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Hydrochemical Characteristics of Groundwater in Yinchuan Plain and Their Control Factors

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Based on the geology and hydrogeology, the hydrochemical characteristics of phreatic water and the first confined water in Yinchuan Plain were analyzed according to the chemical analysis results of 364 water samples and 88 soil samples collected in year 2003, using statistical and geostatistical methods. The factors controlling the compositions of groundwater were investigated as well. Results show along the flow direction from SW to NE, the TDS, concentrations of Na^+, Cl^- of phreatic water generally increase and the chemical types change in the sequences of $HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-}$. TDS in the first confined water shows a zonation characteristic from west to east. The chemical types of confined water show a similar distribution to phreatic water. The factors controlling and affecting the chemical compositions of groundwater in Yinchuan Plain are mainly (1) geological and hydrogeological conditions, (2) the compositions of recharge water, (3) the soluble salt content of soils, (4) water-rock interaction and (5) evaporation of phreatic water.

Key Words: Hydrochemical, Groundwater, Control factors, Yinchuan Plain.

INTRODUCTION

The in-depth research and analysis on the regional groundwater chemical field will not only deepen the understanding of the local hydrogeological conditions which provides basis for the decision making for the rational development and utilization of groundwater resources, but also a basic work for groundwater pollution prevention and control[1]. Through chemical characteristics research and evolution research, the chemical characteristics and its distribution pattern of drinking groundwater can be identified, the mechanism of interaction between groundwater and the environment can be revealed through groundwater chemical evolution research and all of these are of great theoretical significance and practical significance to promote the regional socio-economic development, environmental protection and governance. Study on the hydrochemical characteristics has drawn the attention of many hydrogeologists[2-9] around the world.

Yinchuan Plain, stretching from the city of Qingtongxia in the south to Shizuishan in the north, is heavily populated with recent (last 20 year) urban developments. The Yinchuan Plain is not only an over populated area, but also a traditional agricultural area where farming activities such as vegetables and greenhouse cultivation continue all year long. Due to population and agricultural expansions, needs for fresh groundwater here is ever-growing. Therefore, water resources in Yinchuan Plain are subject to intensive demands, stresses and pollution risks.

The groundwater in Yinchuan Plain is mainly used for irrigation, industry and drinking. Groundwater chemical characteristics and groundwater quality greatly influence the living standards of local people and the development of agriculture in this region, especially in the Yinchuan area which is the capital of the Ningxia Hui Autonomous Region, where local communities rely upon fresh groundwater directly for their water supply. However, little is known about the hydrochemical characteristics and the natural phenomena that govern the chemical compositions of groundwater in this region. This paper attempts to solve these questions. The main objectives of this paper are: (1) to assess the chemical characteristics of groundwater and (2) to identify the control factors that presently affect the water chemistry in the region.

Study area

Location: The Yinchuan Plain, in the upper reaches of the Yellow River, is located in the northern part of Ningxia Hui autonomous region. It is bounded by Qingtongxia in the south, Shizuishan in the north, Helan Mountain in the west and Ordos Basin in the east. It is 165 km long from south to north and 42-60 km wide from east to west. The total area of the Yinchuan Plain is 7790 km^2 and ranges in elevation from *ca.* 1100-1200 m above mean sea level, being the lowest in

Ningxia. It is situated between 105°45'-106°56'E, 37°46'-39°23'N (Fig. 1). The plain covers Yinchuan City, Shizuishan City and Wuzhong City. The population in 2003 was 2.6633 million and the national economic output value was 29.06587 billion RMB.

