且以春季和夏季下降最为明显徐宗学等（水文，2005）。黄河流域局部区域与整个流域的气候变化趋势并不完全同步，黄河流域上游和下游蒸发皿蒸发量呈下降趋势，中游呈持平并略有上升趋势（邱新法等，自然资源学报，2003）。郭军等（水科学进展，2005）认为近50年来黄淮海流域蒸发量减少十分显著，造成蒸发量减少的直

接气候原因可能是日照时数及太阳辐射的减少，平均风速和气温日较差的降低可能也起着重要的作用。

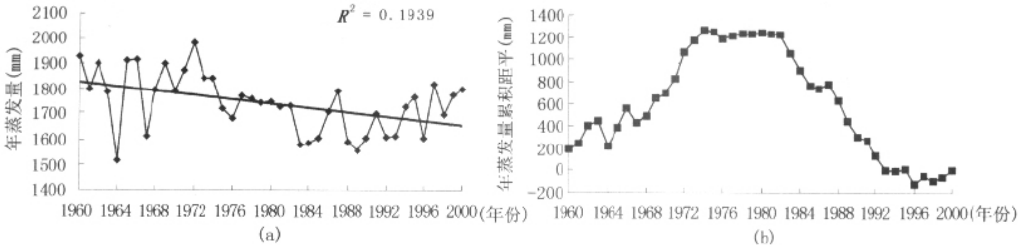

图2-6 1960～2000年黄河流域蒸发皿蒸发量特征变化曲线

与蒸发皿蒸发相反，黄河流域实际蒸发呈逐年增大的趋势。李林等（气象，2000）认为黄河上游流域日照时数、气温及饱和差的增加，加剧了草地蒸散量的增大，而蒸散量的增大和降水量的减少则直接导致了黄河上游流量的减少和草地荒漠化的蔓延。孙睿等（孙睿，等. 自然资源学报，2003）的研究表明，黄河流域多年平均年蒸散量年际间变化很大，且以东南部蒸散量最大，其次是兰州以上区间，宁蒙河段及鄂尔多斯高原蒸散量最小。徐宗学等（水文，2005）认为整个黄河流域的年平均蒸发量分布规律是从东北部向西南地区逐渐减少，随着气温升高，水面蒸发量减少的原因与日照和太阳辐射有关。买苗等（气象，2006）的研究认为，，就整个流域日照百分率呈明显下降趋势，年平均日照百分率在20 世纪90 年代较60 年代下降了2.49 %；日照百分率的下降主要表现在夏季和冬季，春季和秋季下降不明显。

多数研究认为：蒸发皿蒸发呈下降趋势，而实际蒸发却表现为明显升高；蒸发变化的空间特征研究存在很大差异，原因可能是与所选用的资料有关。据分析（刘昌明，水科学进展，2004），蒸发皿蒸发

下降的主要原因是近年来全球辐射的下降；黄河流域陆面实际蒸发量明显增加，这是由于灌溉等用水量加大造成的，尽管太阳辐射有所减弱，但在比较干旱的地区，供水条件才是决定陆面蒸发的主要因素。

2.5 地下水

1980 年～2000 年黄河流域平均年地下水资源量为 377.6 亿 m^3，其中矿化度不超过 1g/L 的地下水资源量为 352.3 亿 m^3，占 93%，矿化度 1g/L～2g/L 的地下水资源量为 25.3 亿 m^3，占 7%。在黄河流域地下水资源量中，山丘区地下水资源量为 265.0 亿 m^3，平原区地下水资源量为 154.6 亿 m^3，山丘区与平原区之间的重复计算量 42.0 亿 m^3（潘启民等，2007）。

2.6 泥沙

黄河多年平均输沙量约为16亿t，多年平均含沙量37.6kg/m3，最高含沙量920 kg/m3，居世界之冠。黄河泥沙的来源比较集中，并有“水沙异源”的特点。黄河源区（唐乃亥以上）面积仅占全流域的15 %，泥沙量极少，多年平均径流量却占到黄河总径流的1/ 3 以上，是黄河重要的产水区, 被称为“黄河水塔”； 黄河泥沙主要来源于中游（河口镇至花园口），占全河沙量的90%以上，位于黄河中游7. 86万km2 的多沙粗沙区更是水土流失的重中之重，该区域年输沙量达9亿t之多。

黄河流域泥沙的突出问题是水沙关系不协调（李国英，黄河重大问题和对策，2001）。水沙关系不协调造成泥沙淤积，抬高河床，加

剧“二级悬河”发展，降低水利工程防洪能力，提高对气候变化的脆弱性，引发洪涝灾害。黄河沙量伴随着水量减少，1986年以来沙量减少近40%。一方面由于近期大暴雨较少，另一方面上中游水利水保综合治理措施起到减沙作用。但治理措施在暴雨条件下作用甚微，因此沙量减少并不稳定，在一般降雨年份水量减少较大，而在发生高强度大暴雨的年份出现高含沙量洪水，沙量仍很大，出现两极分化趋势（张学成，黄河流域水资源评价，2006）。

需要指出的是，尽管黄土高原区的人类活动影响增强，甚至有的区域已超过气候变化对水沙的作用，但是，黄河中游降水稀少、植被稀疏的特点决定了其水资源状况对气候变化，尤其是降水变化特别敏感，因此气候变化对产水产沙的影响研究十分重要。

2.7 水文极值

黄河的暴雨洪水主要来自中游河口镇到花园口区间和兰州以上区间。其中，三花间无控区的暴雨洪水最为严重，是气候变化影响研究的重点之一。20 世纪 80 年代以来，黄河上中游地区暴雨洪水的量级和频次均明显减少（图 2-7）。进入 21 世纪以来，少有 5000m^3/s 以上的洪水出现。如以花园口洪峰流量大于平滩流量的洪水为下游漫滩洪水，20 世纪 50 年代为 9 次，接近每年一次；而 1986～2000 年的 15 年期间只有 3 次。从 2002 年至今年调水调沙以前，下游最大洪峰流量只有 4200m^3/s。气候变化和水利工程的调节都会影响洪水的频次和强度。

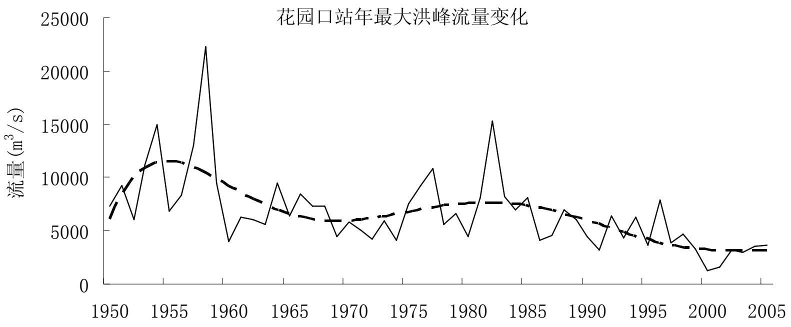

图 2-7 花园口站历年最大洪峰流量变化

干旱缺水是黄河的主要问题。据观测资料记录，黄河流域从 1965 年起连续干旱，自 19 世纪 90 年代以来，干旱程度不断加剧，范围逐渐扩大。气候变化导致的来水量减少是流域干旱的重要要原因。

黄河流域纬度差异较大，黄河凌汛是其他江河所没有的，黄河干流宁蒙河段和下游河段冰情最为严重，容易泛滥成灾。19 世纪 90 年代以来，黄河流域冬季气温明显偏高，黄河宁蒙河段凌情呈现出新特点，表现在：① 封河天数减少，封开河日期不稳定，预报难度增大；② “地上悬河”发展，开河期水位持续增高（图 2-8），堤防压力增大。2007～2008 年度凌汛期，宁蒙河段三湖河口水位高达 1021.22m，较历史最高水位高出 0.41m，导致内蒙古杭锦旗段出现溃堤。

