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Water cycle evolution in the Haihe River Basin in the past 10000 years

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The water shortage problem in the Haihe River Basin is the most severe in China, and has restricted its economic development. Over-extraction of groundwater has been very severe in the past 30 years. To solve this problem, scientific decisions should be made from a historical perspective. It is important to describe water cycle evolution in the Haihe River basin over the past 10000 years. Datasets of paleoclimate, paleogeography, palynoflora, historical record, isotopic abundance ratio and content were collected for research on different time scales. Some interesting conclusions were drawn by a comprehensive analysis method. First, radiation was the intrinsic force driving the evolution of water cycle. Generally, precipitation increased with temperature. Second, precipitation was high during 8 ka–5 ka B.P., the so-called Yangshao warm period of the Middle Holocene, which recharged the major part of the Quaternary groundwater. Third, heavy floods during this period transported sediment to the seaside, forming the Coastal Plain where cities such as Tianjin, Huanghua, Cangzhou are now located. In the last 3000 years, intermittent moderate floods did not have enough energy to transport sediment to the sea. Rivers usually overflowed in the piedmont region of the Taihang Mountains, and sediment deposited there formed the Piedmont Plain, where locate Shijiazhuang, Xingtai, Handan, Baoding and other cities. Precipitation had a high correlation with temperature in Haihe River Basin in the past 10000 years: the high temperature usually coupled with high precipitation. Today precipitation in the Haihe River Basin is relatively low, owing to low temperature. This study reveals the relationship between temperature, precipitation and river networks in the past 10000 years in Haihe River Basin, which has great scientific and practical importance in understanding the current water circulation and water shortage.

water cycle evolution, 10000-year scale, temperature changes, water resources, Haihe River Basin

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The Huang-Huai-Hai Plain is the largest enrichment area of groundwater in China [1,2], and is also one of the three largest water-bearing structures in the world. The Haihe Plain, on the northern Huang-Huai-Hai Plain, has suffered severe, continuous overextraction of groundwater during the past 30 years; the accumulated consumption is more than 120 billion m^3 [3]. The decline of groundwater level has not only negatively influenced the surface water cycle, but has also presented serious challenges to sustainable use of water resources in the future. The severe water problems of the Haihe River Basin were caused not only by short-term water resource development and use, but also by climate change and water cycle evolution over a long period. It is therefore instructive to study water cycle evolution in this basin from a long-term, historical perspective. At present, studies of water cycle evolution are mostly based on hydrological records and scientific experiment data. The earliest measured precipitation record of the Haihe River Basin was traced to

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the year 1841 [4]. This time series is too short for study of long-term water cycle evolution. On the 10000-year scale, the main influences on the water cycle are temperature and water system changes. The effect of temperature is mainly reflected as follows: In warm periods, precipitation was abundant, and groundwater was recharged by precipitation, rivers and lakes. Energy exchange and moisture transfer flux between atmospheric water, surface water and groundwater systems were high. In cold periods, precipitation was scarce, and groundwater could not be sufficiently recharged. Energy exchange and moisture transfer flux between the atmospheric water, surface water and groundwater systems were small. The influence of water system changes is mainly as follows: The ancient Yellow River moved from north to south, gradually making the Haihe River water system independent. This formed the general pattern of the modern Haihe River, known as "nine rivers flowing down to meet in Tianjin". In the Yangshao warm period of the Middle Holocene, sediment from the Loess Plateau and Taihang Mountains was transported to the Bohai Sea by frequent and heavy flooding through a broad and stable river course. This sediment deposited in the estuary delta, which formed the Coastal Plain embracing the cities of Tianjin, Huanghua, and Cangzhou. In the last 3000 years, intermittent moderate floods were not strong enough to transport sediment to the sea. Rivers usually overflowed in the piedmont region of the Taihang Mountains, and the sediment deposited there formed the Piedmont Plain, on which the cities of Shijiazhuang, Xingtai, Handan, and Baoding are situated. Human activities have had direct and indirect impacts on the water cycle; however, on the 10000 year scale, the roles of temperature and water system changes were more significant.

1 Temperature change

In this study, we performed a comprehensive literature review and case research. The previous work was analyzed [5–9], and Haihe River Basin sample data from those studies were collected. Using analyses of sedimentary characteristics [10], pollen [11–13], organic matter, and radioactive isotopes, it was discovered that there were mainly four stages of temperature change in the basin during the last 10000 years (Figure 1): (1) At the end of the late Pleistocene, the basin was in prime Würm glaciation; the climate was cold and dry. (2) In the early Holocene (about 11 ka–8 ka B.P.), the climate rapidly became warm and wet. (3) In the middle Holocene (about 8 ka–3 ka B.P.), the Yangshao warm period, the climate was warm; however, it became warm and dry in the later years. (4) In the late Holocene (from 3 ka B.P.), the climate changed frequently, but was cool and dry overall. About 1660, temperature in the basin reached its lowest value in the past 3000 years; then, it began to rise. The present temperature is near the 10000-year average.