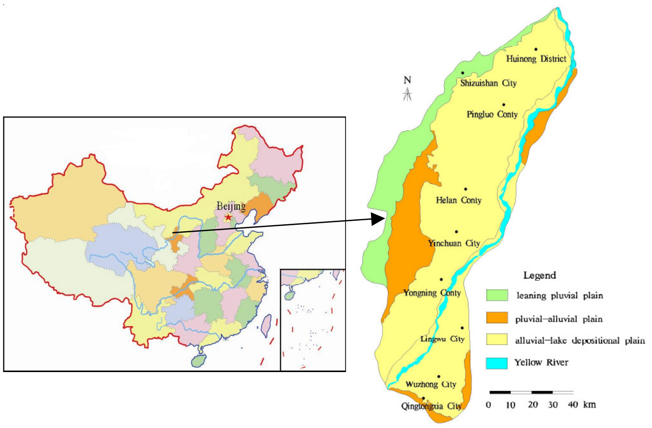


Fig. 1. Location map of Yinchuan Plain

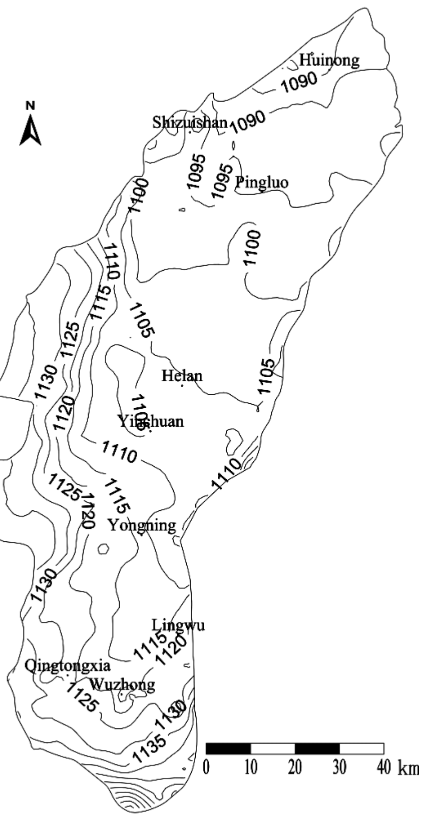
Climate and hydrology: The Yinchuan Plain is situated in the continental arid to semiarid climate region of northern temperature zone, with a long winter and short summer, more droughts and less rain, ample sunshine, dramatic temperature difference and much wind and sand. The annual mean temperature is 8.92 ºC, the minimum temperature is -30.6 ºC and the maximum temperature is 41.4 ºC. The annual average precipitation is 185 mm and mainly concentrates from June to September, which accounts for 68.1 % of the annual precipitation. The distribution of the precipitation shows a horizontal zoning characteristic with more rain in the southeast and less rain in the northwest. The annual evaporation is 1825 mm, ten times of the precipitation.

Yinchuan Plain belongs to Yellow River drainage. Main rivers flowing through the plain include the Yellow River and its tributaries Kushui River. The Yellow River flows into the plain from the southwest side and flows out of the plain in the north west of Shizuishan City. The annual sediment discharge of the Yellow River is 0.98×10^8 m^3 and the average salinity is 0.4 g/L. Kushui River originates from Huan County, Gansu Province and intersects the Yellow River at Xinhua Bridge in Lingwu City. It is characterized by small runoff and poor water quality, the annual runoff is only 0.26×10^8 m^3/a, with salinity of 4.5-4.85 g/L.

Hydrogeology: Yinchuan Plain is formed by river, lake and flood deposition on the basis of a Cenozoic fault Basin[10,11]. The landforms in the plain from the foot of Helan Mountain to Yellow River show a zonal distribution: leaning pluvial plain, pluvial-alluvial plain and alluvial-lacustrine plain, respectively (Fig. 1). The maximum thickness of Quaternary sediments in the plain reaches to 2000 m. According to the analysis of geological, geomorphologic and hydrogeological conditions and drilling data, the pore water in loose rocks in the Yinchuan Plain is divided into two areas: the single phreatic water area and multi-layer structure area. The single phreatic water area is mainly in the western and southern parts of the plain, composed of pluvial deposits of Helan Mountain and alluvial sand gravel in Qingtongxia. Other areas are mostly characterized of multi-layer structure. The aquifers within the depth of 250 m can be divided into three groups. From top down, they are the phreatic aquifer, first and second confined aquifer, respectively. There are usually continuous aquitards with a thickness of 3-10 m between the aquifers.

The recharge of groundwater in Yinchuan Plain is mainly by the leakage of channels, the seepage of irrigation water, precipitation and inflow through the boundaries, infiltration of flood water during rain seasons and the Yellow River. The groundwater discharges primarily by drainage ditches, evaporation, exploitation and drainage to Yellow River. According to the calculated results of groundwater balance, from July 1, 2003 to June 30, 2004, the total amount of the groundwater recharged is 23.4138×10^8 m^3/a, the total amount of groundwater discharged is 25.9749×10^8 m^3/a.