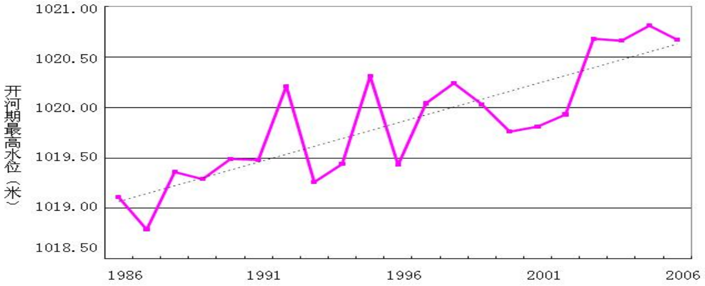

图 2-8 三湖河口水文断面 1986 年以来开河期最高水位变化曲线

3 气候变化对黄河上中下游的影响

目前，基于观测数据的黄河流域水资源变化研究较多，从区域划分来看，主要进行了源区、上游、中游与下游的相关研究，部分研究则从全河的角度对水资源变化情况进行了分析，基于对所收集文献资料的分析，主要研究观点分河段叙述如下：

3.1 源区与上游

黄河源区称为黄河流域的“水塔”，其地处高寒，人类活动影响比较少，对气候变化尤为敏感，因此关于黄河源区径流变化的研究相对比较多。相对于源区，黄河上游人类活动影响程度较强，数据积累较为丰富，因此，也有一部分学者把源区与上游结合起来进行研究，总之，源区与上游相关研究主要有：

（1）径流变化及原因分析

多数学者认为，20 世纪 90 年代以来黄河源区与上游径流量大幅度减少，流量年内分配由 50-80 年代的双峰转变为 90 年代以来的单峰，如图 3-1 与图 3-2。张士锋等（2004）认为，黄河源区的水文循环规律在 20 世纪 90 年代发生了很大的变化，河源地区水循环变化的主要特点是：在降水量变化不大而且略有增加的前提下，径流量有比较明显的下降，而且，径流也更加集中在汛期。刘晓燕等（2005）对源区径流变化研究进展进行了总结和分析，通过分析唐乃亥水文站径流量变化过程证明了这一点。常国刚等（2007）利用 1955～2005 年黄河源区玛多气象站和黄河沿水文站气象、水文资料，分析了该区域

地表水资源、气候及冻土演变规律。认为，黄河源流量丰枯转化频繁，进入 20 世纪 90 年代以来，黄河源流量呈减少趋势，流量年内分配表现为单峰型。李林等（2004）利用 1961－2002 年黄河上游唐乃亥水文站水文资料及同期该流域气象资料，研究黄河上游流域气候变化及其对地表水资源的影响;结果表明：黄河上游年流量呈现出逐年减少趋势，20 世纪 90 年代以来减少趋势更为明显。

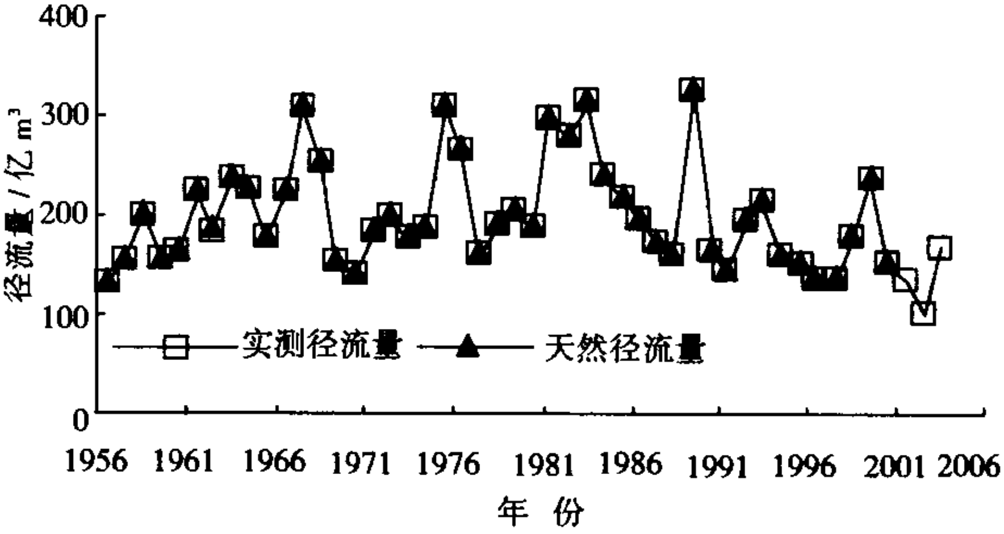

图3-1　黄河唐乃亥水文站径流量变化(1956～2003年)