The above curve is basically consistent with Zhu [14], and was also proven by studies in different areas of the basin. The study sites of Xu et al. [15], Tong et al. [16], Wang [17], Guo et al. [18] and Jin et al. [19] are shown in Figure 2.

Xu et al. [15] studied the ancient climate of the piedmont, sedimentary and coastal plains by pollen combination and sedimentary characteristic analyses. These prove that the temperature change in Figure 1 is reasonable. In the early Holocene, from about 11 ka to 7.5 ka B.P., the climate was relatively cool. In the middle Holocene, about 7.5 ka–2.5 ka B.P., average temperature was 3.5±1°C higher than that of today. The climate has been slightly cool and dry over the last 2500 years. Tong et al. [16] investigated five boreholes and a pollen profile on the eastern North China Plain (Baodi-Puyang). This research revealed the following: (1) The temperature was about 4°C lower than 10000-year average during 12 ka–10 ka B.P. (2) During 10 ka–9 ka B.P., the temperature clearly rose and was about 1°C higher than that of today. (3) There was a short cooling period during 9 ka–7.5 ka B.P. (4) During 7.5 ka–5 ka B.P., the climate was warm and wet, and about 3–4°C higher than present. (5) During 5 ka–2.5 ka B.P., there was a cooling and drying process. The temperature dropped 2–3°C over that of 7.5 ka–5 ka B.P, but was still slightly higher than present. (6) During about 2.5 ka–1 ka B.P., there were two warming stages and a cold stage. These were the warm period of the Zhou and Han Dynasties, the cold period of the Jin Dynasty, and the warm period of the Tang Dynasty. (7) About 1000 years ago, a modern cold stage began, with low temperature and precipitation as during the period of the Ming and Qing

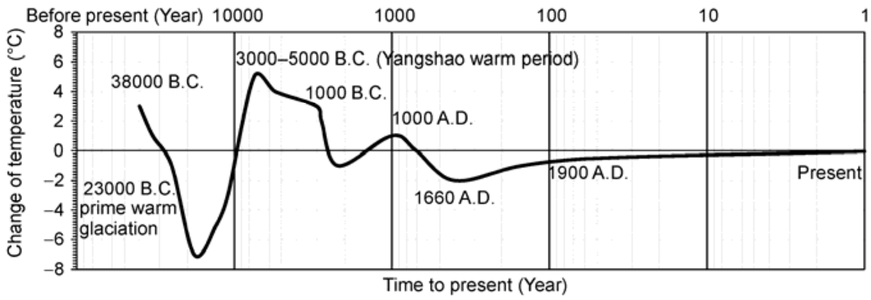

Figure 1 Temperature change in Haihe River Basin over the last 10000 years.

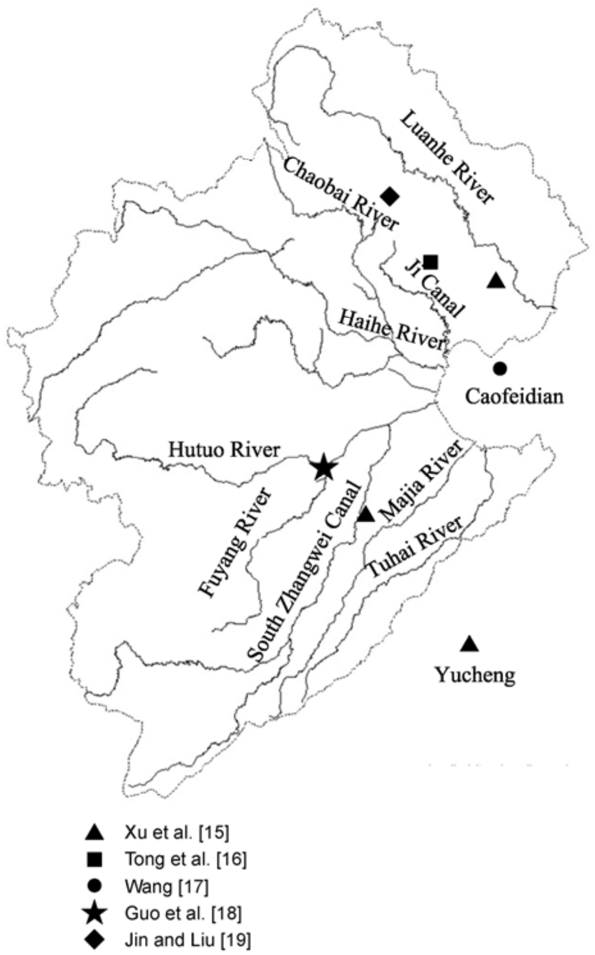

Figure 2 Study sites distribution in the Haihe River Basin.