The runoff of the phreatic water is influenced by topography, lithology of soils, ditches and other natural and human factors. It can be seen from the contour map of phreatic water table (Fig. 2a) overall the phreatic water flows from northeast to southwest, but in different areas, the runoff direction and flow conditions exist some differences. From the contour map of the first confined water level (Fig. 2b) one can observe that the hydraulic gradient of the first confined water is 1.5-3.8 % in the west of the plain and in Kushui River delta in the south end of the plain. Groundwater flow direction in the western border is from west to east, while in Kushui River delta area it flows from southeast to northwest. Due to exploitation of groundwater in the first confined aquifer, depressions of groundwater have formed in Yinchuan area and Shizuishan region and groundwater flows to the centers of the depressions.



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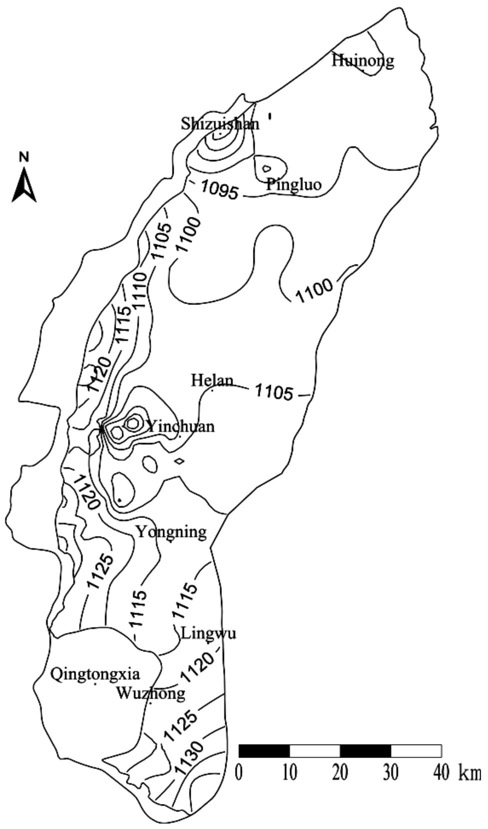

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Fig. 2. Contour maps of groundwater level (year 2003). (a) Contour map of phreatic water table, (b) Contour map of the first confined water level

In most regions of Yinchuan Plain, the depth to groundwater level is less than 3 m. In the northern part of the plain, this depth is generally less than 2 m. The movement of phreatic water is mainly affected by topography, lithology, distribution of channels and ditches and groundwater exploitation. The phreatic water in Yinchuan Plain generally flows from SW to NE. Near the south and west boundaries of the plain, the hydraulic gradient is usually large, the movement of groundwater is fast. Towards the middle and northeast parts of the plain, the hydraulic gradient becomes small, movement of groundwater gets slow. Because of the shallow depth to groundwater and the slow movement, evaporation is intensive.

EXPERIMENTAL

For the study, total 364 groundwater samples and 88 soil samples were collected from different locations in 2003. Sampling locations are shown in Fig. 3. Samples were collected in pre-cleaned plastic polyethylene bottles for physicochemical analysis of sample. Prior to sampling, all the sampling containers were washed and rinsed thoroughly with the groundwater to be taken for analysis. Each of the groundwater samples was analyzed for 16 parameters including water temperature, HCO_3^-, Cl^-, SO_4^{2-}, PO_4^{3-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, pH, total dissolved solid (TDS), total iron (Tfe), total hardness (TH), nitrogen, fluoride and chroma. Water temperature and pH were measured in the field with portable Hanna pH meter. For the pH measurements the electrode was calibrated against pH buffers at each location. Others were analyzed by laboratory of Ningxia Monitoring Station for Geological Environment using standard procedures recommended by Chinese Ministry of Water Resources.

