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Article

Groundwater balance and circulation in key areas of the Yellow River basin

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Han Zhantao, Zhang Eryong, Hou Xinwei, Gao Cunrong, Shi Yingchun, Zhao Hongmei, Ding Jianqing, Liu Xingchun, Li Baogui, Zhao Runlian, Jiao Xili, Shan Lijun, Zhu Zhongdao and Wang Ning (2009) Groundwater balance and circulation in key areas of the Yellow River basin. *Bull. Geol. Surv. Japan*, vol. 60 (1/2), p. 59-86, 19 figs, 6 tables, 2 plates.

Abstract: Since the main plain and basin areas in the Yellow River basin are regions of great importance to the social and economic development of China, it is important work to understand the groundwater balance and circulation in these regions. We have selected the Yellow River source region and the Yinchuan, Hubao, Taiyuan and Guanzhong basins, as well as the Lower Yellow River zone for study on groundwater balance and circulation. This paper shows characteristics of stable isotope ratios of hydrogen and oxygen, and water quality in the main plain and basin areas in the Yellow River basin. Moreover, the groundwater flow system and water balance in these regions are estimated by the results of field data.

Keywords: Yellow River basin, stable isotope ratio, water quality, groundwater flow system, water balance

1. Groundwater in major areas of the Yellow River basin

The Yellow River source region is an important zone of water resource conservation. The main plain and basin areas in the river basin are regions of dense population and developing economy. The groundwater balance and circulation in these regions have determined the mode of exploitation and utilization of groundwater in the basin. Those are of great importance to the social and economic development of the local regions. Therefore, in the present work, we have selected the Yellow River source region and the Yichuan, Hetao, Guanzhong and Taiyuan basins, as well as the Lower Yellow River Plain for our study on groundwater balance and circulation.

1.1 The Yellow River source region

A variety of data on the ecological and environmental geology reveal that the groundwater level in the source region shows a dropping trend in recent years. This is mainly evidenced by: downward migration of spring vents, reduction in spring flow capacity, downward shifting of discharge zones at the front of fans and shrinkage of low moors and wet land in those zones, disappearance of ancient thermal water remains and warm springs, drop of groundwater level in densely-populated areas etc. (Geological Environmental

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Monitoring Station of Qinghai Province, 2002).

1.1.1 Downward migration and decreased capacity or drying up of spring vents in mountain areas

In places such as north of the Bayan Har mountain pass, Tuoluoqu, Bukao and Delakao, regional groundwater level has dropped owing to regression of perennial frost (increased depth of seasonally melted layers), resulting in decreased flow capacity of outcrop springs of suprapermafrost water, and notable downward migration of groundwater of the spring vents.

1.1.2 Downward migration of discharge zones at the front of alluvial-pluvial piedmont fans and decreased flow capacity

According to the comparison and interpretation of remote sensing data and field investigations, there is an obvious downward migration of the discharge zone at the front of the Karinaqin-Lena River Tangchama alluvial-pluvial piedmont fan at the front of the Kali’enkazhuoma-Yeniugou fault-block Mountains, and on the south side of Zhaling Lake and Eling Lake. The flow capacity has decreased and the low moors and wet land recharged by groundwater shrank remarkably. A comparison of remote sensing images shows that the largest distance of downward migration has reached 2.0 km.

1.1.3 Dropped groundwater level in the river valley at Madoi county seat

Based on the long-term observation data of supply wells in Madoi County the depth of groundwater level varies with season. It is generally greatest in May, begins to rise in early June, and reaches highest in November. After that, it begins to drop. The fluctuation in a year is about 1.38 m. According to a correlative analysis of the water levels at Minjing in 1992, 1995, 2000 and 2001, the groundwater level in the Madoi area has continued to drop since 1992, at 0.52-1.18 m annually for 8 years with a maximum of 1.68 m. The average rate of drop is 0.1 m/a. Up to the present, domestic water in the area is fetched with buckets from wells, while that for agricultural production is taken from surface water. Thus, the drop of groundwater level in the area is mainly attributed to natural factors.

1.1.4 Shrunken lakes and dropped groundwater level in dried-up areas

In the past decades, such phenomena as shrinkage and drying up lakes were quite notable, mainly reflected in the continuous drop of lake levels and intensified salinization. Particularly, since 1998 the shrinkage of lakes tends to accelerate; for example, the level of Xingxinghai Lake dropped 12.7 cm during 1988-1999, 19.8 cm during 1999-2000, and 29 cm during 2000-2001. During that period, many surrounding lakes were dried up, with the yellowish white lake bottom exposed. Correspondingly, local groundwater level drop occurred in places recharged by lake water.

According to a survey by the Geological Survey of Qinghai Province, before the 1980s, the lakeside plain around Niutoubei (Cuorigaze) was one of the rich pastures in Madoi County, with plenty of water and lush grass. Streams were full of flowing water above suprapermafrost layers. After 1980s, however, because of such factors as overgrazing, warming climate trend, changes in annual precipitation and monthly raining frequency, drop of lake levels etc., the level of water above the suprapermafrost dropped, and water volume reduced. As a result, the streams gradually disappeared, and the spring vents retreated.

1.2 The Yinchuan Plain

This plain is one of the large Yellow River diversion irrigation areas, where Quaternary strata are widely distributed with the thickness exceeding 1,699 m. The occurrence of Quaternary loose sediment type groundwater at depths smaller than 250 m makes it possible to divide the groundwater in the plain into unconfined groundwater formation, first confined groundwater formation, and second confined groundwater formation. There is generally a continuous watertight stratum 3-10 m thick between unconfined water and confined water. The confined water occurring beneath unconfined water is complicated with multiple layers. Generally, aquifers at 50-150 m are ascribed to the first confined groundwater formation, and those at 150-250 m to the second confined groundwater formation.

1.2.1 Unconfined water

In the plain, groundwater extraction is mainly for industry and domestic uses. The main aquifer mined is the first confined aquifer, which accounts for 66 % of the total volume extracted. Unconfined water utilized is of minor volume and poor quality, so that it is seldom mined, with a mined volume of only 0.05 %. A large part of unconfined water in the plain is easily recharged by precipitation and infiltration from the Yellow River diversion irrigation, and the extracted volume is small. Therefore, the water level shows notable seasonal changes, and is basically consistent from year to year (Figs.1 and 2). However, the unconfined water has a close hydrologic relation with the first confined water, so that when the water level of the first confined aquifer drops, its water level tends to drop correspondingly.

1.2.2 First confined aquifer

The first confined groundwater formation has long been extracted, resulting in a regional cone of depression. Prior to 1993, its water level continued to drop, accompanied with the continuous expanding cone of depression. Since 1993, management of groundwater pumping has been strengthened. Measures have been taken for the running-water companies to reduce water taken from their individually-owned wells. Consequently, the water level at the center of the depression cone began to recover, and drop in the peripheral areas also reduced in amplitude (Fig. 3). From the figure it can also be seen that the high-water level period for that formation mostly occurs in July-August, and the low-level period occurs in March-April, indicating its close relationship with unconfined water.

1.2.3 Second confined aquifer

In recent years, due to increase of urban water uses, pumping of water from the second confined groundwater formation has been expanding resulting in a regional cone of depression. In the cone of depression the water level also showed a rising trend after restriction of extraction, very similar to the case of the first confined groundwater formation. It is obviously influenced by seasonal changes: the high-water level period occurs mostly in July-September, and the low-level period mostly in March-April. In the runoff zone, the curve of the second confined groundwater formation is also very similar with that of the first formation. The long-term water level remains stable; the high-water level period occurs mostly in July-November (period of winter irrigation), while the low-level period mostly in February-April.

It can thus be seen that in both areas of depression cone and that of runoff, the above two formations show similar changes in water level regimes indicating that there is a close hydrologic relation between the first and second confined groundwater formations in the monitoring areas.

1.3 The Hubao Plain

The unconfined water regimes of this plain are mainly affected by weather, landforms and human activities. They differ greatly from place to place, because of their different natural conditions and factors, and can be summed up into the irrigation-evaporation type, the runoff-pumping type and the river-lake lateral infiltration-evaporation type. As the confined water regime is mainly affected by pumping, it belongs to the runoff-pumping type.

1.3.1 Unconfined water

The irrigation-evaporation type: This is mainly distributed in alluvial-pluvial plains, where groundwater is shallow, and the unconfined water regime is dominated by vertical movement of water. The groundwater level is controlled by irrigation and evaporation, varying with alternate seasonal regularity and lengths. The water level changes are closely related to irrigation. In the irrigation periods, two large variation periods occur, and when irrigation ceases in

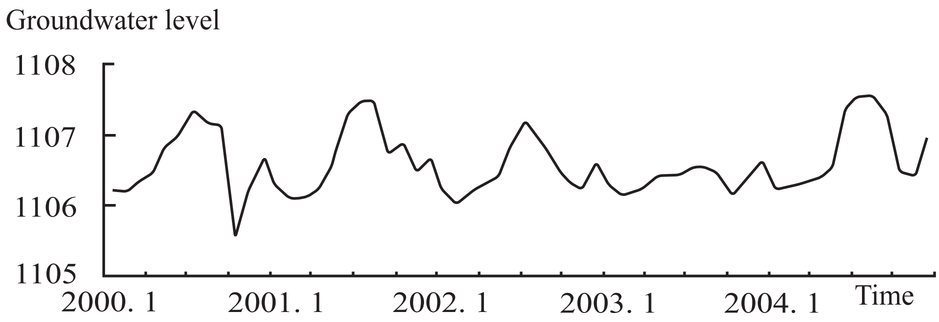


Fig. 1 Unconfined water level in the monitoring well K045

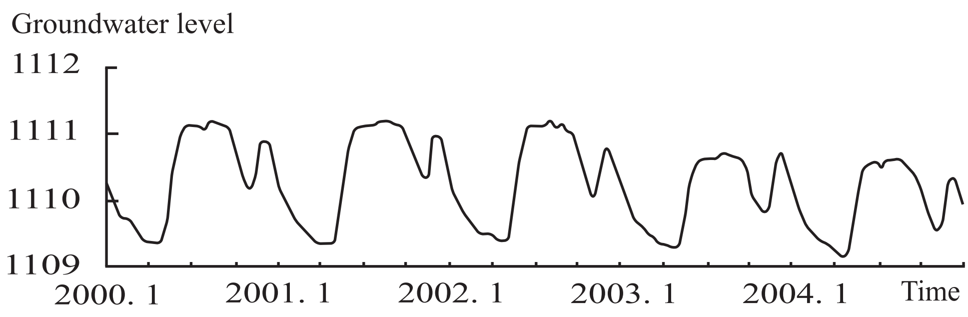


Fig. 2 Unconfined water level in the monitoring well K052

spring low-level period follows. During a year, because of the alternation of irrigation, precipitation and pause of irrigation, superposed by effects of melting, the groundwater regime shows alternating changes, with variation of water level of 1.2-2.0 m.

The runoff-pumping type: This mainly occurs in piedmont plains, where groundwater level is deeper and dominated by horizontal water movement. Both infiltration recharge from precipitation and evaporation have minor effects on the groundwater level changes, mainly controlled by lateral runoff recharge in mountain areas and artificial pumping.

The river-lake lateral infiltration-evaporation type: This is distributed along the Yellow River and the areas surroundings large lakes such as Hasuhai Lake. The groundwater regime is mainly controlled by surface water bodies, and the variation in water level corresponds to that of surface water. The lateral infiltration of rivers and lakes is main recharge source of unconfined water, and discharge is dominated by evaporation, with an annual water level variation of 1-2 m.

In general, the unconfined water level in the plain is rather stable. For many years, it only showed remarkable drop in the piedmont plain, while in other plain area the drop is of minor amplitude.

1.3.2 Confined water

The confined water is all of the runoff-pumping type. The aquifer is recharged by the lateral runoff from the upper river, and the discharge is dominated by runoff and artificial pumping. The water regime of the aquifer is of the runoff-pumping type and featured by lateral recharge being far smaller than pumping in volume. The long-term excessive pumping of groundwater has consumed the groundwater resources, so that the boundary of artesian water continued to shift southward, and the cone of depression kept on expanding.

1.4 The Guanzhong Basin

The evolution of groundwater fields varies greatly depending on landforms and hydrogeologic conditions. The diversity is affected by differences in geology, geomorphology, meteorology and hydrology resulting in a regional circulation mode, modified further by human activities. Spatially, the diversity of the unconfined water field can be divided into three areas, i.e., the circum-basin alluvial-pluvial piedmont fan area, the river bank area, and the large farmland irrigation area. Besides, owing to strong impact of artificial pumping, the cities and surrounding areas all show dynamic changes of groundwater level either in the piedmont area, the river bank area, or the farmland irrigation area.

1.4.1 Circum-basin alluvial-pluvial piedmont fan area

In this area groundwater is relatively deep, and its level is affected mainly by precipitation and hydrologic regime of the river at the mountain stream mouth, and followed by artificial activities. When precipitation and river water infiltrates underground, the groundwater level will show slow changes regulated by thick vadose piedmont zone. It shows the following features:

(1) Within a year two peaks occur, the first in March-April, and the second in July-September.

(2) As the groundwater is deep, the vadose zone is smooth and the retardation function is obvious, the changes of groundwater level generally lag by 6-15 days with respect to recharge by rivers and precipitation.

(3) River water at the foot of mountains is closely related to groundwater. As affected by drastically fluctuating surface runoff, the amplitude of variation in groundwater level is relatively large, reaching 4-10 m within a year. It indicates that the groundwater field as well as natural regeneration and regulation functions of groundwater capacity is affected by surface runoff.

(4) The annual changes in groundwater level coincide with the meteorological cycles, having high-water, mean-water and low-water cycles in many years.

1.4.2 The river bank area

The groundwater movement is mainly controlled by hydrological factors of the interference from artificial pumping superposed on the source zone along the river. Spatially, groundwater is affected by the river when its distance from the river is within 0.5-1 km, at which the monthly differential curve and historical observation curve of groundwater changes are synchronous with those of the river water. However, when it is far away from the river, the groundwater level shows little relationship with the river level.

1.4.3 The irrigation area

In the 1990s, continuous low-water cycles occurred in this area; for example, the precipitation in the Guanzhong region was only 413.3 mm and 375.4 mm for 1995 and 1997, respectively. The volume of irrigation by water diversion was reduced, but with further application of water-saving techniques such as spray irrigation and utilization of surface water, the lowering of groundwater level was effectively controlled.