Dynasties. Wang [17] studied pollen data in Caofeidian, in the northwest Bohai Gulf. About 7500 years ago, the climate was warm and wet. Average temperature in January was 3–5°C higher than present, and average temperature in July was about 1–2°C higher than today. About 6000–5000 years ago, the climate became colder and drier. Approximately 5000 years ago, there was a short cold stage. Guo et al. [18] studied the pollen profile of Nanwangzhuang in Longyao County of the Ningjinpo area through literature review and pollen analyses. They obtained ancient climate change data of Huang-Huai-Hai Plain and suggested the following: During approximately 10.83 ka–10.06 ka B.P., there was a rapid temperature-rise process, and humidity also increased. The climate changed from cool and dry to cool and wet. During about 10.06 ka–8.35 ka B.P., the climate was mild and wet. During about 5.4 ka–4.9 ka B.P., it was cold. Subsequently, during about 4.9 ka–4 ka B.P., the temperature rose quickly and the climate was warm and more stable. Over the past 630–1010 years, the climate was warm; however, the climate was cold and dry over past 200–630 years. Jin and Liu [19] obtained high-resolution environmental evolution records from 6 ka–3 ka B.P. for the Taishizhuang site, by methods of ^{14}C dating, pollen and oxygen isotopic analyses. The results showed the following: During 5.7 ka–5.4 ka B.P., the climate was cold and wet, and warm and wet from 5.4 ka–4.8 ka B.P. During 4.8 ka–4.2 ka B.P., the climate changed abruptly, with some cooling events. This led to sparse vegetation in this period. During about 4.2 ka–3.3 ka B.P., the climate was warm and dry. The cooling events revealed by peat records of Taishizhuang were universal in the northern hemisphere. The isotope and pollen studies above proved that it is reasonable to divide temperature changes of the Haihe River Basin over the past 10000 years into four periods (Figure 1). However, some abrupt cooling events are not reflected in the curve since they were of short duration relative to 10000 years. Examples are 5.4 ka–4.9 ka B.P. as reported by Guo et al. [18], and 5.7 ka–5.4 ka B.P. as reported by Jin and Liu [19] (which could be the same event as Guo). These omissions may be ignored when analyzing water cycle evolution trends on the 10000-year scale.

2 Precipitation change

Measured precipitation records of the Haihe River Basin can be traced to the year 1841 [4]. The trend of precipitation over the past 500 years can be estimated by the Network Share Database for Flood and Drought Disasters, which is shared online [20]. Drought and flood grades for 63 sites during 137 B.C.–1469 can be ascertained using 22567 records of drought and water-related disasters logged in ancient Chinese documents [9]. Continuing back in time, precipitation changes over the past 10000 years can be estimated by consulting Quaternary research on pollen, tree rings and animal remains.

The study of precipitation change was divided into six periods: (1) Würm glaciation; (2) 6000 B.C.–137 B.C.; (3) 136 B.C.–1469; (4) 1470–1841; (5) 1841–1955; and (6) 1956–present.

In the earlier part of the Würm glaciation period, it was humid, and the Taihang Piedmont Plain was chiefly covered by spruce and fir forest together with wormwood, pigweed and other herbaceous plants. In the later part of this period, it became cold and dry, and precipitation greatly declined. The spruce and fir forests disappeared and were gradually replaced by desert steppe and semiarid grass vegetation [21]. According to relativity and similarity speculation based on latitude, vegetation and precipitation, precipitation in the Haihe River Basin at that time was similar to that of the Wulanchabu Pasture at present (about 300 mm).

Precipitation from 6000 B.C. to 137 B.C. mainly refers to the research of Shi et al. [22], because of the lack of historical literature. It was pointed out that Asian elephants lived in Yangyuan County (of Hebei Province) in the Haihe River Basin 3000–8000 years ago. These elephants were accustomed to living in Asian tropical rainforest regions and lived on bamboo shoots, tender leaves, wild banana and similar vegetation. According to their living environment and foods, precipitation during the warm period of the Holocene in China was estimated. This suggests that the amount of precipitation in the North China Plain at that time was 200–300 mm greater than present [22], which is about 800 mm. *Ceratopteris thalictroides* spores now living in subtropical areas were found in contemporaneous strata of Jinghai and Beitang, which proves that Haihe basin precipitation at that time was similar to current amounts in the Huaihe River Basin and the middle and lower Yangtze area. Historically, annual precipitation in short time series of the Beijing station exceeded 800 mm, and annual precipitation over 11 years (1884 to 1894) was 904 mm (the most abundant recorded precipitation over this duration, between 1841 and 2010). This warm stage ended about 3000 years ago.