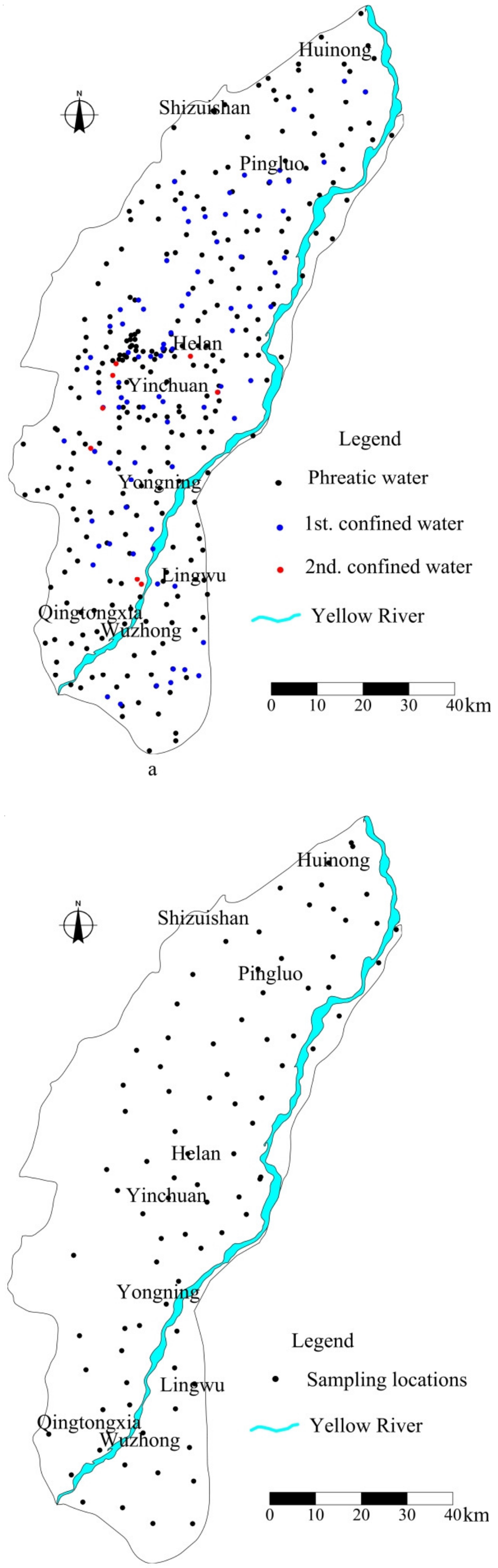

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Fig. 3. Map of sampling locations. (a) Sampling locations of groundwater, (b) Sampling locations of soils

RESULTS AND DISCUSSION

Statistical analysis: The basic characteristics of groundwater chemical composition in Yinchuan Plain were summarized in Table-1.

It can be seen from the table that in the study area the pH values range from 7.02-8.45. Various ion concentrations and water chemistry indices vary greatly, such as the maximum TDS reaches 21.47 g/L, while the minimum is only 0.24 g/L. The concentrations of the cations in unconfined aquifer decrease in the following sequences: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and anions: $Cl^- > SO_4^{2-} > HCO_3^-$. The decreasing sequences of the cations in the first confined aquifer are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and anions: $HCO_3^- > SO_4^{2-} > Cl^-$. In the second confined aquifer, the sequence is $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and anions: $HCO_3^- > SO_4^{2-} > Cl^-$. Since both relative independence and hydraulic connection exist among different water bearing formations, the chemical compositions of groundwater in different aquifers have both similarities and differences. Compared with phreatic water, the concentrations of various major ions in confined water are lower.

Spatial distribution of total dissolved solid (TDS) and hydrochemical types: Total dissolved solid is an important indicator to evaluate groundwater quality. Total dissolved solid is usually affected by topography, lithology, burial conditions, groundwater recharge, runoff and discharge conditions as well as human activities. According to the level of TDS, groundwater can be divided into fresh groundwater (TDS < 1000 mg/L), moderately salty water (1000 < TDS < 3000 mg/L) and salty water (TDS > 3000 mg/L). Due to the insufficiency of data, only phreatic water and the first confined water are analyzed and studied.