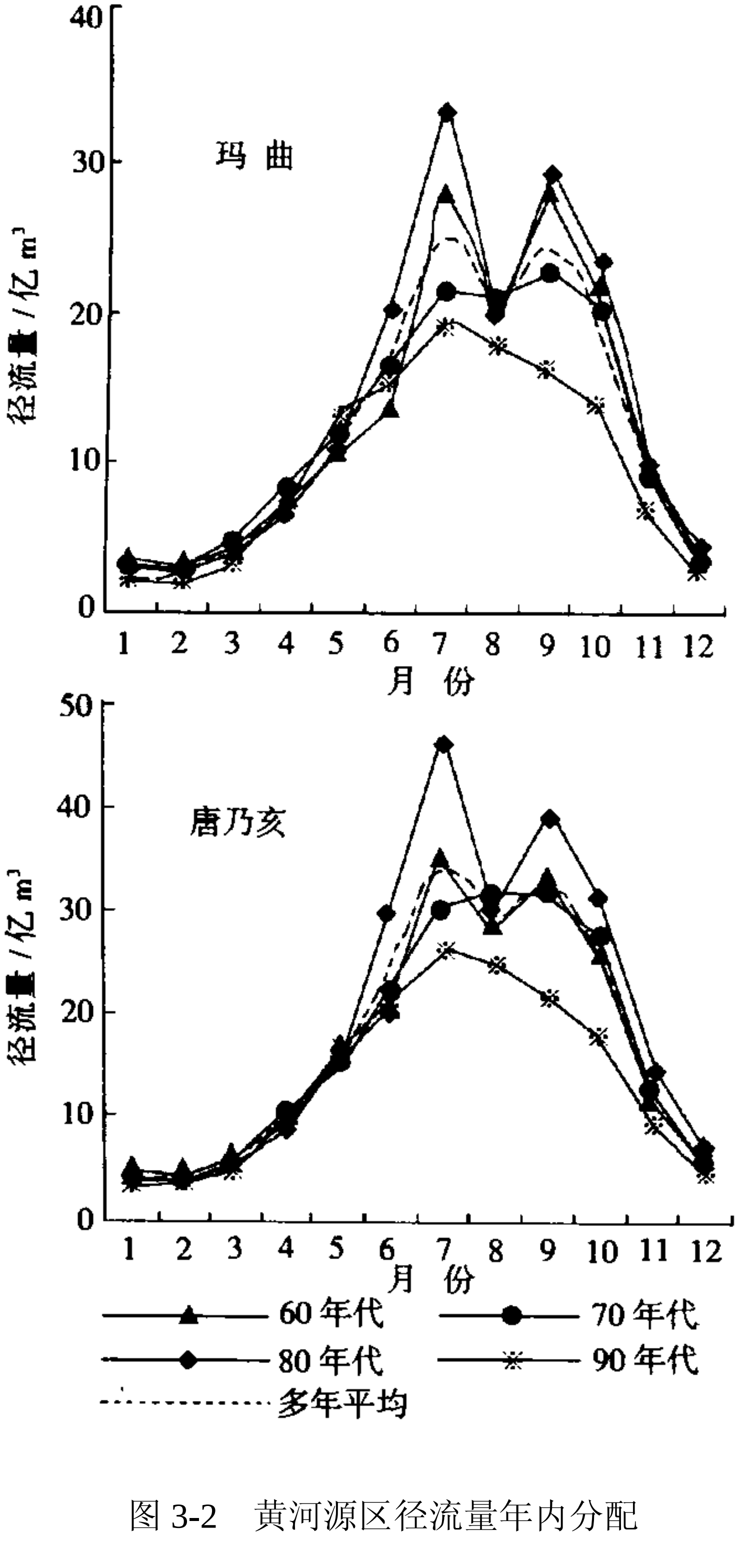

图 3-2　黄河源区径流量年内分配

至于径流量减少的原因，国内研究还有一定的分歧，但多数人认为是降水量的减少。刘晓燕等（2005）认为，降水是引起径流变化的重要原因,不同区域降水变化、季节降水变化以及降水强度变化等原因可能导致了径流量减少;源区下垫面发生变化影响了降水量与径流量关系,但尚难明确气候变化和人类活动分别对下垫面变化的影响程度。谢昌卫等（2007）通过互谱分析方法认为，20 世纪 80 年代后期，长江-黄河源区径流量大幅下降的主要原因是区域内降水量的减少。常国刚等（2007）认为，源区降水量对流量有着较为显著的影响，且具有一定的持续性；黄河源区气温的显著升高对于加大流域蒸发量导致流量补给的减少作用要大于其升高致使冰雪融水的补给作用，其中春季气温回升的这一效应更为显著。周德刚等（2006）分析了黄河源区 1960～2000 年气候变化特点,对蒸发进行了估算, 并分析了植被和冻土的变化，对径流在 20 世纪 90 年代后明显减少的原因进行了探讨。认为，黄河源区径流减少的直接原因是降水的减少；在 90 年代后降水强度的减弱也可能是径流减少的重要原因。史辅成等（2005）经过对河源地区降水量与径流量关系分析，以及对中游地区渭河、伊洛河、沁河 2003 年汛期径流量和汛期多年径流量的对比分析认为，径流量偏小应与降水量连续偏小、超过一定量级的暴雨次数偏少、气温的增高以及蒸发量增大等多种因素有关。蓝永超等（2006）分析了黄河上游几十年来降水、温度、径流等水循环素的变化过程与特征。认为，受主要产流区域降水减少,气温上升的影响,黄河上游产水量呈持续递减的态势。

张士锋等（2004）则认为，径流减少的主要原因是蒸发量的增加，河源区径流量与上游各水文站的径流量有较好的相关关系，河源区径流减少，整个黄河上游来水量也有下降的趋势，影响全流域的水资源供需平衡。蓝永超等（2006）利用相关台站的降水、径流观测资料, 分析了黄河上游汛期径流的丰枯变化特征及其环流背景。认为，黄河上游(唐乃亥以上) 流域丰、枯水段基本上是交替出现的，总体上枯水持续时间多于丰水，一个完整的丰枯循环周期大约在 18 a 左右。黄河上游径流的丰、枯，与大气环流的异常有着非常密切的关系。

黄河源区多年平均径流量为 205 亿 m^3。唐乃亥站 20 世纪 90 年代平均天然径流量为 176 亿 m^3，比多年平均减少 15%。黄河源区是黄河的主要产流区，近 40%的黄河总径流来自黄河源区，因此黄河源区又称为黄河流域的“水塔”，黄河源区地处高寒，人类活动影响比较少，对气候变化尤为敏感，因此关于黄河源区径流变化的研究比较多。一些研究认为气候变化是黄河源区天然径流减少的主要原因[蓝永超, 2006]。尽管 20 世纪 90 年代以来，黄河源区降水减少 5%，但降水强度明显减少，土壤下渗量增加，导致产流量减少；黄河源区近 50 年来气温明显升高造成至少 4%以上的径流量的损失（Wang S.W. 2002; Ding Y.H. 2002，Li. 2002）。黄河上游和源区降水从 20 世纪 90 年代有所减少，黄荣辉等（气候变化与环境，2006）研究认为气温明显上升，导致了黄河源区和上游径流量锐减，黄河断流天数增多，黄河上游来水量的多少是影响华北地区水资源的重要原因。

（2）冰川冻土与湿地

冰川冻土是黄河源区水资源赋存的一种形式，多数学者认为，源区冻土退化趋势明显。常国刚等（2007）认为，黄河源区冻土呈现出显著的退化趋势，冻土厚度与流量总体上呈显著的正相关关系，其不断减小削弱了自身天然隔水层的作用。基于归一化植被指数(NDVI)数据分析，周德刚等（2006）认为，植被在 90 年代后期呈现退化的趋势，冻土在 80 年代以后表现出的明显的退化趋势，植被冻土的退化可以使得冻结层上水位下移，土壤水向土壤下层的渗漏增加, 也会造成径流的减少。曹文炳等（2006）认为，黄河源区多年冻土退化总体趋势表现在以下几方面：由连续多年冻土区逐渐变为不连续冻土分布区、富含冰冻土逐渐退化为干燥冻土、季节融化深度增加、冻土下界高程上升等。潘竟虎等（2005）对黄河源区 1986～2000 年土地利用和景观结构的时空变化特征进行分析表明，源区林地、湿地、草地和冰川面积减少，建设用地、耕地和未利用土地面积显著增加，土地综合利用程度下降。

（3）冰川和积雪

冰川退缩是气候变暖的佐证。据统计，中国西部有 82%的冰川都在迅速缩减。黄河源区的冰川主要分布于阿尼玛卿山和巴颜喀拉山。阿尼玛卿山位于青藏高原的东昆仑山，为黄河源区重要冰川作用区，山脉分布范围在北纬 34 20’至 35 ，东经 99 10’至 100 间，分布有现代冰川 58 条，面积在 125km^2 左右.

对源区近 50 年来的气温、降水资料分析表明，源区气温持续上升，

降水量明显减少，气候总体向暖感化方向发展，这种变化导致源区冰川加速消融，冻土广泛退化，湖泊玉沼泽地疏干，草场退化等。源区冰川面积在 1966-2000 年间面积减少了 17%（刘时银等），年均减少比例是 1966 年前数百年来冰川退缩比例的 10 倍; 冰川水资源损失达 23.9 亿 m3，相当于兰州段多年平均径流量的 10%左右。伴随气候变化，冻土退化、鼠害和过牧的影响，草地生态系统变化明显，覆盖度总体降低，“黑土滩”。与土地沙化发展较快。源区干流自 20 世纪 90 年代以来进入到相对较强的枯水期，水资源量有所减少，这加剧了黄河中下游地区水资源的紧缺程度。

表 3-1 黄河流域典型冰川作用区不同时期冰川面积变化（刘时银等，2002）

年　代	冰川面积（km2）	变化面积（km2）	面积变化率（%）
末次冰盛期	391.6		
小冰期最盛期	147.8	-243.8	-62
1966 年	125.5	-17.5	-15.1
2000 年	103.8	-22.74	-17.3

3.2 中游

黄河中游是黄河泥沙的最重要来源区，生态环境脆弱，人类活动强烈，径流变化研究侧重于水沙关系协调方面。

（1）水沙变化

与黄河上游来水减少的趋势相似，黄河中游水沙总体上也呈现在减少的趋势，年内分析表明，降水、径流与输沙较为集中。许炯心（2004）研究认为，黄河中游河口镇至龙门区间的径流可再生性指标有减小的趋势。饶素秋等（2001）对 1950 年以来黄河上中游水沙变