Then a cool and dry period began, and plants and animals living during the warm period began their decline. According to the records from "bamboo books" (ancient Chinese texts written on bamboo strips), the north frost expanded to the Yangtze River Basin during the reign of Emperor Xiao of Zhou (891 B.C.–886 B.C.). The Hanjiang River froze twice, in 903 B.C. and 897 B.C., followed by a severe drought [14]. According to historical records, precipitation in that period was similar to that of a severe drought in North China during the rule of Emperor Guangxu (1875–1908) of the Qing Dynasty. Thus it is speculated that precipitation during 891 B.C.–886 B.C. was very similar to that of the nineteenth century, about 490 mm. The earlier cold and dry period only lasted for 100–200 years, and then it turned warm in the Chinese Spring and Autumn period (770 B.C.–476 B.C.) [14].

There are many records of drought and floods from 136 B.C. to 1469. During that period, precipitation periodically changed from dry to wet, with a main cycle about 80 years. After the Western Zhou Dynasty period (1046 B.C.–771 B.C.) characterized by low temperature and little precipitation, Haihe Basin precipitation first increased, then diminished overall. There was a short warm period during the Song and Yuan Dynasties (1200–1300). In that period, the famous Taoist called Qiu Chuji (1148–1227) lived in Changchun Palace of Beijing for several years. In 1224, he wrote of the Spring Outing on Cold Food Festival, "Almond flowers are blooming on Qingming Day; thousands of families come and go." It is evident that the phenology of Beijing was the same as today [14]. Therefore, the precipitation estimated for that time in the Haihe basin is about 550 mm.

Flood and drought disasters during 1470–1841 were recorded in detail in chorographies of the Ming and Qing Dynasties. Changes in precipitation during that period can be accurately reconstructed–first decreasing, then increasing with a historical low value in the year 1640. According to estimated results of Zhang [20] from the Network Share Database for Flood and Drought Disasters, precipitation in the Haihe Basin from 1637–1643 are given in Table 1. The mean value (378 mm) was taken as the drawing sample value of the extreme low point.

To obtain average precipitation in the basin during 1841–1955, we used average precipitation values from Beijing station. According to hydrologic periodicity and consistency, it is estimated by correlation analysis that average precipitation was 490 mm.

Average precipitation since 1956 is 535 mm, according to precipitation data from the second Haihe River Basin Integrated Water Resources Planning [23].

Based on the seven feature points analyzed above, a precipitation trend chart of the basin over the past 10000 years is obtained (Figure 3).

3 Water cycle evolution dominated by temperature

Based on the changes of temperature and precipitation in the Haihe River Basin, two main functions of temperature on water cycle evolution are found. In warm stages, precipitation was abundant; river flow increased and aquatic wetlands developed. There were significant effects on landform changes and formation of alluvial plains. Meanwhile, groundwater was sufficiently recharged, forming a large reservoir. During cold stages, precipitation decreased. Groundwater was recharged less; the annual net recharge rate was even negative at times. Groundwater evaporation and the salinization process were obvious. Based on the relation between temperature and water cycles mentioned above, the following analysis is separated into three parts, according to time.

(1) Late Pleistocene (the prime Würm glaciation period) to early Holocene. The climate was cold and dry; energy exchange and moisture transfer flux between atmospheric water, surface water and groundwater reached the minimum of the past 10000 years on the North China Plain. The sea level was low. Water flow speed of the third and fourth

Table 1 Precipitation in Haihe River Basin during 1637–1643

Year	1637	1638	1639	1640	1641	1642	1643
Precipitation (mm)	358	401	368	283	294	466	479

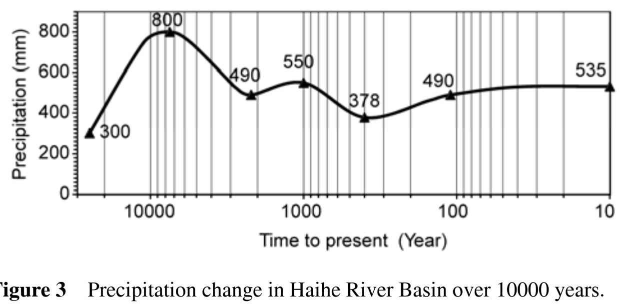

Figure 3 Precipitation change in Haihe River Basin over 10000 years.

aquifer accelerated, and the level of groundwater decreased. Older water was replaced, and the content of hydrogen and oxygen stable isotopes was low. Lixiviation was the main salinization process of groundwater in the Piedmont Plain, and this groundwater had a high content of calcium carbonate. Evaporation was the main process in the middle-eastern part of the plain, and phreatic water became saline. Therefore, this was a developmental stage during which the groundwater reduced and salinized before the last glacial period.