1.4.4 Xi'an City and surrounding areas

Xi'an is situated on the south edge of the Weihe River, where groundwater is of poor quality. From the 1950s to 1990s, water supply for the city was dominated by groundwater pumping. As the demand for water continued to increase, over-extraction of groundwater caused large drop of groundwater level in the area. It caused release of water from soil resulting in compaction of the soil, and expanded cracks in the ground, thereby leading to serious ground subsidence. Hazards such as cracks were intensified, bringing great losses to the urban construction and infrastructure. Since 1995, water supply has been provided by the Shitou River and Heihe River diversion projects successively, and most of the individually-owned pumping wells have been shut up. Consequently, the groundwater level is gradually rose, and such problems as cracks and ground subsidence have been controlled.

(1) Unconfined water

The annual curve of groundwater level in urban Xi'an is affected by landform, lithology of the aquifer, depths of groundwater level, as well as lithology and permeability of the vadose zone. In general, during January-April, the water level drops slowly in a fluctuant mode; during May-September, the lowest water level occurs owing to large amount of evaporation; in October, it rises up slowly (Fig. 3).

(1) Confined water

In 2005, the authorities closed most of the deep wells in the urban planning areas. The mined volume of groundwater was reduced, and the water head in the center of the depression cones formed by urban and suburban individually-owned wells began to rise (Fig. 4). For example, the water head in the Xiaozhai depression cone rose up by 0.67-1.75 m.

To sum up, the pumping volume has a direct influence on the water head. For example, the well in the Northwest Technology University was shut up in 1999. Compared with the same period of the previous year, the water head rose 1.66 m in August 1999, 4.26 m in 2000, 3.43 m in 2001, and 3.84 m in 2002. The annual average water head of 2005 rose 0.67 m in comparison with that of 2004, and altogether the level rose 15.42 m in 7 years from 1999.

1.5 The Taiyuan Basin

The groundwater formations in the Taiyuan Basin and surrounding mountain areas mainly consist of the carbonate rocks-type and the Quaternary groundwater type within the basin. The former is dominated by Ordovician and Cambrian karst water, while the groundwater in the latter mainly occurs in Cenozoic loose sediments, which can be grouped into unconfined groundwater system (with depths smaller than 50 m), and the confined groundwater system (depths 50-2500 m). In the middle watertight stratum there is some leakage.

1.5.1 Karst water level

The karst water in the periphery of Taiyuan Basin is located in the discharge zone of the karst groundwater system. It can be seen from its curve (Fig. 5) that the groundwater level shows a dropping trend. The drop is caused by the factor that the discharge volume (mainly the artificial pumping volume) of the system is greater than the recharge volume. The annual changes in groundwater level are fluctuant, being generally the

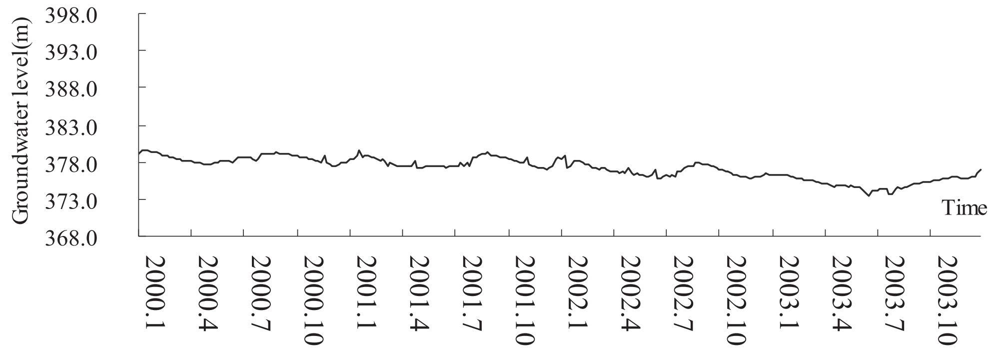


Fig. 3 Unconfined water level in monitoring well K395, Xi'an City

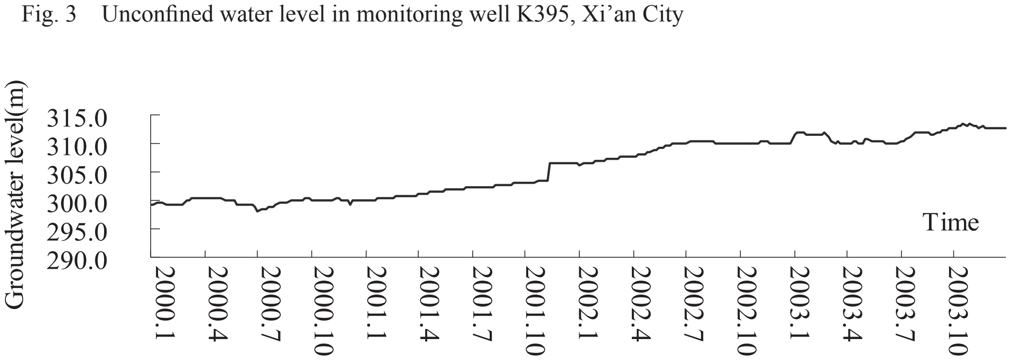


Fig. 4 Confined groundwater level in Station S38, Xi'an

highest at the beginning of the year, and the lowest at the end of the year, mainly affected by the intensity of pumping. It belongs to the pumping-type regime.

1.5.2 Shallow groundwater level

The shallow groundwater level regime in the basin is constrained by multiple factors, mainly by precipitation, artificial pumping, hydrological conditions of the deep underlying confined water, and lateral runoff, reflected in periodic changes of water level with season and meteorology. Generally, precipitation is rare in March and April, which are just the time when farm irrigation needs large-scale pumping of shallow groundwater, so that the water level drops rapidly until June and July. In July, the rainy season begins, the pumping volume reduces, and precipitation infiltration is concentrated, so that the water level rises drastically. The high-level period lasts until the first and second month of the following year, owing to the lagged recharge of precipitation infiltration and the lateral runoff recharge. The shallow groundwater regime may be summarized into the precipitation-runoff type, the pumping-precipitation type and the pumping-irrigation type.

The precipitation-runoff type occurs mainly in the loess hills and the upper part of the piedmont fan, which are not directly affected by precipitation because of the large depths of groundwater. The recharge sources are dominated by underground runoff in the mountain areas and lagged recharge by precipitation. The lowest water level occurs in June-September, and it rises slowly after the flood season. The peak value of water level occurs in January-March of the following year, followed by slow drop beginning in March. The dynamic changes of the shallow groundwater remain basically at the natural state.

The pumping-precipitation type is distributed in the middle and lower parts of the piedmont fan, which are the main pumping areas of groundwater. It is shallow, generally 4-20 m. The groundwater is mainly recharged by underground runoff and precipitation infiltration. It is strongly influenced by pumping, by which water level drops greatly. The low level generally occurs in June-July. With the coming of flood season and reduction of pumping volume, the water level rises, and the peak values occur in October-November (Fig. 6).

The pumping-irrigation type occurs mainly in the irrigation zones of alluvial plains. In the Fenhe River alluvial plain area, the water level is located at 2-10 m, and fluctuates with large amplitude. The water level fluctuations are affected by multiple factors such as irrigation, precipitation infiltration and groundwater pumping. In spring, with the surface water being infiltrated, the groundwater level rises drastically. The peak values occur generally in April-May. After that, pumping starts, and the water level drops rapidly. When it is charged by precipitation infiltration, or pumping ceases, the water level rises again.

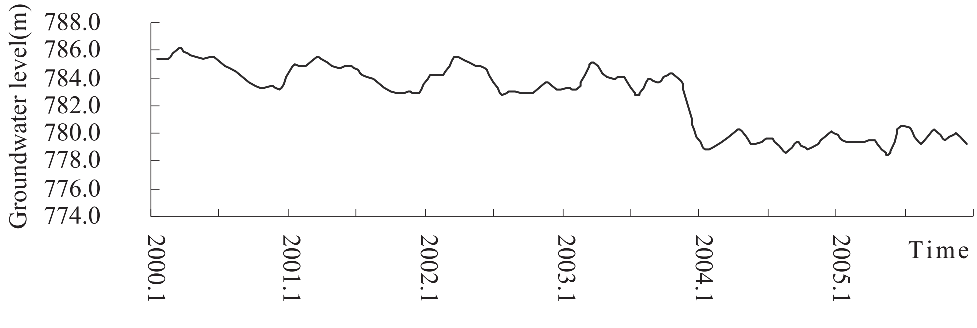


Fig. 5 Karst groundwater level in Shanglan

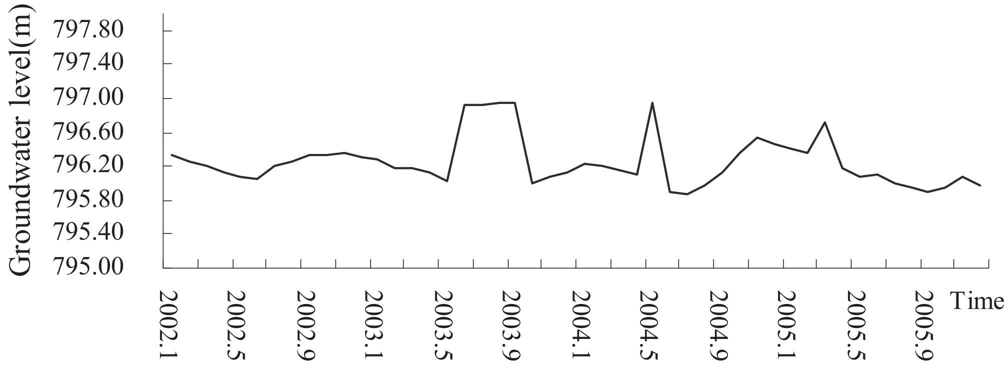


Fig. 6 Unconfined water level in Jiancaoping, Taiyuan

1.5.3 Medium-deep groundwater level

The medium-deep groundwater are constrained synthetically by lateral runoff, shallow water leakage recharge, and pumping. Because of large amount of pumping of the deep groundwater, the water level shows a declining trend. In recent years, measures have been taken to shut up some wells and reduce water pumping in the Taiyuan area. Consequently, since 2003, the medium-deep groundwater level has shown a slow rising trend in some areas (Fig. 7). According to their features, three types are discriminated, namely, the runoff-pumping type, the pumping-declining type and the precipitation-runoff type.

The runoff-pumping type is distributed in the upper part of alluvial-pluvial fans and the extensive piedmont fan areas, where main pumping occurs. The groundwater regime is affected jointly by runoff and pumping. The groundwater level shows a general declining trend, and drops greatly during the pumping period. The variation curve for the past shows a concave shape, with the lowest level in a year occurring in March-June. Generally, the water level begins to rise about a month after the rainy season, indicating that the groundwater movement is dominated by horizontal runoff. The amplitude of water level changes 3-20 m within a year, and varies greatly from year to year.

The pumping-declining type is spread in the alluvial plain and most of the mid-lower areas of the piedmont fan. The water level regime is controlled by the volume of pumping. Natural factors only have minor affects on the groundwater level. It drops after April when the pumping volume of groundwater increases rapidly, and reaches the lowest in July. After that, precipitation increases while pumping is reduced, and the water level begins to rise again (Fig. 8).

1.6 The influence zone in the lower reach of the Yellow River

The lower Yellow River is a well-known “raised bed river”. Water level is 3-8 m higher than the groundwater level of the surrounding plain areas of both sides of the river. The river is the most important recharge source for the groundwater on both banks. Its influence reaches up to 20 km for the south bank, and 13-26 km for the north bank, with the circulation depth of water less than 350 m. The zone being influenced has a flat landform, belonging to the Yellow River alluvial plain. Groundwater mainly occurs in Quaternary loose sediments, the total thickness of which exceeds 300 m. Four groundwater formations are defined. They are named as Q4, Q3, Q2 and Q1. Combining the groundwater hydrological conditions and pumping situation, the four formations can be grouped into the shallow unconfined groundwater formation, the semi-confined groundwater formation (Q4 and Q3) and the deep confined groundwater formation (Q2 and Q1).

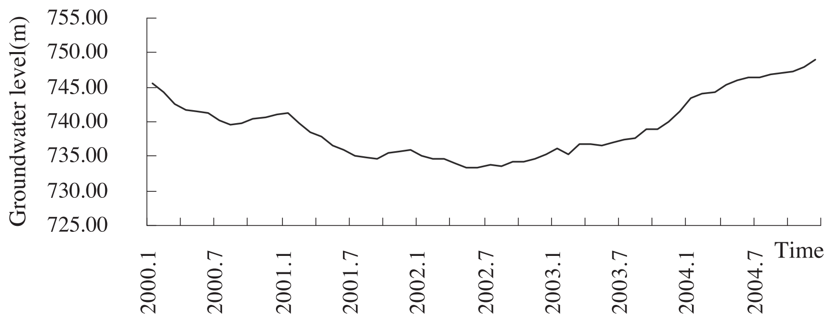


Fig. 7　Confined groundwater level in Jiancaoping, Taiyuan

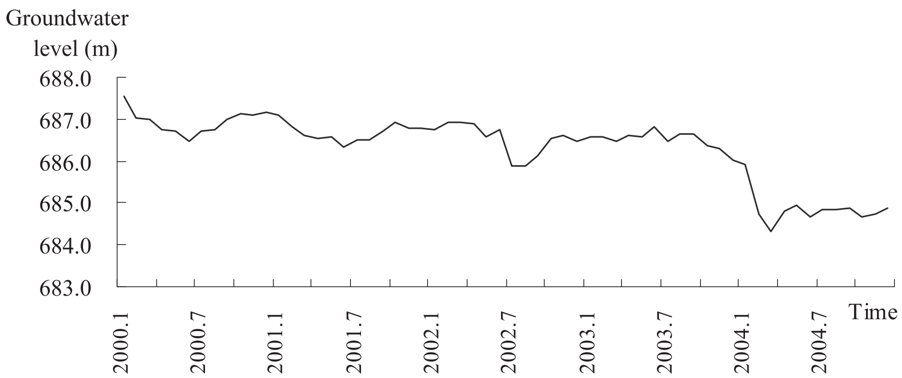


Fig. 8　Confined groundwater level in Wujapu, Taiyuan

The groundwater in the zone is mainly recharged by precipitation infiltration, channel leakage, irrigation infiltration and lateral infiltration from the river, while the discharge is mainly by evaporation and pumping. Pumping of groundwater is concentrated on both banks of the Yellow River and its former river course.