化特点进行了分析。分析认为，自 50 年代以来黄河上中游水沙总体上呈逐年代递减的趋势，其中尤以 80 年代和 90 年代减少最为显著。90 年代是 1950 年以来黄河上中游径流总量最少的十年，而输沙量较 80 年代有所增加。尹国康（1998）认为，多沙粗沙区年内降水、径流、尤其是输沙十分集中, 汛期 4 个月的侵蚀产沙量占到全年的 97%以上, 而汛期的产沙又往往集中于几场大暴雨。高国甫等（2002）对河龙区间 1950－1999 年近 40 年 75 场次实测洪水资料的统计分析认为，与黄河上游洪水时空分布特性不同，河龙区间洪水特性是时空分布集中在 7、8 月份，其中 67%的洪水又集中在 7 月 15 日至 8 月 15 日，俗称“七下八上”。

（2）原因

从气候的角度，于淑秋（1996）应用 T 检验方法对中国黄河中游地区 1470～1991 年夏季（5～9 月）旱涝等级序列进行分析，结果表明: 该地区气候存在着两次百年尺度突变, 即 17 世纪 50 年代前后（旱转涝）和 18 世纪 60 年代初期（涝转正常）。王云璋等（2004）利用流域内旱涝等级和部分树木年轮资料，重建了黄河中游 1575 年以来的干旱指数序列，分析了干旱的历史规律和变化趋势。认为：①干旱变化的阶段性显著，近 429 年大体经历了 6 个干旱段和 5 个不旱段，干旱段特旱、大旱出现概率分别是不旱段的 3.3 倍和 2.1 倍，而不旱段涝、不旱出现的概率则分别是干旱段的 6.5 倍和 1.8 倍；②干旱变化还具有较显著的周期性，主要周期长度为 5、7、22.5、32、55、69 年和 123 年。王昌高等（2004）根据黄河中游夏半年各季干旱指数系

列，分析了干旱发生频率及其变化特点。认为，黄河中游干旱发生概率较高，初夏和秋季发生干旱与否的比例大体是 7:3，盛夏为 6:4；1955 年以来发生三季连续特旱的有 1997 年，而无三季连涝，只有两季连涝情况；干旱发生概率随年代递增，1986-2002 年夏半年特旱、大旱出现概率是前期的 3 倍多，秋季干旱指数一直维持高值，基本没有秋汛。

从植被覆盖减水的角度，刘昌明（2004）根据流经黄土高原子午岭与黄龙山大面积天然范围内不同森林覆盖率的河流水文站资料，分析建立了中小流域森林率与年径流关系方程组，采用反问题计算求解了河川径流与森林覆盖率的定量关系。认为，流域完全退耕还林封育后，未来森林率接近或达到 100%时，年径流将减少 30%～53%。许炯心（2004）研究认为，水土保持措施的实施增加了蒸发和蒸腾作用，气温的升高增加了蒸发，因而导致了河龙区间径流可再生性指标的降低。

黄河中游，特别是黄土高原是黄河泥沙的最重要源区，大约 80% 的泥沙来源于该区域； 20 世纪 70 年代以来，人类活动影响强烈（张胜利等, 1996；陈江南，2004）；生态环境脆弱。因此，对黄河中游的研究，主要集中在如何评估气候变化和人类活动对径流和泥少的影响方面。建国以来，黄河中游开展了大规模的水土保持工作，河龙区间水沙来量自 70 年代以来开始减少，80 年代大幅度减少。与 1950～1969 年平均值相比，80 年代河龙区间径流量减少了 $36.15\times10^8 m^3$，输沙量减少了 $6.2325\times10^8 t$。黄河中游水沙变化是气候变化和人类活动共

同作用的结果，区分气候变化和人类活动对流域减水减沙的作用是非常必要的。黄河中游水沙变化主要以水文法和水保法研究为主，陈浩等(陈浩等, 地理研究， 2002)在此基础上发展了地理环境要素法分析水沙变异及成因，认为径流量和输沙量与地理环境因子的影响密切相关，20 世纪 70 年代以来, 降雨减水减沙作用不断减小, 随着水土保持措施的提高, 人类活动减水减沙所占比重不断增大。70 年代与 80 年代气候波动和人类活动影响的平均减水减沙作用分别为 53.4%、28.6%和 46.6%、71.4%。王国庆等（王国庆）分析了气候变化和人类活动对黄河中游径流量影响的分析结果，表明 1970～2000 年期间人类活动是黄河中游径流量减少的主要因素，气候变化和人类活动对径流量的影响分别占径流量减少总量的 38.5%和 61.5%。

3.3 下游

相关研究（刘国旭，2002）表明，先秦时期,黄河下游冲积平原上形成众多的分流,而且在冲积扇的前沿洼地和河间洼地,天然湖泊十分发育,据先秦文献记载统计,当时黄淮海平原范围内,约有大小湖泊 40 个,可以肯定文献记载有不少遗漏,而且地域上很不平衡。汉唐时期,影响河湖布局的自然因素变化并不激烈。平原湖泊虽有逐渐淤浅趋势,但总体布局却没有发生根本性的变化。先秦时期的天然湖泊在这一时期内基本尚存。《水经注》中记载的湖泊超过 500 处,其中位于黄淮海平原上的湖沼共有 190 多个。唐宋以后,黄淮海平原的湖泊发生了根本性的重大变化,众多的湖泊淤为平陆。《水经注》上记载的比较大的

湖泊,如河北省的大陆泽,山东省的大野泽、菏泽,河南省的圃天泽、黄泽等,现在有的已完全消失,有的也只残存极小部分。

当前，黄河下游径流变化与上、中游及重点支流来水息息相关。刘昌明（2004）根据黄河流域下游花园口站以上流域面平均年降水量与天然径流深的资料统计分析认为，从 20 世纪 60 年代以来水循环要素均呈减少的趋势。以黄河流域花园口以上年径流系数的变化以 1968 年为界, 把 1952－2001 年的数据可以分为两个阶段。两个阶段的径流系数分别为 0.185 和 0.168。认为，在气候变化和土地利用土地覆盖变化共同影响下, 径流系数减少 9 %左右, 导致年径流的减少为 56 亿 m^3 左右。

黄河入海水量的计算，采用利津水文站实测径流量扣除利津以下工农业用水得到的。黄河入海水量 1956～2000 年平均为 313.2 亿 m3，其中，1956～1979 年平均 409.8 亿 m3，1980～2000 年平均 202.7 亿 m3（较 1956～1979 年减少了近 50%）。黄河入海水量总体上呈减少的趋势。一方面是由于天然来水量的不断减少，另一方面则是国民经济用水不断增加。

黄河下游断流始于1972年,20世纪90年代以后不断加剧。1972～1999年的28年间,黄河下游发生断流的年份达22年, 平均5年4次断流，累计断流1092天，平均每年断流50天。1997年，花园口实测径流量是仅次于1928年的枯水年，断流历时与断流河段长分别为226天和704公里（到开封附近），是创造了黄河断流的历史记录（管华，2001；张学成，2006）。

黄河流域的生态环境状况与黄河的水资源问题紧密联系。天然径流量的锐减的同时，黄河流域社会经济的迅速发展对水资源的需求不断扩大，二者矛盾日益尖锐，河道内大量生态环境用水被挤占，入海水量急剧减少（图 3-3）。入海水量减少甚至断流导致黄河下游河道萎缩严重，二级悬河迅速发展，不仅使堤防“冲决”和“溃决”的可能性增大，还导致下游河道内湿地萎缩，水质恶化，生物多样性受到破坏等。根据 20 世纪 90 年代统计，因黄河下游断流，河口区植被面积减少了近一半，鱼类减少近 40%，鸟类减少 30%。21 世纪以来的水量调度和调水调沙对缓解下游及河口地区身态环境问题初见成效，但功能性断流问题和流域层面上的生态环境问题还远未解决。