(2) Middle Holocene. The climate was warm and wet. The rivers were broad and stable. About 7 ka B.P.–5 ka B.P., the processes of evaporation and precipitation maximized. Annual precipitation in the basin was more than 800 mm. The Piedmont Plain formed in the late Pleistocene was eroded into a valley, mainly by the action of floods. Valleys lay along the front edge of the proluvial fan, with water separating them from this fan. Sandy loam soil and sandy soil accumulated by channel extensions were built up. The central plains to coastal plains were a proluvial fan, which deposited on an alluvial plain, forming a flood plain (coastal plain) between the ancient fine sand river bed and ancient sandy loam and soft clay river bed. During this time, meltwater from the process of glacial retreat recharged the aquifer in the post-glacial period and early Holocene. Together with abundant precipitation and the recharge from rivers and lakes, the main groundwater processes returned to desalinization and accumulation. In fact, the current overexploitation of groundwater in the Haihe River Basin essentially extracts water stored 10000 years ago in aquifers (Aquifers II and III in Figure 4) mainly formed in the Yangshao warm period (8 ka B.P.–5 ka B.P.) [24].

Aquifer Groups I to IV correspond to strata from the Pleistocene to Holocene. The first aquifer was formed about 20 ka–60 ka B.P., with a buried depth of 350 m and 50–60 m thickness [25]. The buried depth of the aquifer in the Piedmont Plain was less than 300 m, with 20–40 m thickness, and was composed of cemented gravel and thin-layer weathered sand. The water yield was 5–10 m^3/(h m) and salinity was less than 1 g/L. The buried depth of the aquifer in the middle plain was more than 350 m with a 10–30 m thickness, and composed of medium-fine and fine sand. The water yield was 2–3 m^3/(h m). The aquifer in the coastal plain was composed of fine sand and silt, with thickness around 20 m. Salinity of groundwater in the middle and coastal plains was 0.5–1.5 g/L and 1.52 g/L, respectively.

Aquifer group II was of the confined aquifer type. The thickness was more than 90 m and it was composed of coarse sand with gravel, medium sand and fine sand. The lower boundary was buried at 170–350 m, and it formed during 8 ka–22 ka B.P. [26]. Groundwater types from the piedmont to the Bohai Sea were HCO_3-Na-Ca, Cl-HCO_3-Na and Cl-Na. Salinity was 0.3–0.5 g/L, and the water yield was 50 m^3/(h m). The buried depth of the aquifer bottom in the piedmont region was less than 100 m, and the aquifer was mainly composed of gravel. The buried depth of the aquifer in the central and coastal plains was more than 170 m, and these were mainly composed of medium-fine and fine sand.

Aquifer group III was a shallow, confined aquifer. The thickness was about 60 m and the bottom depth was typically 120–170 m. Formation was during the Yangshao warm period, about 4.6 ka–8 ka B.P. [26]. This aquifer was composed of grit, medium sand and fine sand, similar to the first aquifer group. Underground water was saline from the central plain to the coastal plain, with salinity greater than 2 g/L.

Aquifer Group IV was a phreatic aquifer, with an age of 1.55–40.73 years, averaging 15.8 years [26]. From piedmont to coastal plains, granularity of the sediment ranged from grit to fine sand. The piedmont was a freshwater area, and salt water was widely distributed from the middle plain to the coastal plain.

(3) The late Holocene. The climate was cool and somewhat dry. Precipitation varied greatly, with alternation between wet and dry periods. Average annual precipitation in the Haihe basin was about 500 mm. River flow was weak, with high sand content. The hydrodynamic force was weak, and the type of channel was wandering. In drought periods,