Under natural conditions, the shallow groundwater regime is mainly constrained by hydrological and meteorological factors. With the distance from the Yellow River increasing, the influence of the river on the shallow water becomes weaker. The degrees of influence changes from strong-influenc to weak-influence and finally to non-influence, and the meteorological constraint gradually changes from secondary position into leading position. Besides natural factors, there are artificial factors (mainly pumping and irrigation) that also affect the shallow groundwater regime.

1.6.1 The strong-influence zone

The strong-influence zone is generally located at distances of 2-4 km from the Yellow River including the flood plain, and the width of the zone may reach 6-8 km of local flood plains. The shallow groundwater is not mined, and its regime is mainly constrained by the river as well as such factors as precipitation and evaporation. The groundwater level changes with the Yellow River's water level, with an annual variation between 2.0 m and 3.5 m. The farther it is from the river, the smaller the annual variation. The highest water level generally occurs in July-August, roughly coincident with the river's flood period and major precipitation. The lowest water level appears in May-June, corresponding to the lowest-water, smallest precipitation and largest evaporation period.

1.6.2 The moderate-influence zone

This zone is at distances of 4-8 km from the Yellow River. The groundwater in the zone is of the precipitation-runoff type, the precipitation-irrigation type and the precipitation-irrigation-pumping type.

In the areas where groundwater has not been mined the water level variation is 1.5-2.5 m. The highest water level occurs in early-middle July, corresponding to the maximum precipitation. The lowest appears in late May to early June, which is the period of small precipitation and large evaporation. The whole high-water and low-water periods coincide with the flood and low-water periods of the Yellow River, respectively. In the areas with concentrated pumping of groundwater, the annual variation of groundwater level is 3-5 m.

1.6.3 The weak-influence zone

This is located at distances of 8-20 km from the Yellow River, mainly consisting of the Yellow River diversion irrigation area and the sewage water irrigation area. The shallow water regime is mainly controlled by weather factors and irrigation, consisting of the precipitation-pumping-runoff type and the precipitation-irrigation type. The annual water level variation is generally 2-3 m, locally strongly affected by pumping. The highest water level occurs in early-middle September, while the lowest appears in late May to middle June, related to high evaporation and low precipitation. The relatively small peak values occurring in July-early October and February-May are mainly related to the Yellow River diversion and sewage water irrigation. When neither precipitation nor irrigation is dominant, the water level drops slowly owing to evaporation.

1.6.4 Peripheral parts of the Yellow River-influence zone

This refers to the area at distances beyond 20-40 km from the Yellow River. The shallow water regime is little affected by the Yellow River water level, but mainly controlled by meteorological and pumping factors, and locally influenced by the river water irrigation. The annual water level variation is generally 2-3 m. A regional cone of depression forms on the north bank of the river, outside of the influenced zone.

2. Isotopic features and hydrochemistry of groundwater

The Yellow River basin spreads over the three huge terrace geomorphology of China. Its meteorological, hydrological, topographic and hydrogeological conditions are complicated and varied, which, superposed by human activities, have resulted in very complex hydrochemical compositions and isotope contents of groundwater. Fig. 9 and 10 are δD versus δ^{18}O diagram and Piper diagram of the groundwater in the Yellow River basin, respectively.

Geographically, the Yellow River source region lies on the highest topographic step of China, with elevations between 3,700 and 4,800 m. The upstream Yinchuan Plain and Hubao Plain are located on the middle step, the former with elevations of 1,100-1,200 m and the latter ～1,000 m. The midstream Taiyuan Basin and Guanzhong Basin are also on the middle step, with elevations of 735-830 m and 320-800 m, respectively. The elevation of the lower Yellow River-influenced zone is below 100 m, and that of the Yellow River delta is below 15 m.

The groundwater in the Yellow River source region is dominated by bicarbonate water with the mineralization degree larger than 1 g/L, in which δD and δ^{18}O are low, and ^{3}H varies within a large range. In the Yichuan Plain, the groundwater changes along the flow direction from the bicarbonate type gradually to the sulfate-bicarbonate type, the mineralization degree

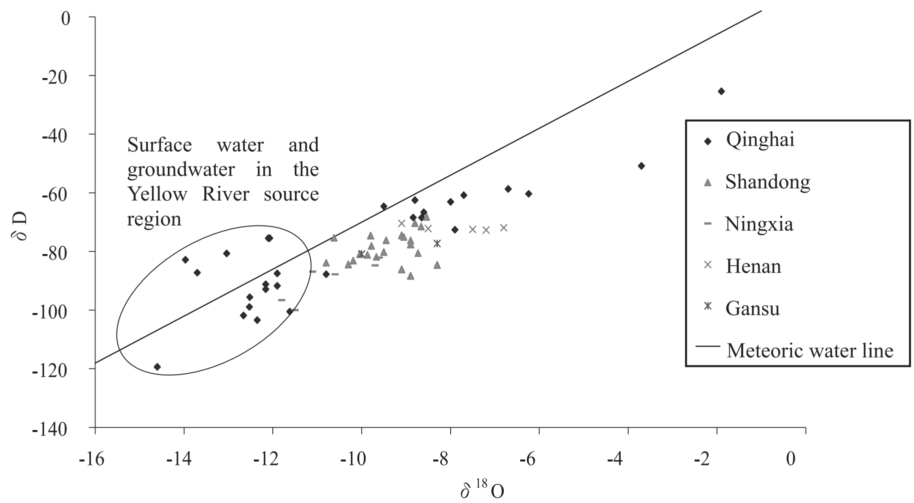


Fig. 9 δD versus δ^{18}O in water samples from the Yellow River basin

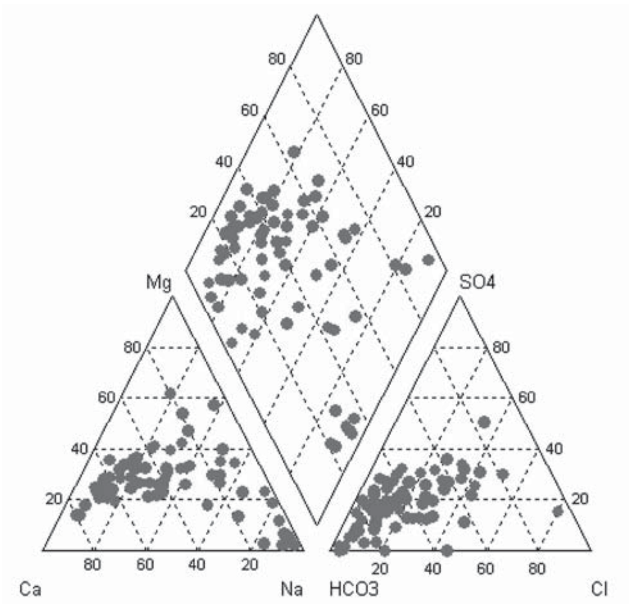


Fig. 10 Piper diagram of hydrochemistry of groundwater in the Yellow River basin

from less than 1 g/L to larger than 10 g/L, and the δD, δ^{18}O and ^{3}H values vary greatly corresponding to the different circulation conditions. In the Hubao Plain, the groundwater changes along the flow direction from the bicarbonate type gradually to the sulfate-chloride type and to the chloride-sulfate type, with the mineralization degree from less than 1 g/L to larger than 10 g/L. The δD and δ^{18}O values vary depending on the different recharge sources, while the ^{3}H changes over the great range depending on different groundwater runoff conditions. The groundwater in the Taiyuan Basin is dominated by bicarbonate water, with the sulfate type in local areas. The mineralization degree is generally less than 2.0 g/L; the δD and δ^{18}O values vary in a small range, those for deep water are smaller than for shallow water; and the ^{3}H value varies greatly in both deep and shallow water. The groundwater in the lower Yellow River-influenced zone changes gradually from the bicarbonate type gradually to the bicarbonate-chloride type and to the chloride-sulfate type, and finally to the chloride type in the littoral plain. The mineralization degree also changes from less than 1 g/L to larger than 10 g/L gradually, and the δD and δ^{18}O values are smaller in deep water than in shallow water. The ^{3}H value varies greatly in both the deep and shallow water, all between 1 TU to several tens of TU.

2.1 The lower Yellow River source region

2.1.1 Hydrochemistry of groundwater

As there is a special type of frozen soil layer water in the Yellow River source region, the following discussion on the hydrochemical features of groundwater is made in terms of the frozen soil layer water and the non-frozen soil layer water.

(1) Hydrochemistry of the frozen soil layer water

The loose sediment-type frozen soil layer water has a mineralization degree generally less than 0.5 g/L, dominated by the HCO_3-Ca•Mg in hydrochemical type. In the inside flowing zone and Tertiary red-bed hilly areas, groundwater is of poor quality, with the mineralization degree ranging between 0.80-3.26 g/L, mostly of the Cl•SO_4-Na•Ca, HCO_3•SO_4-Na•Ca and SO_4-Na•Ca types. The subpermafrost groundwater is of complex hydrochemical types, mainly attributed to its different recharge-runoff-discharge conditions. Areas of good recharge conditions, where water quality is good and mineralization degree is less than 1.0 g/L, are dominated by the HCO_3-Ca•Mg type; Areas of poor recharge condition and slow runoff, where water quality is poor and mineralization degree is between 2.26-4.06 g/L, are dominated by the Ca-Na type.

The hydrochemistry of the bedrock-type frozen soil layer water: It consists of suprapermafrost water and the subpermafrost water. The former has a mineralization degree less than 0.5 g/L, hydrochemical types dominated by the HCO_3-Ca type and the HCO_3-Ca•Mg type, with subordinate types of HCO_3-Mg•Ca and Cl•SO_4-Na•Ca. The subpermafrost water is of good quality, with a mineralization degree of 0.18 g/L, and of the HCO_3•SO_4-Na•Ca•Mg type.

(2) Hydrochemistry of the non-frozen soil layer water

It consists of loose sediment-type pore unconfined water and confined water. The former is freely circulating, of good quality, with the mineralization degree less than1 0 g/L, and of the HCO_3-Ca•Na•Mg, HCO_3-Ca, and HCO_3-Mg•Ca types. The latter is relatively slow in circulation, of poor quality, mineralization degree generally less than 3 g/L, and of

Table 1 Isotopic compositions of precipitation, surface water and groundwater in the Yellow Riversource region

Serial No.	Point No.	Elevation	Sampling location	D (‰)	^{18}O (‰)	^{3}H (TU)	Type
1	QH0503-2	3933	Wenquan Township	−11.62	−100.46	10.26	Spring
2	S-11	4253	Left bank of lower Eling Lake	−13.70	−87.20		Spring
3	S-12	4786	Bayan Har mountain pass	−11.90	−87.50		Spring
4	QH0503	3933	Wenquan Township	−14.6	−119.32	24.46	Rain
5	S-10	4275	Eling Lake	−3.70	−50.80		Lake
6	S-8	3748	Dahe Dam, Heka Mountain pass	−8.60	−66.60		River
7	QH2	4638	Roadside of Madoi-Bayan Har	−13.97	−82.82	21.29	River
8	QH3	4820	Roadside of Madoi-Bayan Har	−12.10	−75.49	2.92	River
9	QH4	4734	Roadside of Madoi-Bayan Har	−13.04	−80.69	12.2	River
10	QH0505	4391	Roadside of Madoi-Bayan Har	−12.16	−91.21	19.26	River
11	QH0506	4630	Roadside of Madoi-Bayan Har	−10.8	−87.77	10.07	River
12	QH0507	4805	Roadside of Madoi-Bayan Har	−12.16	−92.86	7.2	River
13	QH0508	4278	Roadside Madoi-Bayan Har, potable water well of the Madoi Tibeten Middle School	−12.66	−101.78	20.96	Well
14	QH0509	4273	Potable water well of the Madoi Telecommunications Office	−12.53	−98.91	16.65	Well
15	QH0510	4230	Potable water well in the compound of the Highway Office	−12.35	−103.41	0.88	Well
16	QH0504	4279	Potable water well of the Madoi Meteorological Bureau	−12.52	−95.55	15.88	Well

the Cl-Na•Mg and Cl-Na•Mg•Ca types.

2.1.2 Isotopic features of groundwater

In the present work, a total of 16 groups of D and ^{18}O isotope samples and 12 groups of ^{3}H have been collected in the source region, all of which were taken in the rainy season, including surface water, groundwater, spring water and rain water (Table 1). The δD and $\delta^{18}O$ relationships of the samples are shown in Fig. 11.

The rain water sample was collected from the Wenquan Township, Xinghai County, at an elevation of 3,933 m. Both the δD and the $\delta^{18}O$ values are small, being -119.32 ‰ and -14.6 ‰, respectively, which are obviously influenced by the elevation effect of isotopes.

The surface water samples include river and lake samples. The former were collected from a tributary of the Yellow River, and the latter from the Eling Lake. As can be seen from the figure both the δD and the $\delta^{18}O$ values of surface water are remarkably higher than those of rain water, indicating that the former has undergone evaporation to various degrees. Among them, the δD and the $\delta^{18}O$ values in the river water at the Heka mountain pass and the Eling Lake are notably higher than those of other river water, especially those of the Eling Lake water, reaching -3.70 ‰ and -50.80 ‰ respectively, resulted from strong evaporation.

The δD and the $\delta^{18}O$ values of groundwater are smaller, being -12.66 ‰ to 12.35 ‰ and -103.41 ‰ to 95.55 ‰ respectively, with small variation. These groundwater samples were all collected from the Madoi county seat and nearby areas. They have similar hydrogeological conditions, with their stable isotope values being close to each other.

The measured results of ^{3}H indicate that most of the values for surface water and groundwater are in the range of 10-22 TU, and lower values are found only in a few stream water and groundwater samples. Among them, the ^{3}H values for two sampling points at the Bayan Har mountain pass are 2.92 and 7.2 TU respectively, suggesting subpermafrost water recharge of slow runoff controlled by hydrogeological conditions. The ^{3}H value of the groundwater from a deep well in the compound of the Madoi Highway Office is 0.88 TU, indicating that the deep groundwater has a sluggish runoff and slow water replacement.