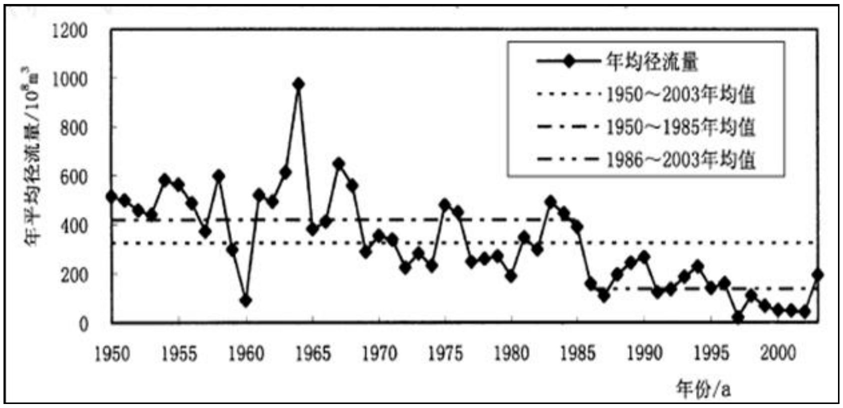

图 3-3　黄河入海口年平均径流量变化

4 影响机理研究

4.1 成因分析

气候变化对黄河流域水资源系统影响机制研究主要侧重用于气候变化的基本规律、旱涝事件成因分析、气候变化和人类活动对水资源影响识别等方面。

关于黄河流域旱涝事件规律及其成因的研究比较多。王云璋等（人民黄河，2004）利用流域内旱涝等级和部分树木年轮资料，重建了黄河中游1575年以来的干旱指数序列，分析了干旱的历史规律和变化趋势。马柱国等（马柱国等，地理学报，2003）利用中国1951-2000年的月降水和月平均气温构造了北方地区地表干湿状况的地表湿润指数，认为华北地区近10年极端干旱频率显著增加，是近百年来少有的大范围高强度的极端干旱频发期，同时极端湿润发生的频率相对减少，极端干旱频发区往往对应着增暖明显的区域，极端干旱频率增加是否与区域增暖有关，尚需进一步研究。叶笃正等（叶笃正，黄荣辉，等. 长江黄河流域旱涝规律和成因研究. 1996）分析了黄河流域近百年的旱涝变化情况，指出黄河流域从1965年起连续干旱，自90年代以后，干旱不断加剧，指出影响黄河流域旱涝变化的主要环流因子及其对应关系。根据史料和树木年轮重建近400年来的降水量序列，研究了全球变暖的条件下的黄河流域降水量的可能变化，指出全球平均气温偏高（低）与黄河中游地区年降水量偏少（多）存在一定的对应关系（刘晓东等，2002）

在全球变暖大背景下探讨黄河上游大范围降水发生的物理气候成因，取得了许多重要成果。通过分析海温异常所造成的大气物理场的变化，揭示了海洋-大气系统动态对中国降水时空分布影响的许多重要事实，探讨了东亚冬、夏季风的强弱对青海高原及西北地区汛期降水的影响（张存杰等，高原气象，2002）；研究认为全球变暖使西北地区域夏季风减弱，8月偏南风分量减少，偏北风分量加强，并存在变干的趋势。受其影响，黄河上游主要产流区吉迈-玛曲区间降水持续减少，这是导致黄河上游天然来水近十余年持续减少的主要原因之一张广周等（新疆气象，2000）。黄河上游降水变化是周期性的，主要受天体运动规律和太阳黑子强弱变化周期、副高脊线位置变化周期、地极移动振幅变化周期的影响（杨建平，中国沙漠，2005）。

黄河流域气候变化对水资源的影响研究方面，认为受气候变化和人类活动的双重影响，并从径流形成机理方面进行深入研究。夏军等（夏军等，地理学报，2003）依据系统理论方法，对黄河干流水资源量的调控分析表明，20世纪90年代严重的黄河断流问题主要受人为因素影响；黄河天然年径流序列的趋势成分自20世纪50年代以来的变化与人类对水土资源的开发利用有很好的对应关系，人类活动对水土资源的开发利用是黄河河川径流演变的主要原因之一（蒋晓辉等，自然资源学报，2003）。刘昌明（刘昌明，水科学进展，2004）指出兰州以上黄河流域近50年来降水量减少了5 %～10%，相应地径流则减少了15%～20 %，径流的减少程度大于降水量的减少，其原因与下垫面的变化相关，在气候变化和土地利用土地覆盖变化共同影响下，径流

系数减少9%左右，导致年径流的减少为56亿m3 左右；王西琴等（自然资源学报，2006）认为20世纪80年代以后，人为因素的影响程度在逐渐增强，其原因在于人类活动改变下垫面导致径流减少。郑红星等（地理科学进展，2003）的则持另一观点，20世纪90年代的径流年内分配特征出现了较大的变化，突出表现在汛期径流量的减少，气候变化是主要有原因；在河源区，特别是一些不易开展生态保护建设的干旱、高寒地区，植被覆盖呈下降趋势（下降速率约0-3.0%/年），反映了气候暖干化的影响（杨胜天等，2002）。

4.2 模拟技术

大尺度的海气耦合模式（AOGCMs）对于未来气候预报来说目前是最为可信的。有关黄河流域未来气候模拟预测的研究，以气候模式预测结果为主，也有在历史和现状基础上的综合分析结论。一般认为，黄河流域未来几十年，甚至100年内，气温将继续升高，降水可能略有增加，气象旱涝事件有所增加。

基于气候模式和水文模型的气候变化评价模型也应用于黄河河流域气候变化影响研究。徐影等（赵宗慈，徐影，2002；徐影，2002；赵宗慈等，2003；丁一汇，徐影，2003）（徐影，2002；丁一汇，徐影，2003）。利用 IPCC 提供的 7 个全球模式模拟结果，进一步计算了中国 10 大流域 21 世纪气温和降水的变化，其中黄河流域气温和降水总体上均呈上升趋势（表 4-2,4-3），但 2050 年以前，降水增加仅5%左右，气温上升了近 3℃，这一结果可能会导致黄河流域水资源的

减少。当然，由于全球气候模式对区域尺度的模拟存在较大的不确定性，未来还需做更多的深人研究。

表4-2 全球模式预估21世纪黄河流域年平均温度变化（单位：℃）

	2020年	2050年	2070年	2100年
SRES-A2	1.3	2.8	4.7	5.9
SRES-B2	1.5	2.7	3.7	4.1

表4-3 全球模式估计21世纪黄河流域年平均降水变化（单位：%）

	2020年	2050年	2070年	2100年
SRES-A2	-1	4	9	12
SRES-B2	0	5	8	11

许吟隆等（许吟隆，气候变化研究进展，2005）利用区域气候模式系统（PRECIS: Providing Regional Climates for Impact Studies）对IPCC 提供的 SRES A2 B2 情景进行降尺度计算得到 21 世纪末华北和西北地区夏季增温大而降水增加少，暖感化趋势十分明显。张勇等（张勇等，自然灾害学报，2006）利用区域气候模式 PRECIS 单向嵌套Hadley 气候中心海-气耦合模式 HadCM3 的 SRES B2 情景，研究认为黄河一带 2080s 时段年平均大雨、暴雨事件呈增多趋势；年平均日最大降水事件的分布型与大雨事件基本一致。

施雅风等（第四纪研究，2003）综合分析了西北地区气候环境变化的事实，认为包括黄河上游在内的西北东部地区有潜在的向暖湿转化的趋势，但具体时间难以确定。有些学者认为，今后数十年里，随着全球升温，黄河上游径流总体上呈减少趋势（刘昌明，自然资源学报，2003）。也有学者认为，由于全球变暖所导致的水循环加强，海

洋和陆地蒸发量增加，大气中的水汽含量增加，结果将是降水量总体上增加。张士锋等(张士峰等, 中国科学（E 辑）,2004)认为 21 世纪西北地区温度持续变暖，水循环的演变趋势将是蒸发量增加、径流量进一步减少。