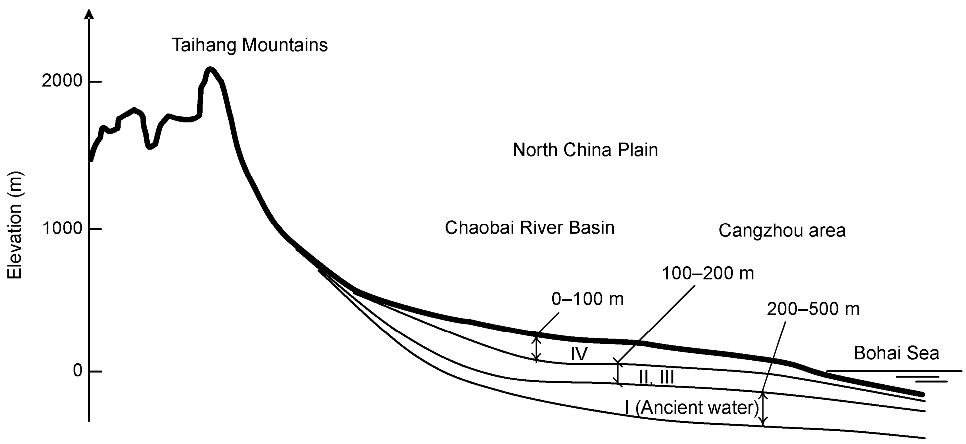

Figure 4 Distribution of aquifers in the North China Plain.

rivers shrunk. In wet periods, river flow increased and there was flooding on the Piedmont Plain when the channel failed to contain the water. Silt in the river flow sank to become sediment and formed fan-shaped Piedmont Plains, which finally joined from south to north. This conclusion was confirmed by Xu [27]. We studied the deposition rate of the North China Plain, obtaining a chart of average deposition rate change with time. This shows that the deposition rate increased 2 to 8 times over that of 5000 years ago. This demonstrates that the river with small discharge and low hydropower helped form the Piedmont Plains. Deep confined aquifer water was recharged less with the decreased precipitation and low stream flow in the rivers. On the contrary, previously stored groundwater began to discharge out of the aquifer as the sea level declined. Only the piedmont aquifer was intermittently recharged, after a few flood events.

4 Influences of water system meander

Water system meander and water cycle evolution are interactional. On one hand, the water system is the main land channel of the water cycle. The water system pattern determines pathways of surface water flow. On the other hand, sediment erosion and deposition associated with the water cycle drive water system meander, and change the geomorphological environment of a river Basin. The formation and evolution of the Haihe River Basin vividly reflects this interaction.

The Haihe River system became gradually independent from the Yellow River system by sedimentation, during the middle and late Holocene. This formation can be summarized in two stages: (1) In the middle Holocene, with siltation and resultant extension of the coastal plain, rivers originating from the Taihang and Yanshan mountains, including the Zhanghe, Hutuo, Daqing, Yongding, Chaobai and other rivers, converged channels and ultimately merged at Tianjin under the strong hydrodynamic effect. (2) In the late Holocene, the climate turned cool and dry. The flow rate was low, and the hydrodynamic force of rivers was not sufficiently strong to transport sediment to the Bohai Sea. Sediment transported by small- to medium-scale floods was usually deposited near the junction of mountain and plains, forming the Piedmont Plains. With increased deposition on those plains, the Yellow River channel was gradually crowded out and forced to move south (Figure 5; the regime of the Yellow River during the Northern Song Dynasty is described in [28]). Finally, the Haihe River system became independent. In fact, since the second year of the reign of Emperor Jianyan (1128), the Yellow River has never intruded into the present Haihe basin.

The separation of the Haihe river system from that of the Yellow River had two effects on the water cycle: The first is that direct hydraulic connections between the two basins

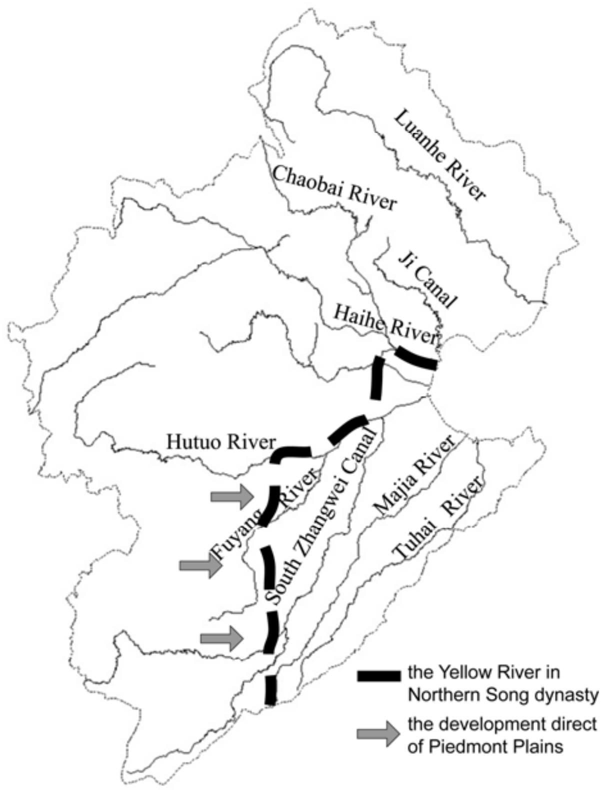

Figure 5 Sketch map of the ancient Yellow River.