2.2 The Yinchuan Plain

2.2.1 Hydrochemistry of groundwater

(1) Horizontal change of unconfined water hydrochemistry

During flow of unconfined water from surrounding areas to the plain, its hydrochemistry shows a remarkable change. West of the Yellow River, the mineralization degree of groundwater increases gradually along the flow direction of groundwater (i.e., from west to east, and from southwest to northeast), changing from less than 1 g/L to 1-3 g/L, to 3-6 g/L, to 6-10 g/L, and finally to larger than 10 g/L, and the hydrochemical types from the HCO_3•SO_4-Ca•Mg and HCO_3•SO_4-Mg•Ca gradually to the SO_4•HCO_3-Ca•Na.

(2) Horizontal change of confined water hydrochemistry

The confined water in the plain occurs below 60 m under the surface. The mineralization degree of groundwater increases gradually from west to east, and from south to north, changing from less than 1 g/L to 1-3 g/L, to 3-6 g/L, to 6-10 g/L, and finally to larger than 10 g/L. The highest degree of mineralization reaches 16 g/L in the eastern edge.

(3) Vertical change of groundwater hydrochemistry

In the plain the mineralization degree and the concentrations of main ions of groundwater decrease gradually with increasing depth. The water quality is characterized by higher salinity in upper layers and lower salinity in lower layers. Such vertical distribution is attributed to evaporation in the case of unconfined water, and to the effects of water circulation and replacement in confined water.

Due to evaporation and condensation, the groundwater shallower than 50 m changes to the

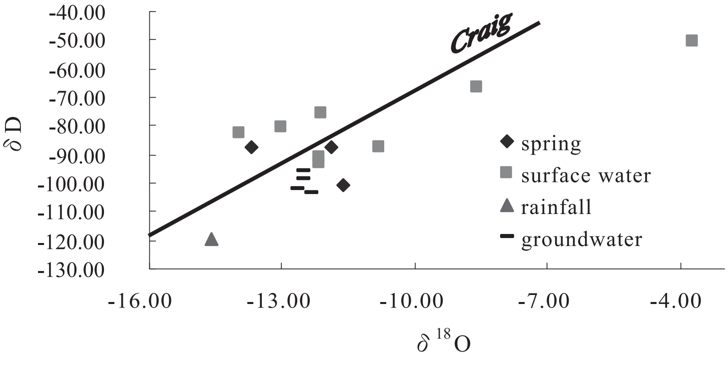


Fig. 11 δD versus $\delta^{18}O$ in water samples from the Yellow River source region

$Cl•SO_4$-$Na•Mg$ type, showing typical surface salinization. In the groundwater at depths of 50-120 m, HCO_3^- and Ca^+ are dominant, resulting in HCO_3•Cl-Na•Ca water with a mineralization degree of about 0.4 g/L; in the groundwater deeper than 120 m, HCO_3^- and Na^+ are dominant, resulting in HCO_3-Na water with the mineralization degree ranging between 0.2-0.4 g/L (Fig. 12)

2.2.2 Isotopic features

The values of δD and δ^{18}O show a large range in the plain; the δD from -52 ‰ to -99 ‰, and the δ^{18}O from -5.34 ‰ to 11.8 ‰.

In a simple unconfined water zone of the pluvial fan at the foot of the Helan Mountains, the δD values vary moderately between -62 ‰ and -71 ‰, averaging -64 ‰; the δ^{18}O from -8.6 ‰ to 10. 7‰, averaging -9.5 ‰; the ^{3}H values vary greatly from less than 0.5 to 33 TU. Samples with low ^{3}H content (less than 0.5-33 TU) are mainly distributed on the top of the pluvial fan and segments with minor pumping volume, while those with high ^{3}H content (15-33 TU) occur in areas of intensive pumping.

In a simple unconfined water zone of the pluvial fan in the Yellow River, the δD values vary between -55 ‰ and -73 ‰, averaging -65 ‰; the δ^{18}O from -8.4 ‰ to 10.2 ‰, averaging -9.3 ‰; the ^{3}H values vary greatly from 6 to 36 TU. Samples with low ^{3}H content (6-7 TU) are mainly distributed in the upper part of the pluvial fan or in deep groundwater; those with high ^{3}H content (36 TU) occur in the middle and lower parts of the fan.

In the multi-layer unconfined-confined water zones in the alluvial-pluvial and alluvial plains, the groundwater δD values vary between -58 ‰ and -70 ‰, averaging -65 ‰; the δ^{18}O from -7.9 ‰ to 10.7 ‰, averaging -9.4 ‰. The δD and δ^{18}O values show a general distribution trend of increase from south to north and from west to east.

The confined water at 60-250 m dpths is characterized by low H and O stable isotopes and low ^{3}H content. The δD values vary from -68 ‰ to -80 ‰, averaging -73 ‰; the δ^{18}O from -9.5 ‰ to -11.8 ‰, averaging -10.5 ‰; the ^{3}H values vary from less than 0.5 to 45 TU. Samples with low ^{3}H content (less than 0.5-3 TU) are mainly distributed in the central and north parts of the plain, accounting 78 % of the total number of samples. Those with a ^{3}H value of 45 TU are distributed in Yinchuan City in the central part of the plain, and those with a value of 24 TU are collected from Yongning County of the central plain. The ^{14}C content in the groundwater ranges 7-90 pmc, among which the samples with values of 7-18 pmc are distributed in western Yinchuan City and Pingluo County in the north of the plain, and those with values of 47-90 pmc are in the central part of the plain and the eastern part of Yinchuan City.

For the samples with depths of 160-245 m, the δD

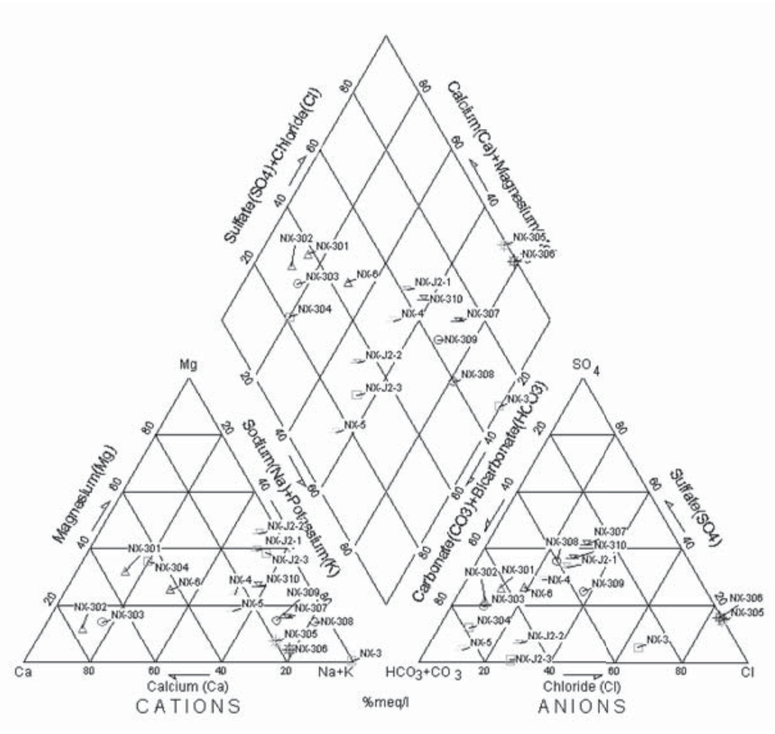


Fig. 12 Piper diagram of hydrochemistry of water in the Yinchuan Plain
Confined water O Spring Surface water Unconfined water Geothermal well

values vary from -67 ‰ to -96 ‰, averaging -84 ‰; the $\delta^{18}O$ from -9.4 ‰ to -12.2 ‰, averaging -11 ‰; ^3H less than 0.5.

As can be seen from the ^2H versus ^{18}O diagram (Fig. 13) for groundwater in the plain, all the unconfined water samples fall on the lower part of the local rain water line, highly correlated with unconfined water evaporation line, Y=4.61 * X - 28.05. The sampling point (11) of a spring on the eastern bank of the Yellow River lies on the extension of that evaporation line, which indicates that the spring is sourced from unconfined water of the plain. As for the other two spring sampling points (10 and 12), the former falls in between the local rain water line and the evaporation line, and the latter below the evaporation line, indicating that they are mixed water of precipitation and unconfined water (10), and that of unconfined water and confined water (12), respectively. The stream water and the Yellow River water samples fall on the vicinity of the local rain water line, demonstrating that they are mainly sourced from precipitation.

The sampling points of confined water are distributed on the lower right of the local rain water line and the unconfined water evaporation line, and the δD and ^{18}O values tend to be negative with increasing depth. It demonstrates that they are moderately influenced by evaporation and recharged by precipitation or the river water under glacial climate conditions in geologic past, through leakage from the overlying unconfined water.

Two samples were collected from a geothermal well in the region with depths greater than 3,000 m. They have very weak hydrological relations with the overlying unconfined and confined water.

2.3 The Hubao Plain

2.3.1 Hydrochemistry of groundwater

(1) Hydrochemistry of unconfined water

The hydrochemical types of unconfined water in the plain show a remarkable zoning. From the piedmont strong-runoff zone to the medium-runoff zone in the eastern and northern parts, the hydrochemical types change from the HCO_3-Ca•Mg gradually to the HCO_3-Mg•Ca, HCO_3-Mg•Na and HCO_3-Na•Mg types. In the Shandai-Tabu section, the unconfined water turns into low-mineralized HCO_3-Na type weakly alkaline water. On the back edge of the southern platform, it changes into HCO_3-Mg•Ca and HCO_3-Mg•Na types. When the strong-runoff zone extends into the plain, it changes into the SO_4•Cl-Na and Cl•SO_4-Na types, and the mineralization degree increases, locally exceeding 10 g/L.

(2) Hydrochemistry of confined water

Confined water east of the Qiao'ershiying-Tiemao zone belongs to the HCO_3 hydrochemical type. Because of the differences in grain sizes of aquifers and in groundwater runoff conditions in the zone, the variation of cations shows a notable zoning. The cations are of the Ca•Mg type in the strong groundwater runoff section, and of the Na•Mg type in the weak groundwater runoff section.

To sum up, the hydrochemical types of the

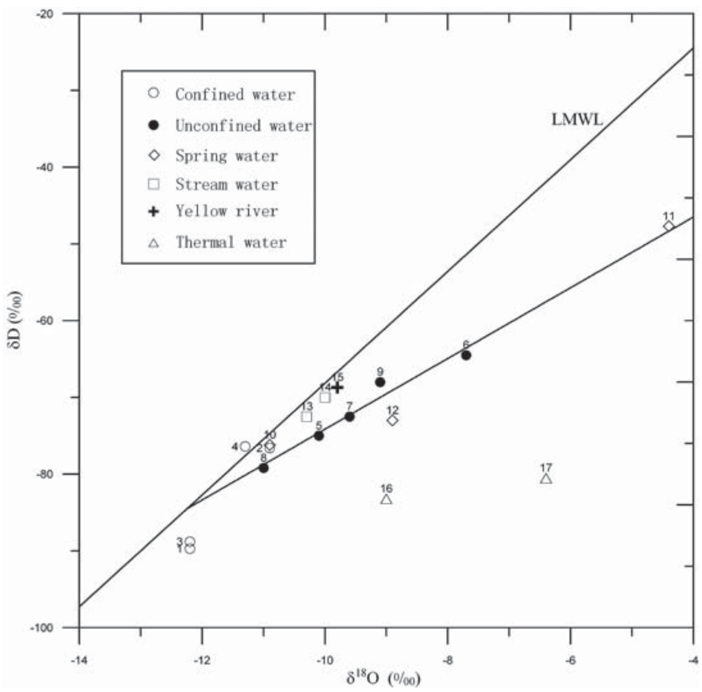


Fig. 13 δD versus $\delta^{18}O$ of groundwater samples from the Yinchuan Plain unconfined and confined water in the plain have similar distribution rules, i.e., in the strong-runoff zone in the northeastern and northern piedmont areas, the HCO_3 type is dominant, mineralization degree is low; whereas in the southwestern stagnant zone, the SO_4•Cl and Cl•SO_4 types predominate, and mineralization is high; in the southern lacustrine platform area, the hydrochemical type and mineralization degree are between the above two because there distributed are pre-Quaternary groundwater strata, and the runoff conditions are relatively poor.

2.3.2 Isotopic features of groundwater

In this work, 32 samples were collected from groundwater and surface water in the Hubao Plain, all of which were taken during the low-water period. The items analyzed include D, ^{18}O and Tritium, and the distribution of sample points is shown in Fig. 14. On the δD versus δ^{18}O diagram (Fig. 15), the unconfined and confined water in the gentle slope piedmont plain have different distributions from those in the alluvial plain. Among them, Zone B corresponds to the distribution of unconfined water in the eastern gentle slope piedmont plain. Zone A represents that of unconfined water in the Yellow River alluvial plain, confined water in the gentle slope piedmont plain, and unconfined water in the southeastern gentle slope piedmont plain, where groundwater runoff is slow. In the southeastern gentle slope piedmont plain unconfined water recharge is poor. Zone C is a drainage zone of groundwater.