4.3 响应机制

许多学者开展了水资源系统对气候变化的响应研究。采用多个GCMs 模型和水文模型预测2030年黄河流域径流量总体上减少，且因气候变化引起的流域缺水量为-1.9～121.2亿m^3 (刘春蓁，1997)。根据IPCC DDC 的13个系列的GCMs成果和大尺度水文模拟结果，在未来100年内，黄河源区和全球变暖的趋势一致，未来气温将持续增加，蒸发明显加强，降水虽有增加，但综合起来，未来气候变化将在一定程度上造成水资源量的减少，且水量的年际分布也将越来越不均匀，旱涝威胁日趋严峻（郝振纯等，冰川冻土，2006）。以HadCM3气候模式为基础，结合考虑了封冻融雪、变径流系数的大尺度流域模型分析，认为2030年黄河上游安宁度以上径流量增加，其水量受终年雪线以上的面积比例影响较明显(包为民等，2000)。选择“温室气体+硫化物气溶胶”方案，利用CGCM1、ECHAM4 和HadCM2模型和BP 神经网络算法模拟预测结果是:未来100年黄河流域兰州以上降水将减少20%，至2020，2050和2080年平均气温分别上升2～3，3～5 和5～8℃；不同气候方案下，不同时段、不同区间的河川径流量变化迥异，但总体而言，径流量将减少(郑红星，2001)。

总之，关于黄河流域未来气候变化对水资源影响的评估研究有了一定的基础，但不确定性也很大；对黄河流域未来气候变化对极端事件影响的预估研究做得比较少，研究方法也很不完善，多以平均降水的减增来推测未来旱涝趋势。总体认为，未来黄河流域气温将明显升高，降水略有增加，降水的增加被蒸发的增加所消耗，最终可能导致径流量的减少，黄河流域水资源危机将更加严重。

5 趋势分析

5.1 气候变化趋势

徐影等利用 IPCC 提供的 7 个全球模式模拟结果，进一步计算了中国 10 大流域 21 世纪气温和降水的变化，其中黄河流域气温和降水总体上均呈上升趋势，但 2050 年以前，降水增加仅 5%左右，气温上升了近 3℃，这一结果可能会导致黄河流域水资源的减少。

5.2 水资源变化趋势

关于黄河流域未来气候变化对水资源影响的评估研究工作比较多，但不确定性也很大。施雅风等（第四纪研究，2003）综合分析了西北地区气候环境变化的事实，发现 1987 年以来西北地区西中部降水量与河川径流量显著增加，气候明显出现了由暖干向暖湿的转型；部分地区有轻度转型的迹象，包括黄河上游在内的西北东部地区近十余年来虽一直处于少雨和枯水时期，但可能已达到年代际变化的谷底，有潜在的向暖湿转化的趋势，但具体时间难以确定。有些学者认

为，今后数十年里，随着全球升温，黄河上游径流总体上呈减少趋势（刘昌明，自然资源学报，2003）。也有学者认为，由于全球变暖所导致的水循环加强，海洋和陆地蒸发量增加，大气中的水汽含量增加，结果将是降水量总体上增加。

许多学者开展了水资源系统对气候变化的响应研究。采用多个GCMs 模型和水文模型研究预测2030年黄河流域径流量总体上减少，且因气候变化引起的流域缺水量为-1.9～121.2亿m^3 (刘春蓁，1997)。夏军等（夏军等，武汉大学学报（工学版），2005；叶爱中等，武汉大学学报（工学版），2006）针对黄河流域气候变化对流域水资源量的变化影响问题，把系统论与物理机制相结合建立了大尺度时变增益分布式水文模型（DTVGM）在一定程度上解决了无资料地区的水文问题，模型在黄河流域证明了气候因素对流域水文过程影响很大，降水增加10%比减少10%对径流的影响更强烈。王国庆等（河南气象，2000）利用月水量平衡模型,采取假定的气候方案分析黄河上游水文对气候变化的响应：降水变化对上游水文影响较大，气温影响相对较小；汛期径流量和土壤含水量对气候变化的响应较非汛期强烈；在区域上分布，中游较上游对气候变化更为敏感（王国庆等，应用气象学报，2002）。郝振纯等（2006，冰川冻土）利用气候模型结果和大尺度分布式水文模型评估黄河源区未来的水资源. 根据IPCC DDC 的13个系列的GCMs成果，认为在未来100年内，黄河源区和全球变暖的趋势一致，未来气温将持续增加，蒸发明显加强，降水虽有增加，但综合起来，未来气候变化将在一定程度上造成水资源量的减

少，且水量的年际分布也将越来越不均匀，旱涝威胁日趋严峻。张光辉（地理研究，2006）以HadCM3气候模式为基础，分析了在不同气候变化情景下，黄河流域2006～2035年、2036～2065年、2066～2095年A2情景下多年平均天然径流量的变化分别为5.0%、11.7%、8.1%，B2情景下分别为7.2%、-3.1%、2.6%。而采用GFDL、GISS 等7个模型，结合考虑了封冻融雪、变径流系数的大尺度流域模型分析，大多数模型显示2030 年黄河上游安宁度以上径流量增加，其水量受终年雪线以上的面积比例影响较明显(包为民等，2000)。研究还表明未来黄河河龙区间的产流平均减少2.13 %(中国气候变化国别研究组，2000)。选择“温室气体+硫化物气溶胶”方案，利用CGCM1、ECHAM4和HadCM2模型和BP 神经网络算法模拟预测结果是:未来100年黄河流域兰州以上降水将减少20%，至2020，2050和2080年平均气温分别上升2～3，3～5 和5～8 ℃；不同气候方案下,不同时段、不同区间的河川径流量变化迥异,但总体而言，径流量将减少(郑红星，2001)。有学者人为，今后数十年内，随着全球升温，黄河上游径流总体上呈减少趋势；也有学者认为，由于全球变暖所导致的水循环加强，海洋和陆地蒸发量增加，大气中的水汽含量增加，结果将是降水量总体增加（王国庆等，2002；包为民，2000；蓝永超，2004；刘昌明，2003）。施雅风等通过分析西北地区气候环境变化事实，发现1987年以来西北地区西中部降水量与河川径流显著增加，气候明显出现了由暖干向暖湿的转型。

5.3 蒸发变化趋势

与降水、径流和气温变化的研究相比，对黄河蒸发量的研究相对比较薄弱，气候变化对流域蒸发的影响存在着较大的分歧。李林等（2000）分析了黄河上游地区蒸散量、日照时数、气温、空气饱和差等气候因子的变化趋势，并着重研究了诸因子对蒸散量的影响，结果显示，黄河上游流域蒸散量呈现逐年增大的趋势。张士峰等（2004）分析了黄河源区的水文的水文循环规律，认为由于西北地区温度持续变暖，21世纪水循环的演变趋势将是蒸发量增加。史忠海（2006）建立了简洁且实用的指数型蒸发能力估算公式,分析了气温变化对流域蒸发能力的影响在气温升高1 ℃的情况下,黄河流域蒸发能力约增加5.0% ～7.0%;在地域分布上,黄河中游变化最大,上游次之,下游最小,而以河口镇至三门峡区间增加最为显著（表5-1）。邱新法（2003）利用黄河流域及其周边123个气象站1961～2000年20cm口径蒸发皿资料，分析了黄河流域蒸发皿蒸发量的气候变化趋势，研究表明黄河流域上游和下游蒸发皿蒸发量呈下降趋势，中游呈持平并略有上升趋势。张光辉（2006）计算黄河流域各个区域未来不同时期的潜在蒸发量（表5-2）。A2 情景代表人口增长加快,经济发展缓慢。B2 情景代表技术进步相对较慢, 但强调社会技术创新。研究人为从2006-2095蒸发量是增大的。

表 5-1　蒸发能力在气温变化 1℃情况下的变化　　%

站名	玛多	兰州	岷县	西宁	中宁	榆林	延安	太原	天水	西安	郑州	济南
蒸发量变化	5.24	5.78	5.66	5.88	5.59	6.78	6.59	6.66	6.31	5.44	5.02	5.18