abated, and the groundwater recharge on the North China Plain decreased. Before the Song Dynasty, the Yellow River mainstream traversed the North China Plain directly. Leakage recharge of the Yellow River formed the ancient Yellow River groundwater system [29]. Modern Yellow River water can leak into the Haihe River Basin groundwater system only because of the high potential energy of the suspended river. This volume of water is very small, about 400 million m^3/a [30]. The second effect is that the absence of Yellow River water dramatically reduced water resources available to the Haihe River Basin, and the basin has clearly dried. Since the Northern Song Dynasty, the ancient Ningjin Lake shrank and gradually disappeared; the area of Baiyang Lake also greatly decreased. The reduction of surface water resources has had such negative effects as a shortage of phreatic water recharge, greater evaporation loss, imbalance of surface water and salt, aggravation of soil salinization, and others [31].

5 Conclusion and discussion

We collected a dataset of paleoclimate, paleogeography, palynoflora, historical records, isotopic abundance ratio and content, for research on various time scales. We drew interesting conclusions from a comprehensive analysis. First, radiation was the intrinsic force driving water cycle evolution.

Generally, precipitation increased with temperature. Second, precipitation was abundant during 8 ka–5 ka B.P., the so-called Yangshao warm period of the Middle Holocene, which recharged the major part of Quaternary groundwater. Third, heavy floods during this period transported sediment far to the sea, forming the Coastal Plain that includes the cities of Tianjin, Huanghua, and Cangzhou. Over the past 3000 years, intermittent moderate floods had insufficient energy to transport sediment to the sea. These floods usually flowed over the piedmont regions of the Taihang Mountains, and sediment deposited to form the Piedmont Plain embracing the cities of Shijiazhuang, Xingtai, Handan, and Baoding. Over the past 1000 years, the climate in the Haihe River Basin has been mainly cold and dry. During the Ming and Qing Dynasties, there were frequent Antarctic ice sheet events. At this time, precipitation was slight, wetlands shrank, groundwater was insufficiently recharged, and water levels fell. Temperature in the year 1660 reached its lowest value of the past 3000 years, and then began to rise. Today's temperature is near the average, which is much lower than that during the Song and Yuan dynasties. The current period is one with relatively low precipitation.

There are several shortcomings in this study. First of all, temporal resolution of the analysis from which the above conclusions are drawn is about 500 years. Some short-term temperature and precipitation fluctuations may not be captured. Therefore, the results may have some deviations for periods with unstable climate changes, which require further study within millennial-scale or centennial-scale water cycle research.

Secondly, some researchers may differ with the statement that temperature leads precipitation change and that their relationship has a positive correlation. The reason may be that over the past 50 years (1956–2005), average temperature in the Haihe River Basin increased 1.5°C, but precipitation decreased more than 10% [23], representing a warm, dry trend. However, this was a short-term, abnormal phenomenon. Contradictory conclusions originated from different research scales. The general trend is still wet and warm over the past 10000 years.

Thirdly, the stratifications and ages of groundwater show great spatial variation across different regions. In the low eastern coastal plain, groundwater from earlier than 30000 years ago was found in deep phreatic water by isotope age tests, which demonstrates that not all groundwater was recharged in the past 10000 years. The old water is mainly ancient groundwater stored before the Würm glaciation. In the late Pleistocene, because of the small water potential gradient of the low plains region and slow horizontal velocity, this water did not have time to be replaced. As the climate became warmer and wetter in the Yangshao warm period, sea level rose and sea water invaded the surface aquifer; the original ancient water was sealed underground. The ancient water was generally buried deep and accounted for a small percentage of the whole ground water. Therefore, it stands to reason that the presently overdrawn groundwater in the Haihe River Basin was recharged over the past 10000 years.

In summary, this study reveals the relationship between temperature, precipitation and river networks in the past 10000 years in Haihe River Basin, which has great scientific and practical importance in understanding the current water circulation and water shortage.