As can be seen from the diagram of the section I-I′ (Fig. 16), groundwater of different hydrogeological conditions is located in different areas. Zone B is the northern gentle slope piedmont plain area, belonging to the recharge-runoff area of groundwater, which accepts lateral recharge of bedrock fissure water from the northern mountain area and infiltration recharge from precipitation. The lateral recharge is large in volume. As

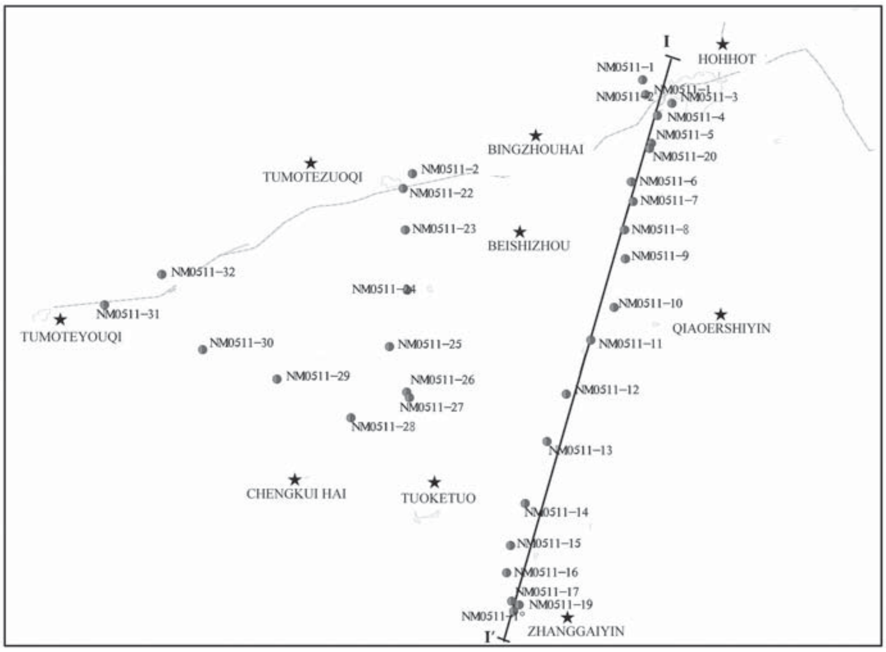


Fig. 14　Distribution of groundwater sampling points in the Hubao Plain

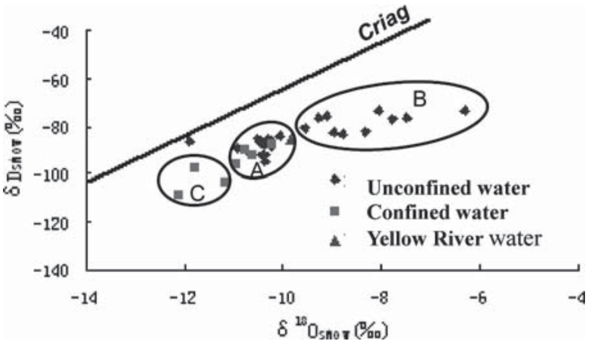


Fig. 15　δD versus δ^{18}O in water samples from the Hubao Plain

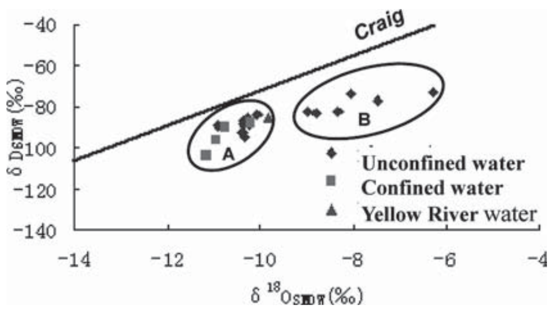


Fig. 16　δD versus δ^{18}O in water samples of section I-I' in the Hubao Plain the recharge area is at high elevation, the δD and δ^{18}O values of groundwater are relatively small. Zone A is the southern gentle slope piedmont plain area, where groundwater receives lateral recharge from hilly area and infiltration recharge from precipitation. Because of the small size of recharge area in the southern hills, the lateral recharge of groundwater is limited in volume. Besides, the hilly area is at an elevation lower than the northern Daqing Mountains, and the δD and δ^{18}O values of groundwater are relatively large. Those facts can also be confirmed by the ^{3}H values of groundwater samples, being 6.1-21.58 TU in groundwater of Zone B, and 20.69-30.51 TU (see the diagram of distribution of TU in groundwater at section I-I′) for Zone A. This indicates that groundwater has recently received recharge from precipitation, so that its circulation is fast. The ^{3}H values of confined water are between 9.35 and 18.35 TU, reflecting active participation of modern water in the circulation of confined water.

2.4 The Taiyuan Basin

2.4.1 Hydrochemistry of groundwater

The hydrochemical types of shallow groundwater in the basin are complex, mainly including HCO_3-Ca•Mg, HCO_3-Na•Ca, HCO_3-Na•Mg and SO_4-Ca•Mg types. The cations are dominated by Mg^+ and Na^+ in the central and northern parts of the basin, and by Na^+ in the southern part. The groundwater has mineralization degrees of 0.99-1.90 g/L, Sr contents of 1.18-2.02 mg/L, and pH values 8.44-8.77, belonging to the weak alkaline water. The hardness of unconfined water is relatively high, ranging between 236.0-856 mg/L.

The hydrochemical types of medium-deep groundwater consist of HCO_3-Na•Mg, HCO_3-Na•Mg and HCO_3-Na•Ca types distributed from north to south. In the western part and local areas of eastern part of the basin, there is SO_4-Ca•Mg type water, which is mainly influenced by coal seams. In the urban areas of Taiyuan City, cations are dominated by Na^+ and Ca^{2+}, and anions by HCO_3^-; in the vicinity of Sangei in northern Taiyuan City, cations are dominated by Ca^{2+} and Mg^{2+}, and anions by HCO_3^- and SO_4^{2-}; in the vicinity of Xiaodian, cations are dominated by Na^+ and Mg^{2+}, and anions by HCO_3^-. In the central basin, cations are dominated by Na^+, and anions by HCO_3^-, and in the groundwater stagnant zone, the water is rich in Cl^-. In the southern part of the basin, cations are dominated by Na^+ and Mg^{2+}, and anions by HCO_3^-. Mineralization of the medium-deep groundwater is low, mostly 0.48-0.98 g/L, and up to 1-2 g/L only in the central basin. The pH values are between 7.2 and 8.01, so it belongs to neutral and weak alkaline water. Its hardness ranges from 161 to 435.9 mg/L.

2.4.2 Isotopic features

In the shallow groundwater, the δD values range from -83.0 ‰ to -74.4 ‰, averaging -80.1 ‰; the δ^{18}O from -9.9 ‰ to -8.4 ‰, averaging -9.3 ‰. The weighted average value of δD in local precipitation is 61.67 ‰, and that of δ^{18}O -8.49 ‰, indicating that the unconfined water receives lateral recharge from groundwater of high-elevation surroundings in addition to the infiltration recharge from precipitation. The ^{3}H values are high, ranging 17.55-22.55 TU, reflecting a relatively fast circulation of groundwater.

In the medium-deep groundwater, the δD values are -88.9 ‰ to -72.10 ‰, averaging -78.94 ‰; the δ^{18}O from -10.80 ‰ to -7.40 ‰, averaging -9.24 ‰. As main recharge comes from lateral runoff, relatively low δD and δ^{18}O values reflect high elevation of the recharge area (Fig. 17).

2.5 The Guanzhong Basin

The mineralization degree of groundwater shows a general trend of gradual increase from the piedmont to the center of the basin, and from the lower to the upper reaches. On the south bank of the Weihe River west of Chishui and on its north bank west of the Jinghe River, all the unconfined water belongs to the bicarbonate type with a mineralization degree less than1 g/L, excepting seriously-polluted areas. On the north bank east of the Jinghe River and in Erhuajiacao on the south bank, the water is of HCO_3•SO_4 , SO_4•Cl or Cl type, and the mineralization intensity is as high as 1-3 g/L, with occasional values of 3-10 g/L. In the large areas of salt and brine ponds north of the Dali-Gushi zone, the mineralization degree is larger than 10 g/L, and

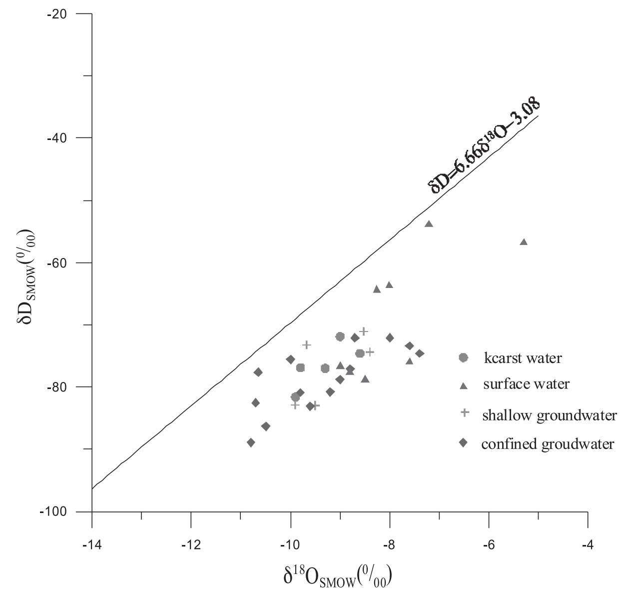


Fig. 17 δD versus δ^{18}O in water samples from the Taiyuan Basin the maximum is as high as 16.78 g/L. The quality of confined water in the fluviolacustrine layer underlying the unconfined groundwater layer is basically identical with that of the above unconfined facies.

2.6 The lower Yellow River-influencing zone

2.6.1 Hydrochemistry of groundwater

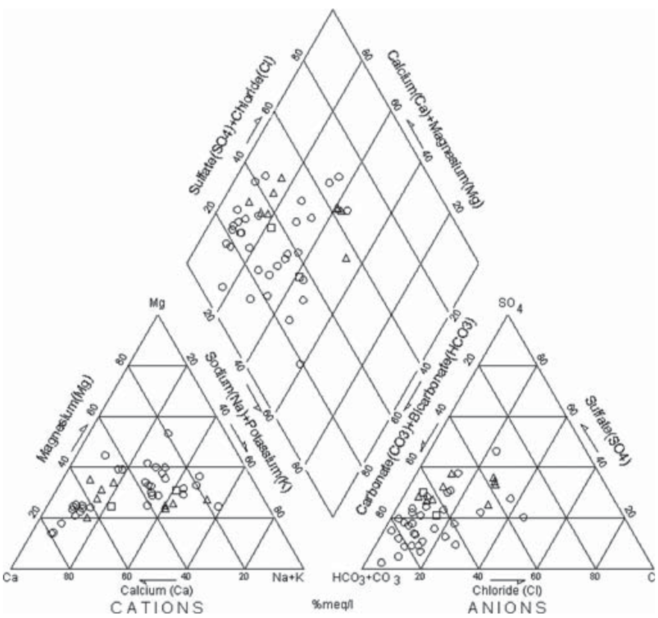
General hydrochemistry of this zone is as follows: On the top part of the fan west of Xinxiang and Zhengzhou, where groundwater runoff is relatively smooth, the groundwater belongs to the HCO_3 type, and the mineralization degree is less than 0.5 g/L. Eastward it gradually transfers into HCO_3•SO_4 type, and the mineralization degree gradually increases to 1-2 g/L. Besides, there is a distribution of banded sulfate groundwater. In the front edge of the river's alluvial fan, e.g., Sangqiu and Nanle-Puyang, there often occurs groundwater of the HCO_3•SO_4, HCO_3•Cl•SO_4, and Cl•SO_4 types, owing to the sluggish groundwater runoff and intensive evaporation. The mineralization degree is as high as 2-3 g/L, and may reach 3-5 g/L in some places.

The distribution of shallow water hydrochemical types in Henan shows a notable regularity (Fig. 18). It is mainly reflected in areas from upper to the lower reaches, from near the river to far away from the river, and from the river's ancient course to the flood-alluvial zone, the hydrochemical types change from simple to complex, and the mineralization intensity also increases gradually. As a whole, the shallow groundwater in the lower Yellow River has good quality, mostly of the HCO_3 type, mineralization degree less than1 g/L, with hardness less than 450 mg/L. The hydrochemistry and distribution of deep groundwater are similar to those of shallow water. There is an obvious zoning from west to east along the groundwater flow direction, i.e., the types change from simple to complex, the mineralization degrees from less than 1 g/L to 3-6 g/L. The mineralization degrees and the hydrochemical types show the following relations: for water dominated by the HCO_3 type, the mineralization degrees are less than 1 g/L; for water of the HCO_3•SO_4 and HCO_3•SO_4•C1 types, they are 1-3 g/L; for that of the SO_4•C1 and C1•SO_4 types, they are generally 3-6 g/L.

In Shandong Province, from western alluvial plain to the littoral plain, the mineralization degrees of shallow groundwater change from low to high, and the hydrochemical types from simple to complex, i.e., from dominant HCO_3 type to alternated distribution of the HCO_3•C1•SO_4 and C1•SO_4 types, and finally into the Cl type. Vertically, along with increasing depth of the aquifers, the mineralization degrees increase, the contents of HCO_3^- and Ca^{2+} decrease while those of SO_4^{2-}, Cl^-, Na^+ and Mg^{2+} increase, and the hydrochemical types from the HCO_3 to the SO_4 and C1 types.

2.6.2 Isotopic features

The δD values of the unconfined water range from -71.5 ‰ to -53.6 ‰, averaging -62.84 ‰; δ^{18}O from -9.73 ‰ to -8.07 ‰, averaging -9.04 ‰; medium-deep water: δD from -69.3 ‰ to -56.0 ‰, averaging -62.5 ‰; δ^{18}O from -9.49 ‰ to -7.95 ‰, averaging -8.83 ‰. From Fig. 4-19 we can see that samples of unconfined water, the medium-deep water and the Yellow River water all plot in the vicinity of the global precipitation



△ Surface water ☐ Confined water ○ Unconfined water

Fig. 18 Piper diagram of hydrochemistry of the zones affected by the lower reaches of the Yellow River line, and spread in a crisscross pattern, which indicates the close hydrological relations among them. The ^{3}H values of unconfined water are 1.3-24.20 TU, in which the samples showing low-value was collected from a zone of sluggish groundwater runoff, where water circulation is slow, mineralization intensity is high, and the pumping volume of groundwater is small. The ^{3}H values for the medium-deep groundwater are 1.2-30.2 TU, reflecting large variation of circulation conditions of groundwater in different areas. The medium-deep groundwater with higher ^{3}H values has a close hydrological relation with the unconfined water as well as fast water circulation, while that with low values is low in the replacement rate of water, suggesting little or no recharge from unconfined water.

3. Groundwater circulation

Groundwater circulation in the main basin and plain areas in the Yellow River are mainly controlled by the hydrogeological conditions. However, the impacts of human activities are growing in recent years, changing natural groundwater circulation mode in some areas. The groundwater in the main basin and plain areas in the Yellow River source region is generally charged by the lateral flow system from mountain areas, the infiltration from precipitation, and that from canal systems, farmland irrigation and surface water, which vary in proportion from location to location. The groundwater flow system generally flows from piedmont plain to alluvial-pluvial plain, from periphery to the center of the basin, riverward or seaward along the terrain, or toward the center of a depression cone. Its discharge is dominated by unconfined water evaporation, artificial pumping and lateral flow system. The proportion of artificial pumping has been expanding, which has exerted increasing impacts on the circulation mode of groundwater. The main basins and plains in the river catchment are connected by the Yellow River, and the river water has become the main medium of groundwater circulation.