表 5-2　各区域不同变化情景下的平均年潜在蒸发量(mm)

区域	1961 ～ 1990	A2			B2		
		2006-2035	2036-2065	2066-2099	2006-2035	2036-2065	2066-2099
河源- 贵德	668.8	706.0	765.0	874.3	732.1	765.4	810.6
贵德- 兰州	835.7	871.4	929.7	1026.6	918.5	922.5	936.0
兰州- 头道拐	944.7	1003.2	1063.3	1167.4	1062.8	1067.5	1100.9
头道拐- 龙门	991.7	1036.5	1091.4	1200.5	1092.5	1098.5	1130.3
龙门- 花园口	1033.0	1081.5	1144.3	1270.3	1149.0	1161.3	1192.9
花园口- 利津	1035.0	1154.4	1267.9	1536.5	1280.7	1297.6	1355.9

5.4 泥沙变化趋势

饶素秋等（饶素秋等, 泥沙研究, 2001）对1950年以来黄河上中游水沙变化特点进行了分析表明，黄河上中游水沙总体上呈逐年代递减的趋势,其中尤以80年代和90年代减少最为显著。90年代是1950年以来黄河上中游径流总量最少的十年，而输沙量较80年代有所增加，未来10年黄河三门峡以上区域的水沙变化将有增加的趋势。任美锷（2006）认为，今后20-30年黄河流域经济将有较大发展，即使引黄灌溉用水由于农业技术和灌溉技术的进步并不增加，沿黄工业和城市用水必将大大增加，增加的用水量有一大部分将引自黄河。此外，西部大开发生态建设如退耕还林还草等都要用水，故生态用水也将有较大增加，水分蒸发损失增加。近年来，在黄土高原的小支流和沟谷里修建了数以万计的小水库淤地坝，其中容积百万m3以上的小水库有600余座，它们在控蓄泥沙的同时，也增加了水分的蒸发量。此外，黄河干流上已建有大型水库12座，还有3座在建，使河水在陆地上的滞留时间加长，也增加了河水的蒸发损失，任美锷认为在今后20-30

年内，黄河入海泥沙量仍将偏少。刘成等（2007）认为黄河泥沙的变化不是降水变化引起的，水沙量的降低主要是人类活动造成的。赵俊侠等（2001）认为渭河沙量减少是人类活动和气候变化共同引起的，在减少的沙量中，人类活动影响占57.1%，降雨影响占42.9%。尹国康（1998）通过黄河中游多沙粗沙区21条面积逾1 000 km2的独流入黄支流的实测资料，分别建立了精度较高的降水、径流、输沙统计模型，并对水沙变化数量进行了计算分析，揭示了气候波动和人为原因对水沙变化影响的相对权重, 其中气候波动引起的占48.9%，而人类活动原因占到了51.1%。谢玉亭和许志文（1993）对祖历河流域人类活动和降雨因素对径流和泥沙的影响进行了研究并作了预测，1990-2000年，人为活动年均减水8100万m3，减沙3360万t，分别占模拟基准年水沙量的52.3％、50.6％；2000-2030人为活动减水1.12亿m3，减沙4690万t，分别占模拟基准年（1955-1969年）水沙量的72.3％和70.6％。在预测的整个时段内，年均减水量中降水影响约占10％，人类活动约占90％；年均减沙量中，降水影响约占20％，人类活动影响约占80％（表5-3）。在无定河流域，张胜利研究得出，与基准期1956-1969年相比，70年代平均年输沙量减少了10151万t，占基准期平均年沙量的46.7％，其中水土保持、水利措施等人类活动减沙8774万t，占基准期平均年沙量的40.4％，占实测减沙量的86.4％，降雨变化影响减沙只有1377万t，仅占实测减沙量的13.6％；80年代水土保持、水利措施等人类活动减沙占实测减沙量的52.3％，降雨变化减少47.7％；90年代（1990-1993年）人类活动和降雨减沙占分别实测减沙

量的55％和45％。黄河流域的侵蚀和泥沙的变化是多因素综合作用的结果，尤联元认为黄河流域由于受全球降水增加、来水来沙的长周期（天文要素的影响）变化、全球增温以及人类活动的影响，预测2050年前后全年来水量可减至265.08×10^8 -305.08×10^8 m3；来沙量在不增加任何工程的情况下可能增至15.03×10^8t，而在发展库坝工程的情况下可减至8.70×10^8-7.85×10^8t（表5-4）。

表 5-3. 祖历河流域基于基准年（1955-1969 年）预测时段减水减沙量中降水和人类活动影响所占的比例

时段	年均减水	其中				年均减				
（年）	量（亿m^3）	降水影响		水利水保影响		沙量	降水影响		水利水保影响	
		减水量	占％	减水量	占％	（万t）	减沙量	占％	减沙量	占％
1990-2000	0.91	0.10	11.0	0.81	89.0	4180	820	19.6	3360	80.4
2001-2030	1.25	0.13	10.4	1.12	89.6	5650	960	17.0	4690	83.0
1990-2030	1.16	0.12	10.3	1.04	89.7	5260	920	17.5	4340	82.5

表 5-4. 黄河下游 2050 年前后来水来沙状况评估

水利水保方案	来水状况（10^8 m^3）					来沙状况（10^8 t）				
	现状 1986-1990	全球升温增减量	长周期变化增减量	人类活动增减量	合成量	现状 1986-1990	全球升温增减量	长周期变化增减量	人类活动增减量	合成量
1	377.5	+11.2	+18.3	-101.2	265.08	11.90	+0.95	+0.22	+1.964	15.03
2	377.5	+11.2	+18.3	至	至	11.90	+0.95	+0.22	-4.3879	8.70
3	377.5	+11.2	+18.3	-141.2	305.08	11.90	+0.95	+0.22	-5.224	7.85

注：水保方案1、2和3分别是不增加任何新工程，按过去40年平均速度发展库坝工程，按水保大规划速度发展库坝工程

5.5 极端事件

王云璋（2004）根据黄河流域内汉涝等级和部分树木年轮资料及其与干旱指数的关系（图 5-1），认为 2004 起的未来 30 年内，除近期数年和 21 世纪 20 年代中期以前仍以干旱年为主外，其余大多年份可能以不干和涝为主。徐立荣（2001）通过建立日随机模型，认为 $C0_2$ 加倍气候情景下，流域各类干旱事件有所增加，干旱频率平均约增加 5.8%（表 5-5）。许吟隆等（许吟隆，气候变化研究进展，2005）利用区域气候模式系统（PRECIS: Providing Regional Climates for Impact Studies）对 IPCC 提供的 SRES A2 B2 情景进行降尺度计算得到中国 21 世纪末未来极端高温和降水事件都会增大，而极端低温事件减少，同时，华北和西北地区夏季增温大而降水增加少，暖感化趋势十分明显。张勇等（张勇等，自然灾害学报，2006）利用区域气候模式 PRECIS 单向嵌套 Hadley 气候中心海-气耦合模式 HadCM3 的 SRES B2 情景，研究认为黄河一带 2080s 时段年平均大雨、暴雨事件呈增多趋势；年平均日最大降水事件的分布型与大雨事件基本一致。