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1 Chen M X. Regional characteristics and assessment of groundwater resource in China (in Chinese). J Nat Resour, 1986, 1: 18–27
2 Xie Z H, Liang M L, Yuan L, et al. The response of shallow water table depths to climate change in Huang-Huai-Hai Plain (in Chinese). J Chin Hydrol, 2009, 29: 30–35
3 Liu J H, Qin D Y, Wang H, et al. Dualistic water cycle pattern and its evolution in Haihe River Basin. Chin Sci Bull, 2010, 55: 1688–1697
4 Wu Z X. Recordation of neoteric meteorological observation in Beijing area (in Chinese). Meteorol Sci Technol, 1999, 1: 60–64
5 James Z, Mark P, Lisa S, et al. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science, 2001, 292: 686–693
6 Pavel T, Jin G Y, Mayke W. Mid-Holocene environmental and human dynamics in northeastern China reconstructed from pollen and archaeological data. Palaeogeogr Palaeocl, 2006, 241: 284–300
7 Wu C. Geomorphological Environment and Its Formation and Evolution of North China (in Chinese). Beijing: Science Press, 2008
8 Wu C. Study on Paleochannel of the North China Plain (in Chinese). Beijing: China Science and Techndogy Press, 1991
9 Zheng J Y, Shao X M, Hao Z X, et al. Overview of research on climate change in China during the past 2000 years (in Chinese). Geographical Res, 2010, 29: 1561–1570
10 Davis M. Palynology after Y2K—Understanding the source area of pollen in sediments. Annu Rev Earth Planet Sci, 2000, 28: 1–28
11 Heusser L. Pollen in marine cores: Evidence of past climate. Oceans, 1986–1987, 29: 64–70
12 Tauber H. Investigations of the mode of pollen transfer in forest areas. Rev Palaeobot Palyno, 1967, 3: 277–286
13 Kershaw A P, Hyland B P M. Pollen transport and periodity in a marginal rainforest situation. Rev Palaeobot Palyno,1975, 19: 129–138
14 Zhu K Z. Preliminary study of climate change in China for nearly 5000 Years (in Chinese). Acta Archaeologica Sin, 1972, 1: 168–189
15 Xu Q H, Wu C, Zhu X Q, et al. Palaeochannels on the north China plain: Stage division and palaeoenvironment. Geomorphology, 1996, 18: 15–25
16 Tong G B, Zhang J P, Yan F H, et al. Sporo-pollen sequence and division of climatic period in the eastern north China plain since late Pleistocene (in Chinese). Seismol Geol, 1991,13: 259–268
17 Wang Y. Evolution sequences of palaeovegetation and palaeoclimate in the Caofeidian area since the last stage of the late Pleistocene epoch (in Chinese). Mar Geol Quaternary Geol, 2000, 20: 87–92
18 Guo S Q, Wang Y H, Yang L J, et al. Climate change since the deglacial stage in theNingjinpo area (in Chinese). Quaternary Sci, 2000, 20: 490
19 Jin G Y, Liu D S. Mid-Holocene climate change in north China and the effect on cultural development. Chin Sci Bull, 2002, 47: 408–413
20 Zhang W B. Network share database for flood and drought disasters (in Chinese). Chin Water Resour, 2009, 5: 66–67

21 Zhang C L, Duan H Z. Research on the process of civilization of the eastern piedmont area of Taihang mountains (in Chinese). In: Proceedings of the Ancient Civilization and Origin of the State in China. Beijing: Science Press, 2011

22 Shi Y F, Sun Z C. Climate and Environment of the Holocene Warm Period in China (in Chinese). Beijing: Ocean Press, 1992

23 Ren X S, Hu Z L. Water Resources Assessment of the Haihe River Basin (in Chinese). Beijing: China Water Power Press, 2007. 24–25

24 Zhang G H, Chen Z Y, Fei Y H. Relationship between the formation of groundwater and the evolution of regional hydrologic cycle in north China plain (in Chinese). Adv Water Sci, 2000, 11: 415–420

25 Xu Y Z, Tian X W, Zheng Y J, et al. Recharge of groundwater in the Xiaoshan area of Cangzhou (in Chinese). Hydrogeol Eng Geol, 2009, 3: 51–54

26 Wei W. Groundwater age and recharge temperature in the quaternary aquifers in north China plain (in Chinese). Disseration for the Master Degree. Beijing: Chinese Academy of Geological Sciences, 2007. 1–72

27 Xu J X. Study of depositional rate in the north China plain during the past 40000 years, based on 14C dating data from a large wealth of samples (in Chinese). Quaternary Sci, 2007, 27: 437–443

28 Xu Q H, Yang X L, Zheng Z H, et al. Course change and course realignment of the Yellow River (in Chinese). Geogr Geo-infor Sci, 2004, 20: 77–80

29 Zhang G H, Yang L Z, Nie Z L, et al. Assessment of groundwater function in north China plain (in Chinese). Resour Sci, 2009, 31: 368–374

30 Lei W D, Luo Y F, Jiao Z Y. Progress of study on lateral seepage of the lower Yellow River (in Chinese). Yellow River, 2009, 39: 61–64

31 Hao C F, Jia Y W, Gong J G, et al. Analysis on characteristics and rules of climate change of Haihe River Basin in recent 50 years (in Chinese). J Chin Inst Water Resour Hydropower Res, 2010, 8: 39–43