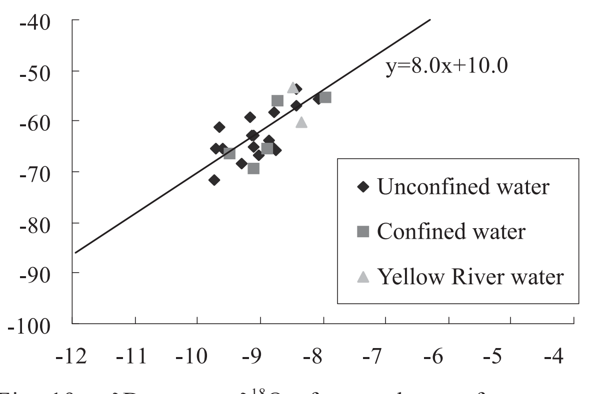


Fig. 19 ∂D versus ∂^{18}O of groundwater from zones affected by the lower reaches of the Yellow River

3.1 The Yellow River source region

The Yellow River source region is characterized by high elevation and frigid climate, where the recharge-discharge conditions of groundwater are not only controlled by the groundwater media, the structure, and geomorphology as well as development of fractures, but also constrained by the climate and frozen soil. In the perennial frost zones and non-perennial frost zones, precipitation is mostly infiltrated directly to recharge the groundwater during warm seasons, while in cold seasons, it is preserved as snow and ice, which melts with the coming of warm seasons and recharge groundwater by way of surface infiltration.

The groundwater in the region can be divided into the loose sediment-type groundwater and the bedrock-type fissure water according to the groundwater media. In terms of the burial conditions and hydrodynamic features, the former can be subdivided into the loose sediment-type groundwater and the frozen-layer loose sediment-type groundwater. The former can be divided into unconfined water and confined water, and the latter into the suprapermafrost water and subpermafrost water. The bedrock-type fissure water can be divided into the suprapermafrost bedrock fissure water and subpermafrost bedrock fissure water.

Groundwater circulation in the region can be summarized as follows: The northern slope north of the highest peak of the Bayan Har Mountains is the main recharge-conservation zone, Karinaqin-Yematan is the discharge zone, and Zhaling Lake and Eling Lake-Madoi is the catchment-discharge zone. Different types of groundwater have different recharge - discharge conditions, which are discussed in detail in terms of the types.

3.1.1 Circulation of loose sediment-type groundwater

The loose sediment-type unconfined groundwater receives infiltration recharge from precipitation, river water and lake water, as well as lateral flow of suprapermafrost water from both sides (of Yellow River). In the upper alluvial plain, the topographic gradient is large, the groundwater medium is composed of coarse-grained sediments with good permeability, and flow conditions are good, so that the circulation is dominated by discharge; in the lower alluvial plain and lacustrine plain areas, the landform is relatively flat and smooth, the groundwater medium is formed by fine-grained sediments, groundwater is sluggish, resulting in rise of water level. Therefore, discharge is dominated by gravity springs, followed by lateral and evaporation drainage.

The loose sediment-type confined groundwater mainly receives recharge from unconfined groundwater in the upper reaches and lateral flow of frozen soil layer water on both sides of the Yellow River. The recharge sources are abundant, but the flow is relatively sluggish;

discharge is in the form of groundwater flow.

The loose sediment-type suprapermafrost water receives infiltration recharge from precipitation and river water, as well as lateral recharge of the suprapermafrost water in the bedrocks of mountains. In the intermontane valleys and the gentle slope piedmont plain areas, the topographic gradient is large, flow conditions are good, so discharge is dominated by drainage; in the central sections of the intermontane basin and the front of the alluvial-pluvial fan, the landform is relatively flat and smooth. The groundwater medium is formed by fine-grained sediments, groundwater flow is sluggish, resulting in rise of water level. As a result, swamps and wetland are often formed. The discharge is dominated by gravity springs and seconded by evaporation and lateral flow drainage.

The recharge conditions of loose sediment-type subpermafrost water are complicated. Most of the areas are recharged from the loose sediment-type suprapermafrost water and surface water through the river's melting zones, while some areas are recharged mainly by the lateral flow of the bedrock-type subpermafrost water. Groundwater migrates along the pore passages under the perennial frost layers toward the lower river, and finally drains as lateral flow to recharge the loose sediment-type unconfined or confined groundwater.

3.1.2 Circulation of the bedrock-type fissure water

The bedrock-type suprapermafrost water mainly receives recharge from precipitation and ice-snow meltwater, and discharges as flow toward the lower areas. In some favorable places, discharge is in the form of gravity springs. Secondarily it may recharge the subpermafrost water through structural taliks.

The bedrock-type subpermafrost water obtains recharge mainly from precipitation and bedrock-type suprapermafrost water through structural taliks. It migrates along fissures under the perennial frozen layers, mostly discharges in the form of flow. Some may be drained to surface as ascending spring along fractured zones at favorable segments.

3.2 The Yinchuan Plain

3.2.1 Groundwater recharge

The groundwater recharge sources in the plain mainly include leakage and irrigation of the Yellow River diversion canal system, precipitation, lateral flow, dissipation of flood water, and infiltration of groundwater irrigation. Among them the leakage and irrigation of the Yellow River diversion canal system is the primary source of groundwater recharge, accounting for 80 % and more of the total volume.

The recharge sources for the unconfined water in the plain areas are dominated by precipitation and the Yellow River water. In the northern plain, the unconfined water receives recharge from precipitation, the Yellow River irrigation infiltration, and lateral recharge of piedmont groundwater. Besides, the upward leakage recharge by the underlying confined water is also one of the recharge modes.

The confined water in the plain areas is recharged by precipitation and the Yellow River water under the glacial climate conditions in the geologic past, and also by lateral recharge of bedrock fissure water from the mountain areas. The confined water around the Helan Mountains in the western part of the plain has a close hydrological relationship with the bedrock fissure water of the mountain areas. There are deep groundwater flows, and the recharged groundwater is of an old age. The central and southern parts of the plain are influenced by artificial activities especially through large amount of pumping of groundwater, which have caused leakage recharge of the confined water by unconfined water, and so the confined water has participated in the circulation of modern water to different degrees.

3.2.2 Groundwater flow

There are two groundwater flow systems in the Yinchuan Plain: the local groundwater flow system and the regional groundwater flow system.

(1) Local groundwater flow system

There are a number of local groundwater flow systems in the plain from west to east and from south to north, from the Helan Mountains alluvial fan to the Yellow River alluvial plain, and from the Yellow River alluvial plain to the fluviolacustrine plain.

The local groundwater flow system in front of the Helan Mountains alluvial fan mainly receives flows from valleys and gullies in the mountain areas and vertical infiltration recharge from precipitation. The circulation depth in front of the mountains is greater than 100 m, and the discharge is made in the fan-edge zones, fine-grained sediment zones and weakly water-resisting layers as springs or overflow lakes. According to calculations, the renewal rates of groundwater are 0.1-1 %/a. The water circulation in the system is at great depth, where groundwater circulation is slow, making it a relatively closed water flow system.

From south to north in the Yellow River diversion irrigation zone, there have formed several local flow subsystems, which mainly receive recharge from the Yellow River diversion irrigation canal system and field seepage. The circulation depth is less than 60 m, and groundwater is discharged in the form of evaporation and drainage ditches. In the southern plain, the renewal rates of groundwater range 11-50 %/a. It is an open system, in which the circulation of water is at small depths. The groundwater is characterized by domination in vertical movement, active circulation and rapid renewal rate. In the northern plain, the renewal rates of groundwater are 0.1-6 %/a. It is a relatively open system, in which the circulation of water is at small depths, the groundwater circulation is slow as is its renewal rate.

In the vicinity of Yinchuan City, over-pumping of groundwater has caused the circulation depth to increase, and the renewal rates of groundwater range 6-11 %/a, forming a local groundwater flow system bounded by the pumping zone of the city. It has changed the original groundwater flow features, forming a relatively open system.

(2) Regional groundwater flow system

The deep groundwater at depths below 60 m in the Yellow River diversion irrigation zone shows an obvious horizontal zoning of hydrochemical features, and thus has regional flow characters. The ^{14}C age of groundwater is larger than 5,000 years, and water circulation is slow.

3.2.3 Groundwater discharge

During its flow process, a part of the groundwater in the plain is drained through evaporation and artificial pumping, and the other part flows into the drainage ditches and the Yellow River, in which evaporation is the dominant discharge mode, accounting for over 45 % of the total volume.

The shallow groundwater in the Helan mountain area generally receives local recharge from precipitation, and drains, after short-period flow, into the valleys and ditches nearby, and then enters the piedmont alluvial fan. On the other hand, the deep groundwater, after having received recharge from precipitation in the mountain area, crops out into springs around the piedmont fault zone.

The discharge of groundwater into the Yellow River occurs on both banks of the river in the southern area of the Yinchuan Plain and the east bank of the river in the northern area.

Under natural conditions, confined water drains into shallow aquifers in the form of leakage flow while unconfined water flows into drainage ditches or discharge by evaporation. The exploitation of groundwater has changed the above modes of discharge, so that artificial pumping has become the main discharge mode for confined water.

3.3 The Hubao Plain

The plain is bounded by bedrock mountain areas of the Wula, Daqing and Manhan mountains in the north and east, and by the Yellow River in the southwest. It is an independent groundwater system surrounded by bedrock mountain areas, with its own recharge-flow-discharge systems. The recharge sources of groundwater mainly include infiltration from precipitation, lateral flow from the bedrock mountain areas and irrigation infiltration from the Yellow River water, while the discharge is by evaporation, artificial pumping and lateral flow into the Yellow River.

The groundwater in the gentle slope piedmont plain of the Daqingshan and Manhan mountains is located in a strong flow zone, where it occurs at depth, and the infiltration recharge by precipitation and surface water is very limited. In the frontal zone of the gentle slope piedmont plain, there is a stable watertight silty layer between the overlying upper Pleistocene-Holocene groundwater system and the underlying lower middle Pleistocene groundwater system, and the piedmont lateral recharge replenishes the two systems. The upper groundwater system is characterized by unconfined water, receiving infiltration recharge from precipitation besides from lateral flow. Therefore it belongs to the strong flow zone. In the direction toward the plain, the flow gradually becomes weaker, the depth decreases gradually, and the recharge from precipitation intensifies gradually. The lower groundwater system is mainly charged by the piedmont lateral flow. As it occurs at greater depths, and it is overlain by stable watertight layer, the discharge is dominated by artificial pumping.

In the southern hilly area, the range in the watershed is small and narrow, the piedmont alluvial-pluvial pan is small, and the overlying Quaternary aquifer is thin. The pre-Quaternary aquifer is exposed at high elevation, even cropping out at the surface at times. It consists mainly of sandstone and sandy conglomerate, the permeability of which is much lower than the sandy conglomerate in front of the northern Daqing Mountains, and the lateral flow recharge from the hilly area is of small volume. Furthermore, as the groundwater occurs at depths, the recharge from precipitation infiltration is limited.

In the lacustrine plain, the aquifers are formed by finer-grained sediments, the hydraulic gradient decreases gradually and the flow intensity also weakens accordingly, so that the lateral flow volume decreases gradually. Within the plain, the groundwater is located mostly at 1-3 m, and the recharge from precipitation infiltration increases gradually. Besides the recharge from precipitation, the irrigation infiltration in the plain area is also an important source of recharge. Only in local segments, because of expansion of the depression cone, the groundwater level is lower than that of the Yellow River, so that the latter replenishes the former. In the middle Pleistocene groundwater system, groundwater in the aquifer is discharged mainly by artificial pumping owing to obstruction of overlying watertight stratum.

3.4 The Taiyuan Basin

The loose sediment-type groundwater in the basin can be divided into the shallow groundwater and the medium-deep confined groundwater, both of which have their own circulation regimes, but have close hydrgraphic relations at the same time.

3.4.1 Circulation of shallow groundwater

It is recharged mainly by infiltration from precipitation, irrigation and canal systems, surface seepage, and lateral recharge from bedrock groundwater in the east and west sides of the basin. The recharge of surface water mainly refers to the unconfined groundwater in sand and gravel in river valleys and the flood water during rainy seasons. The large river valleys include those of the Fenhe River, Wenyu River, Yangxing River, Xiaohe River, Changyuan River and Longfeng River. The lateral recharge from the west side of the basin is connected with the Xishan Mountain karst water system through the fault at the site north of Jiaocheng City, and is dominated by lateral flow of the Xishan Mountain karst water. South of Wenshui County, it mainly receives lateral flow recharge from the unconfined water in the loess tableland. On the east side of the basin, the lateral recharge is sourced by the unconfined groundwater in the loess tableland, while the northern part of the basin mainly receives lateral flow recharge from the unconfined groundwater in the Baiban fan and the loess hilly area.

The flow direction of the shallow groundwater is basically the same with that of the topography, i.e., from periphery to the center of the basin, and from north to south, with a minor part flows out of the basin via the Yitang mouth. In a cone of depression, groundwater migrates toward the center.

Discharge is dominated by artificial pumping, evaporation and leakage into the medium-deep layers. Among them artificial pumping is the major mode of discharge. Because of over-pumping, the shallow groundwater level has been dropping, and even dried up in some areas. Therefore, the volume of groundwater discharged by evaporation is decreasing. Under natural conditions, the groundwater level of medium-deep confined groundwater is higher than that of shallow unconfined groundwater, while the former recharges the latter by way of leakage. However, owing to the over-pumping of the medium-deep confined groundwater, its level became lower than that of the shallow unconfined groundwater, and the recharge mode has been inverted. The south boundary lies at the outlet of the Fenhe River at Yitang, Jiexiu County, where groundwater drains outward as horizontal flows.