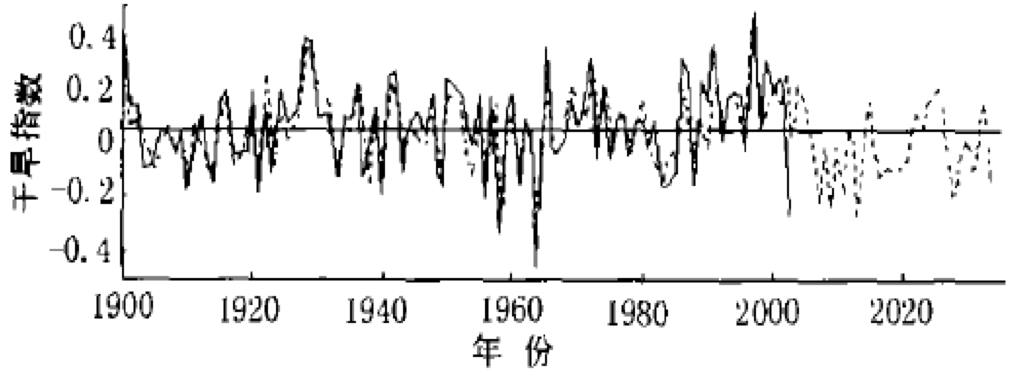

图 5-1　黄河中游 1900 年以来夏半年干旱指数拟合及未来 30 年外延曲线

表 5-5 干旱频率变化

月份	当代气候	2*CO_2
4	57	58
5	50	61
6	63	75
7	59	63
8	56	60
9	59	62

6 分析和总结

根据国内多数学者的观点，得出结论如下：

（1）20 世纪 90 年代以来黄河源区径流量大幅度减少，流量年内分配由 50-80 年代的双峰转变为 90 年代以来的单峰。对于径流减少的原因，国内研究还有一定的分歧，但多数人认为主要是降水量的减少。

（2）黄河中游水沙总体上也呈现在减少的趋势，年内分析表明，降水、径流与输沙较为集中。其原因是干旱变化的阶段性显著，黄河中游干旱发生概率较高。

（3）黄河下游湖泊数量与面积减少趋势明显，黄河下游径流变化与上、中游及重点支流来水息息相关，总体来说，下游径流减少趋势明显。

整个流域而言，对于兰州控制断面而言，地表径流有明显的减少趋势，对于花园口控制断面而言，天然径流、地表径流和地下径流减少趋势显著，下游径流减少趋势比上游更显著。其原因既有气候因素，也有人类活动带来的流域耗水量的大大增加。

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第三部分　相关资料

1950～2000 年黄河入海水沙的逐日变化及其影响因素

1956～2000 年中国潜在蒸散量变化趋势

1960_2000 年黄河流域太阳总辐射气候变化规律研究

1980_2000 年中国 LUCC 对气候变化的响应

1997 年汛期黄河流域干旱气象成因分析

1999 年黄河流域夏旱的天气成因分析

2003 年旱情紧急情况下黄河水量调度工作综述

2006 年皇甫川_7_27_高含沙洪水分析

G.Q.Wang full paper(Canada-20071008)

Yellow River Proposal (En)

北方 13 省 1982 年～1999 年植被变化及其与气候因子的关系

滨州市海河流域水生态恢复对策

长江_黄河源寒区径流量波动变化的气候因素分析

长江与黄河历史洪水对比

大尺度洪水灾害损失与影响预评估

大尺度流域基于站点的降雨时空展布

第四节　黄河流域气候变化对水土流失和泥沙影响后果评估

第五章　黄河流域气候变化对水资源影响的后果评估

对洪水资源化维持黄河健康生命的初探

对黄河主要支流治理开发的若干意见

多维联合分布计算方法及其在水文中的应用

厄尔尼诺事件与汛期黄河中游暴雨

厄尔尼诺与黄河流域汛期降雨洪水的关系分析

二元模式下黄河年径流变化规律研究

二元年径流演化模式及其在无定河流域的应用

风力侵蚀对无定河流域产沙作用定量分析

黄河河源区水文水资源特性分析及变化规律研究

甘肃省最大点雨量量级分布规律及其暴雨衰减指数分析

郭军-黄淮海流域蒸发量的变化及其原因分析

国际水文计划发展与中国水资源研究体系构建

海南州气候变化对生态环境的影响及对策研究

郝振纯-气候变化对黄河源区水资源的影响

河口村水库在黄河下游防洪工程体系中的作用

河龙区间六条流域产粗沙量研究

华北地区气候变化对水资源的影响及 2003 年水资源预评估

环境变化对黄河中游汾河径流情势的影响研究

皇甫川流域产流产沙数学模型及水沙变化原因分析

皇甫川流域土地利用变化与生态安全评价

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利用日最高气温和日最低气压预报 5 月大风

联合国气候变化框架公约

陆面水文过程研究进展

论水资源学和水文学的关系

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蒙阴县降水和极端温度变化特征分析

莫干湖流域土_水生态系统的退化及治理对策研究

内蒙古东部近 54 年气候变化对生态环境演变的影响

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气候变化对黑河上游地区径流的影响分析

气候变化对华北地区水资源供需影响的模拟预测

气候变化对嘉陵江流域水资源量的影响分析

气候变化对陆地水循环影响研究的问题

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气候变化对水资源影响的初步研究

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气候变化国家评估报告（Ⅰ）：中国气候变化的历史和未来趋势

气候变化下的新疆生态环境脆弱性评价

气候异常对水资源影响评估中的关键性技术研究

全球变化与水文科学新的进展与挑战

全球变暖对区域极端气温出现概率的影响

全球环境变化对我国区域发展的可能影响评述

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全球气候变化对新疆塔里木河流域水资源的可能性影响

全球气候变化及其对生态系统的影响

全球气候变化使我国部分流域出现水资源短缺

全球气候变暖对长江三角洲极端高温事件概率的影响

全球气候变暖情景下黑河山区流域水资源的变化

热排放对水生生态系统的影响及其缓解对策

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日极端最高气温挑取之我见

三江源地区气候变化及其对生态环境的影响

社会经济发展及气候变化对中国水资源的影响

湿地生态系统对气候变化的响应

水文尺度转换研究进展

水文科技发展回顾及思考

水循环、水灾害和调控

塔里木河流域气候与径流变化及生态修复

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未来资源,环境,社会经济与全球变化

我国东部夏季降水百年雨型的多时间尺度变化特征研究

我国过去 50a 来降水变化趋势及其对水资源的影响Ⅰ年系列

我国过去 50a 来降水变化趋势及其对水资源的影响Ⅱ月系列

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我国生存环境演变和北方干旱化趋势预测研究_主要研究成果

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我国西北地区地面最高和最低气温变化及分布的特征

我国月平均气温升高时极端气温的变化

西北地区近代及历史时期气候变化趋势分析

西藏高原最高、最低气温的非对称变化

新疆冬季日最低气温分布规律

新疆天山北坡气候变化的生态响应研究

英国 CRU 高分辨率格点资料揭示的 20 世纪中国气候变化

永泰县年极端最低气温的建模及其在林业上的应用

用 CEOF 分析近百年中国东部旱涝的分布及其年际变化特征

用本站气象要素预报最高气温

用地理因子模拟年度极端最低气温模式的探讨

用神经网络试报极端气温

曾小凡-21 世纪前半叶长江流域气候趋势的一种预估

章党日最低最高气温随 850hPa 温度的变化规律

中国 600 个站气温和 IPCC 模式产品气温的比较

中国北方百年四季降水趋势与海平面气压形势

中国北方近百年干湿变化与太平洋年代际振荡的关系

中国地区极端事件预估研究

中国近 50a 来日最低气温的时间演变特征

中国近 50 年冬夏季极端气温场的年代际空间型态及其演变特征研究

中国近 500 年流域性洪涝初步研究

中国近百年来的温度变化

中国近百年气候变化的自然原因讨论

中国近百年气温场变化成因的统计诊断分析

中国近百年温度序列

中国近半个世纪最高气温变化特征

中国气候变化影响研究进展

中国气候干湿变率与 ENSO 的关系及其稳定性

中国全球气候变化影响研究方法的进展

中国水资源响应全球气候变化的对策建议

中国温度降水的长期气候趋势及其影响因子分析

中国自然生态系统对气候变化的脆弱性评估

重庆岩溶区气候变化对水文水资源的影响

自然和人类环境正在遭受气候变化的影响_IPCC 第二工作组第四次评估报告初步解读