3.4.2 Circulation of the medium-deep confined groundwater

Main recharge sources include the leakage of shallow water and lateral recharge from bedrock groundwater in the east and west sides of the basin. North of Jiaocheng City on the western side of the basin, they mainly receive lateral flow recharge from the Xishan Mountain karst water and replenishes the lateral flow of confined water in the Nanhan pluvial fan; south of the city, they mainly receive the medium-deep confined groundwater in the loess tableland, and lateral flow of fissure water in Carboniferous, Permian and Triassic sandstones and shales. The eastern basin is mainly recharged by the medium-deep confined groundwater in the loess tableland, and lateral flow of fissure water in Permian and Triassic sandstones, and the areas around Jiexiu receives lateral flow recharge of karst water. The northern part is connected with karst water, and can thus receive lateral flow recharge of karst water. It is a strongly permeable boundary. In areas along Beiying and Yanjiagou in the Taiyuan Basin, water level dropped year after year owing to over-pumping of the medium-deep groundwater. Now the level of the medium-deep confined water is lower than that of basement fissure water, and the latter can recharge the former via the shallow basement zone or along the fractured zone by upward recharge. The medium-deep confined water also receives leakage recharge from the shallow groundwater (as mentioned before).

The flow direction of the medium-deep confined water basically coincides with that of the shallow water, i.e., from the periphery to the center of the basin. The flow from north flows into the center of the depression cone. Discharge is by artificial pumping.

3.5 The Guanzhong Basin

Groundwater in the basin is mainly recharged by precipitation, and the bordering zones also receives lateral recharge of bedrock fissure water from the mountain areas. When the rivers from mountain areas enter the plain, the groundwater is recharged by large volume of surface water. For example, after the river from the bedrock valley of the Qinling Mountains enters into the pluvial fan and loess tableland, most of the flow recharges the groundwater through infiltration. The low terrace of the Weihe River receives temporary recharge from surface water during the flood period.

The direction of groundwater flow is basically the same as the topography, i.e., from both sides of the basin to the center, or from the upper to the lower reaches, and finally drains into the river and valleys. In areas such as east of the Jinghe River on the north Weihe River bank and Erhuajiacao on the south bank, the landform is low, where groundwater flows slowly. The discharge is dominated by vertical evaporation movement, which has caused salinization of large areas of land, and in local sections the unconfined water flows out of the surface to form swamps. The recharge by leakage in canal irrigation zones and infiltration of irrigation water is also remarkable. The over-pumping of groundwater in recent years has obviously affected the natural regime of groundwater and the recharge-discharge relationship.

3.6 The lower Yellow River zone

In the lower Yellow River zone, the landform is flat and smooth. The aquifers are fine-grained, the hydraulic gradient is small, ranging 0.5 ‰-0.1 ‰, and the horizontal flow conditions of groundwater are poor. Both the aquifers and the water level are shallow, so that groundwater circulation is dominated by vertical infiltration.

3.6.1 Recharge of groundwater

The lower Yellow River plain is flat and smooth in landform, and precipitation is the main recharge source for shallow groundwater. The ground gradient is generally 1/3000 to 1/5000, surface flow is sluggish, and groundwater occurs at shallow depth. Besides, the vadose zone is composed mostly of fine clay and silt clay, with loose structure and most favorable for infiltration recharge of precipitation. The average annual rainfall for many years ranges from 600 to 700 mm, which is considerable, accounting for 86.6 % of the total recharge volume.

The river's lateral infiltration is also an important recharge source for the region especially for the shallow groundwater in sections near the river, comprising 7 % of the total. As the operation of the Xiaolangdi Reservoir and the joint regulation of water resources of the Yellow River basin have guaranteed the river to keep flow all year round, the river can provide continuous recharge to the shallow groundwater, but with periodic changes depending on the low-water or flood period. In the pluvial plain outside the lower Yellow River, the intensity of recharge by the Yellow River water to groundwater is decreasing from Taohuayu to the estuary of the river.

In addition, the recharge by infiltration of irrigation water is also an important source of recharge, which accounts for 6.4 % of the total.

3.6.2 Groundwater flow

The flow of shallow groundwater is controlled by topography and recharge sources. As the modern course of the Yellow River forming a low ridge in the lower plain and the watershed of surface water and groundwater, the groundwater in the river's influencing zone flows from southwest to north. As the river turns north at Dongbatou, the groundwater flow gradually changes direction to northwest. Where the river enters Shandong Province, the hydraulic gradient of groundwater ranges from 1/2000 to 1/5000, and the flow field direction is at an angle of 130° with the Yellow River flow direction. In local areas, such as south of Heze, Juancheng and Yuncheng, the large amount of groundwater pumping has resulted in small-scale cones of depression, changing natural direction of groundwater flow. In the alluvial-pluvial piedmont plain areas from Yinshan Mountains to Jinan south of the Yellow River, the hydraulic gradient of groundwater is larger than1/2000. Recharge comes from precipitation in the mountain areas, and the flow field direction is at 50° with the Yellow River flow direction.

3.6.3 Groundwater discharge

The discharge of shallow groundwater is dominated by evaporation of unconfined water, followed by artificial pumping, and leakage and flow discharge to the medium-deep layers.

In the areas such as the Yellow River diversion irrigation area and the river course area, pumped up groundwater is small, and water level is shallow, generally less than 4 m. The discharge is dominated by evaporation of unconfined water.

In cities and towns and well-irrigated areas, the groundwater is shallow, easy for pumping, and most of them are fresh water, therefore pumping is the main discharge mode.

The water head of the medium-deep groundwater is commonly lower than that of shallow water. In most places the differences in water head are at 2-10 m. Although there is a thick watertight layer of viscous soil between two groundwater levels, there is still some leakage discharge in the zones where the watertight layer is relatively thin, or the grain size of aquifer bed is coarse. Particularly, in the cities and towns with concentrated pumping of the medium-deep groundwater, pumping of the mixed shallow and medium-deep groundwater causes greater leakage. In the lower reaches, the hydraulic gradient is small, flow is sluggish, and discharge by flow is of small volume. Therefore, only in the cone of depression with large pumping volume there is some flow discharge.

4. Groundwater balance

The balance of various groundwater systems in the Yellow River basin is closely interrelated and influences each other through changes in the river water volume. The discharge volume of the source region and all the areas upstream of Lanzhou directly affects the recharge volume of the lower reaches, while the consumption and production of water in major basins of the lower reaches exert in turn greatly influences the changes of the river's flow. Therefore, the groundwater balance of major groundwater basins in the source region acts as the main body of groundwater balance in the basin, the study of which requires in the first place calculations of the balance status of the various groundwater basins. In the present work, such calculations were made for the source region, the Yinchuan and Hubao plains, the Guanzhong and Taiyuan basins and the lower Yellow River zone.

4.1 The Yellow River source region

According to calculations by the Geological Survey of Qinghai Province, the total natural recharge resources of groundwater in the Madoi area amount to 7.95×108 m^3/a. As the source region is sparsely populated, artificial pumping of groundwater is of minor volume, and is mainly concentrated in the county seat. There are 3,000 residents in the county seat, and if an amount of 40 L per capita per day is assumed, its pumping volume is only 120 m^3/d, or 4.38×10^4 m^3/a, much smaller than the mineable volume of resources. Therefore, for many years the groundwater balance in the source region has been little affected by artificial factors, but is mainly influenced by the natural recharge and discharge conditions of groundwater.

The Geological Survey of Qinghai Province has calculated the balance of the total water volume in the source region, the process of which is shown below.

The water balance for areas in the frigid zone is generally expressed in the following equation:

$$\Delta V=Rm+P-E-R,$$

where ΔV is variation of water storage in the basin; Rm is ice and snow meltwater volume; P is average precipitation of the basin; E is average evaporation of the basin; R is flow volume (in flow depth). All the above items are calculated in mm.

The calculated results (Table 2) show that the changes in water environment have the following features: (1) since 1950s, the changes in water storage volume of the source region show positive values only in high-water years, and negative in all the other years. There appear positive values during the 1950s-1980s, while the rest are all negative since the 1990s. It indicates that after the 1990 the drying trend became more serious, and ecological environmental deterioration occurred, e.g., large numbers of medium and small lakes shrank or dried up, large-scale deterioration and desertification of grassland occurred, the swamps and wetland were seriously dehydrated, ice-rich frozen soil degenerated into ice-poor frozen soil, and some exorheic lakes turned into inland lakes. (2) Because of continued droughts lasting for 2-3 years, stored water volume was excessively consumed, resulting in drying up of the Yellow River in winter of 1961, 1979 and 1997.

4.2 The Yinchuan Plain

Taking 5 years from June 2000 to May 2004 as the period of balance, the calculated results of water volumes of the various balance elements are given in Table 3.

The total groundwater recharge of the plain amounts to 22.538×10^8 m^3/a. The main sources of recharge include the leakage from canal systems and infiltration of irrigation, the lateral flow and the infiltration of precipitation, comprising 18.230×10^8 m^3/a, 2.1890×10^8 m^3/a and 1.6504×10^8 m^3/a, and accounting for 80.92 %, 9.71 % and 6.45 %, respectively. The total discharge of the plain is 21.284×10^8 m^3/a. The main discharge modes are evaporation of unconfined water, artificial pumping and drainage by ditches, which amount to 9.9160×10^8 m^3/a, 5.8382×10^8 m^3/a and 4.622×10^8 m^3/a, and account for 46.59 %, 27.43 % and 21.72 %, respectively. During the period of balance, the groundwater resources were at a positive balance.

The groundwater pumping volume of the plain totals 5.8382×10^8 m^3, in which 2.0925×10^8 m^3 of water is consumed by industry, comprising 35.8 %, 1.5804×10^8 m^3 by agriculture, comprising 27.1 %, 1.905×10^8 m^3 by domestic uses in cities and towns, comprising 27.1 %, and 0.2321×10^8 m^3 by men and livestock in rural areas, comprising 3.9 %.

In the plain, water used for agriculture is mainly diverted from the Yellow River, amounting to 41.506×10^8 m^3/a, and the annual consumption is 22.261×10^8 m^3. That used for industry, domestic consumption in cities and towns, and consumption by men and livestock in rural areas almost all depends on groundwater pumping, especially the former two, which are the major consumers.

The mineable groundwater resources in the plain amount to 16.9317×10^8 m^3/a, and the volume extracted is 5.8382×10^8 m^3/a, accounting for 34.48 % of the former. The largest amount of pumping occurs in Yinchuan City, comprising 41.5 % of the total; next are Shizuoshan City and Pingluo County, which account for 12 % and 16 %, respectively. The other cities and counties have smaller pumping volumes. In general, there is over-pumping of groundwater in local areas, while some areas still have potential for groundwater development.

4.3 The Hubao Plain

On the basis of the data collected, the years from 2000 to 2004 are taken as the period of balance for the calculated area of 5,530.2 km^2. The results are given in Table 4.

The total groundwater recharge of the plain amounts to 9.8895×10^8 m^3/a, in which the main source is the piedmont lateral flow, followed by the infiltration of precipitation. As for discharge, groundwater pumping is predominant, amounting to 6.4969×10^8 m^3/a, followed by evaporation. In the whole plain, groundwater still has some potential, but in some areas, particularly major cities such as Hohhot and Baotou, it is already in a state of being seriously over-mined.

4.4 The Taiyuan Basin

In general, groundwater flow is controlled by topography and geomorphology of the basin, and the

Table 2 Average water balance in the Yellow River source region (mm)

Year	Precipitation (P)	Flow depth (R)	Evaporation (E)	Actual evaporation in the region (E′)	Variation of water storage volume (ΔV)
1956	256.0	13.6	1566.8	344.7	−102.3
1957	326.4	17.3	1420.1	312.4	−3.3
1958	439.4	27.4	1378.6	303.3	108.7
1959	217.9	14.8	1535.7	337.9	−134.8
▲1960	247.8	3.4	1575.0	346.5	−102.1
1961	406.1	7.9	1430.6	314.7	83.5
1962	184.0	23.2	1431.0	314.8	−154
1963	245.5	14.6	1442.8	317.4	−86.5
1964	333.1	48.4	1317.0	298.7	−14
1966	255.6	29.5	1397.4	307.4	−81.3
1967	335.4	59.1	1141.7	251.2	25.1
1977	232.7	30.5	1397.2	307.4	−105.2
1978	263.6	16.0	1309.0	288.0	−40.4
▲1979	222.6	9.0	1496.7	329.3	−115.7
1980	283.2	6.4	1379.9	303.6	−26.8
▼1981	368.9	64.0	1366.1	300.5	4.4
1982	330.8	95.6	1178.8	259.3	−24.1
1983	316.2	118.0	1065.8	234.5	−36.3
1984	285.5	59.2	1365.9	300.5	−74.2
1985	338.4	24.6	1281.9	282.0	31.8
1986	291.7	19.3	1297.7	285.5	−13.1
1987	303.9	18.0	1411.7	310.6	−24.7
1988	204.7	13.7	1478.9	325.4	−134.4
▼1989	485.6	99.4	1209.1	266.0	120.2
1990	293.5	52.8	1292.6	329.6	−88.9
1991	330.2	20.8	1438.8	366.9	−57.5
1992	383.3	20.7	1239.7	316.1	46.5
1993	362.5	52.7	1315.6	335.5	−25.7
1994	329.6	30.4	1476.7	376.6	−77.4
1995	332.4	10.9	1395.0	355.7	−34.2
1996	311.9	9.2	1301.4	331.9	−29.2
▲1997	317.3	11.7	1216.7	310.25	−4.6
1998	343.4	19.0	1390.3	354.5	−30.1
1999	347.6	17.0	1368.5	349.0	−18.4

Note: Quoted from the Geological Survey of Qinghai Province, Investigations of Ecological Environment and Geology of the Yellow River Source Region. ▲The year when drying up occurred along the river; ▼the year when down-cut of the riverbed occurred at the outlet of Eling Lake

boundary conditions of the system are constrained by the geological structures in the periphery of the basin. On the other hand, the input-output features of the groundwater system are mainly controlled by hydrogeological, meteorological, geological and artificial factors. In recent years, artificial activities have seriously altered the groundwater system, so that it has changed from a simple natural system into a complex one with the natural system and artificial activities combined. The main controlling factors are those of physiogeography, geo-environment and artificial activities.

The recharges of groundwater in the basin mainly include precipitation, leakage from rivers, leakage from canal systems, return of groundwater irrigation, surface water irrigation, and lateral flow.

The discharges include groundwater pumping, unconfined water evaporation and lateral outflow.

The above items were calculated respectively for the calculation of the water balance (Table 5). The updated data and information were used in the calculation, e.g., the long-term precipitation data, pumping volume, river's flow, water diverted by canal systems, area and quota of irrigation, and groundwater depth. Taking the period from June 2000 to May 2004 as the period of balance, it has been calculated that the average annual recharge of Quaternary groundwater is 7.54×10^8 m^3 and the discharge is 7.62×10^8 m^3 for many years. The Quaternary groundwater was in a negative balance state, which is reflected in continuous drop of groundwater level.

4.5 The Guanzhong Basin

Over 95 % of the landform of the basin belongs to the terraces of the Weihe River banks and the loess tableland. In the loess tableland are accumulated thick bedded Quaternary loose sediments, where groundwater is relatively abundant. Particularly, in the river valleys, the groundwater occurring shallower than 300 m used to be divided into the unconfined water, shallow confined water and deep confined water, all of which belong to groundwater formations, and there is some fissure groundwater in the loess tableland. In the present work, all the groundwater at depths shallower than 300 m is regarded as the same groundwater formation. The main sources of recharge for the groundwater are the infiltration of precipitation, river water, canal water, irrigation water of canal systems, reservoir and pond water, as well as lateral flow. The sum of the above items makes up the natural recharge resources of groundwater. Calculations have been made for the water balance elements in the basin by taking the 5 years from

Table 3 Water balance in the Yinchuan Plain

Balance element	Recharge volume		Balance element	Discharge volume	
	(10^8 m^3)	(%)	(%)	(10^8 m^3)	(%)
Infiltration recharge by canal systems and irrigation	18.2390	80.22	Evaporation of surface water	9.9160	46.59
Infiltration recharge by precipitation	1.6504	7.26	Discharge by drainage ditches	4.6220	21.72
Recharge by lateral flow	2.1890	9.63	Artificial pumping	5.8382	27.43
Dissipated volume by flood	0.3250	1.43	Discharge by the Yellow River	0.9080	4.27
Infiltration recharge by groundwater reinjection	0.3320	1.46			
Total recharge	22.7354			21.2842	

Table 4 Water balance in the Holocene–Upper Pleistocene in the Hubao Plain

Recharge volume (10^8 m^3/a)					Consumption volume (10^8 m^3/a)			
Precipitation infiltration	Irrigation infiltration	Piedmont lateral flow	Surface water infiltration	Total	Pumping	Groundwater evaporation	Flow capacity of artesian wells	Total
3.3182	0.6288	5.8882	0.0543	9.8895	6.4969	2.3939	0.4802	9.3710

Table 5 Water balance of Quaternary groundwater in the Taiyuan Basin

Balance element	Recharge volume		Balance element	Discharge volume	
	(10^8 m^3)	(%)		(10^8 m^3)	(%)
Leakage from canal systems	0.4674	6.20	Pumping volume	6.9393	91.10
Infiltration by irrigation	0.7704	10.22	Evaporation of unconfined water	0.6783	8.90
Infiltration recharge by precipitation	2.8600	37.94			
Leakage of river	0.0757	1.00			
Recharge by lateral flow	3.3649	44.64			
Total recharge	7.5384		Total discharge	7.6176	

June 2000 to May 2004 as the balance period.

The total recharge of the whole region amounts to 436,289.57×10^4 m^3/a, the total discharge is 433,507.15×10^4 m^3/a, and the storage volume in the zone within the annual groundwater level variation is 2,620.65×10^4 m^3/a.

The average recharge of the region for many years is 436,289.57×10^4 m^3/a, in which the infiltration of precipitation is 198,654.37×10^4 m^3/a, leakage of river water is 102,003.43×10^4 m^3/a, surface water irrigation infiltration is 47,399.40×10^4 m^3/a, groundwater irrigation infiltration is 32,357.96×10^4 m^3/a, groundwater flow is 25,645.65×10^4 m^3/a, and lateral surging recharge of water from river banks is 30,288.76×10^4 m^3/a, accounting for 45.53 %, 23.38 %, 10.86 %, 7.41 %, 5.88 % and 6.94 % of the total recharge, respectively.

The calculated results indicate that the main sources of recharge are precipitation, river water leakage and surface water irrigation infiltration, a combination of which makes up 79.77 % of the total recharge. Next are the groundwater irrigation infiltration, groundwater flow and lateral surging recharge of water from river banks, the sum of which accounts for 20.23 % of the total recharge.

4.6 The lower Yellow River-influenced zone

This refers to the zone influenced by lateral infiltration recharge of groundwater in the lower Yellow River and the delta at its estuary, i.e., the Lower Yellow River groundwater system (XI) in the classification mentioned before. The calculations of water balance elements in the region are given in Table 6. As can be seen from the table, the total recharge of shallow groundwater is 55.5510×10^8 m^3, in which the infiltration of precipitation is the main recharge source, comprising 60.43 % of the total. The leakage from the Yellow River is 6.24×10^8 m^3, accounting for 11.23 %, also one of the main sources. The discharge of shallow water totals 58.2626×10^8 m^3, in which the evaporation of unconfined water and artificial pumping are the main drainage modes, which make up 59.255 % and 36.56 % of the total discharge, respectively.

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Table 6 Water balance in the lower Yellow River-influenced zone

Balance element	**Recharge volume**		**Balance element**	**Discharge volume**	
	(10^8 m^3)	**(%)**		**(10^8 m^3)**	**(%)**
Leakage from canal systems	6.017	10.83	Pumping volume	21.3017	36.56
Infiltration by irrigation	8.706	15.67	Evaporation of unconfined water	34.5226	59.25
Infiltration by precipitation	33.567	60.43	Leakage discharge	1.8658	3.20
Leakage of river	6.240	11.23	Lateral discharge	0.5725	0.98
Recharge by lateral flow	0.474	0.85			
Infiltration by flood	0.178	0.32			
Infiltration from ponds	0.369	0.66			
Total recharge	55.551		Total discharge	58.2626	

黄河流域の主要地域における地下水収支・循環

ハンチャンタオ・チャンアルヨン・ホウシンウェイ・ガオスンロン・シインチュン・チャオホンメイ・
ディンジエンチン・リウシンチュン・リバオグイ・チャオルンリエン・ジャオシーリ・
シャンリジュン・チュチョンダオ・ワンニン

要　旨

黄河流域の主要な平野や盆地は中国の社会・経済開発にとって極めて重要な地域であるので，その地域の地下水の収支と循環を明らかにすることもまた重要である．本研究では，黄河源流域，銀川平野，呼和浩特·包頭平野，太原平野，関中平野および黄河下流域を地下水の収支と循環に関する研究対象地域として選定し，地下水の水素・酸素の安定同位体比，水質などの特徴を明らかにする．また，地下水の流動系や水収支について考察する．

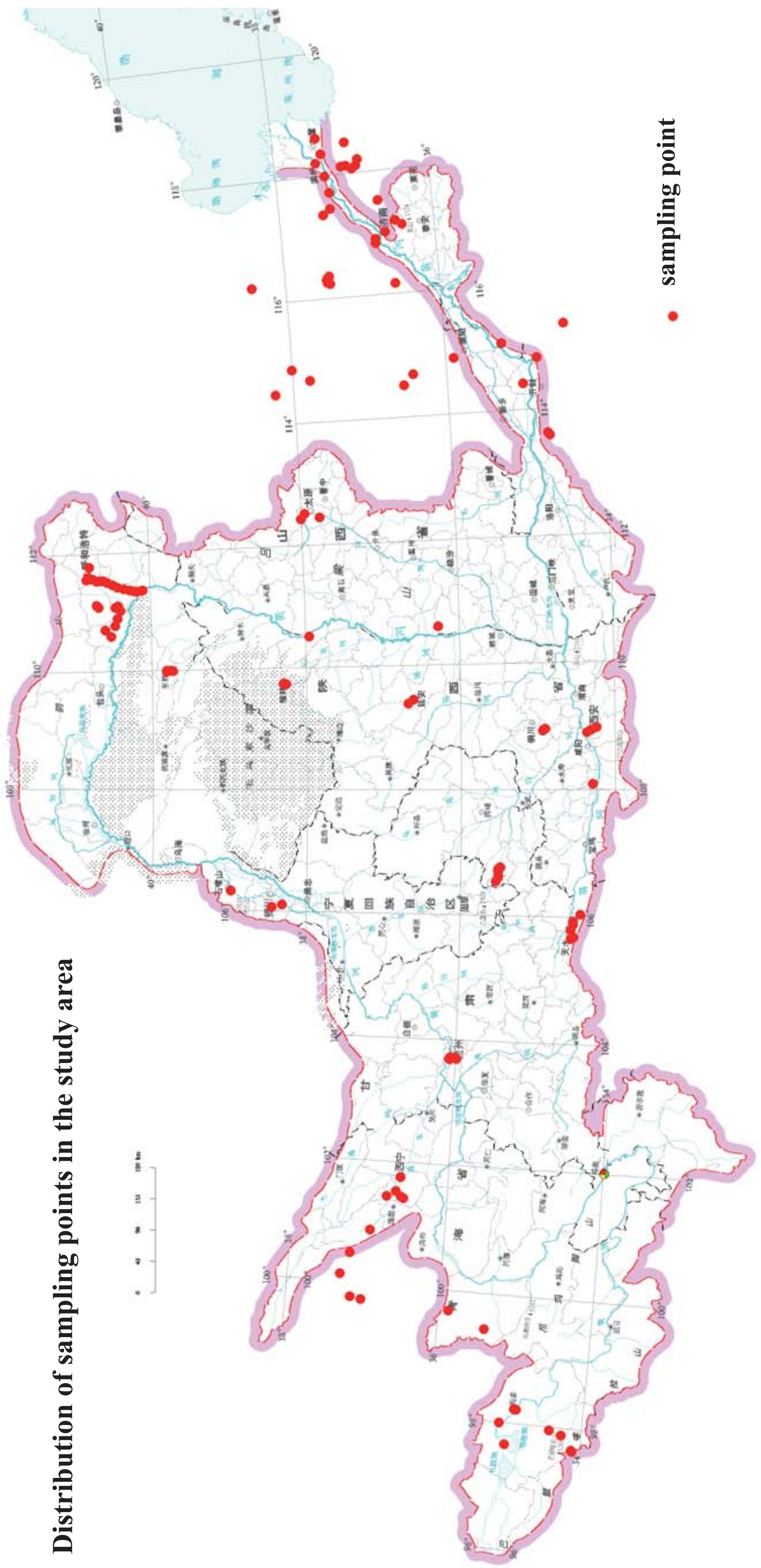

Plate 1 Distribution of sampling points

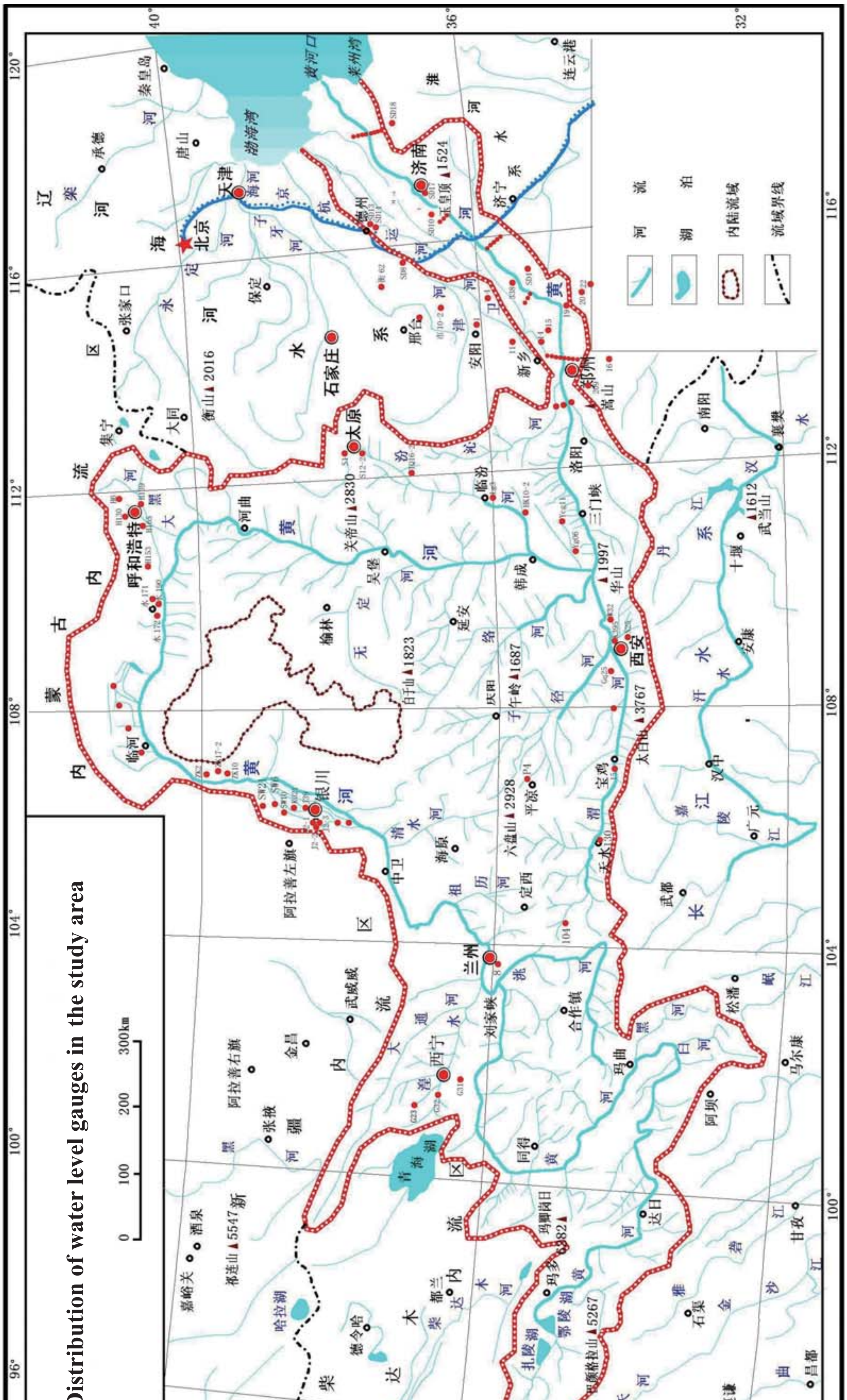

Plate 2 Distribution of installed automatic monitoring apparatuses