Total dissolved solid contour map of phreatic water is drawn using the Surfer 9 which employs geostatistics and kriging interpolation methods (Fig. 4). It can be seen clearly from the Fig. 4a that the TDS of phreatic water has an increasing pattern eastwards and northwards. The area with TDS less than 1 g/L mainly distributes in the west and southwest part of the plain. The phreatic water in the middle part of the plain usually is moderately salty water with TDS between 1 and 2 g/L. The phreatic water in Pingluo County, Huinong County and Taole County is mainly salt water with TDS greater than 3 g/L.

Because of the burial conditions, water quality of the first confined water is hardly affected by the external environment. Compared with the phreatic water, contents of ions in the first confined water are relatively lower and water type is relatively simpler, but overall the two have a similar spatial distribution. Fig. 4b is the contour map of TDS in first confined water. It can be seen from the figure that in the entire study area, TDS shows a zonation characteristic from west to east. In the midwest of the plain, TDS is less than 1 g/L, east of Pingluo-Xidatan-Yinchuan-Yongning, the TDS is generally 1-3 g/L and the area where TDS is greater than 3 g/L mainly distributes in the northeast of the plain.

Generally speaking, in low salinity fresh water areas, bicarbonate or sulfate type water is most likely to be formed and in salt water area, chloride and sulfate type are the main water chemistry types. Piper diagrams were drawn with AQUACHEM software in Fig. 5. It can be seen from the Fig. 5 that for waters with TDS < 1 g/L (Fig. 5a), the dominant types of groundwater are $HCO_3{\cdot}SO_4$-Ca·Mg, $HCO_3{\cdot}SO_4$- Mg·Ca, $SO_4{\cdot}HCO_3$-Mg·Ca and $SO_4{\cdot}HCO_3$-Ca·Mg. For waters with 1 g/L < TDS < 3 g/L (Fig. 5b), the chemical types are mainly $HCO_3{\cdot}SO_4$-Na·Mg,$HCO_3{\cdot}SO_4$-Na·Ca, with some being the type of SO_4·Cl-Na·Mg and Cl·SO_4-Na·Mg. For waters with TDS > 3 g/L (Fig. 5c), the chemical types are mainly SO_4-Na and SO_4·Cl-Na.

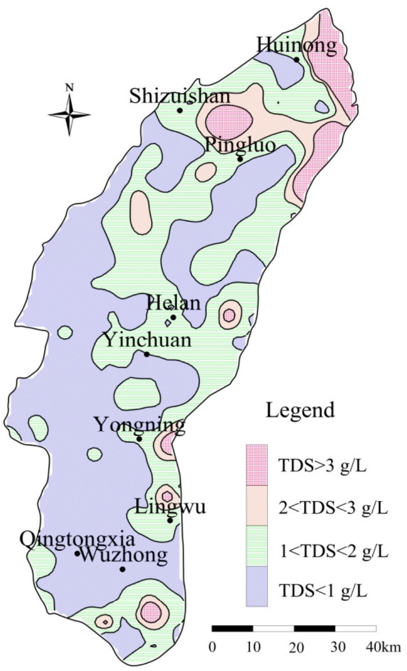

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TABLE-1
STATISTICAL ANALYSIS OF MAIN PARAMETERS

Parameters	Phreatic water			First confined water			Second confined water		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
TDS	21467.67	282.15	1214.257	5903.78	239.72	1141.67	975.29	383.66	519.28
TH	3578.1	117.3	510.2	2395.5	27.34	335.64	429.03	231.78	294.66
pH	8.39	7.04	8.00	8.45	7.02	8.05	8.14	7.87	7.98
Na^+	6800	23	230.85	1896	24	205.37	202	30	67.97
K^+	58	1	4.92	24	0.8	2.83	4.2	1.2	2.3
Ca^{2+}	386.5	27.33	95.25	250.5	15.36	59.30	95.65	37.09	55.14
Mg^{2+}	287.71	8.29	70.29	291.06	4.74	46.97	56.83	28.42	43.07
HCO_3^-	1292.87	111.35	415.74	1046.11	86.66	287.48	544.36	197.95	283.78
SO_4^{2-}	8690.59	16.04	406.15	1709.94	12.9	237.32	212.44	89.1	149.83
Cl^-	4627.75	10.38	177.86	2791.92	13.72	212.12	169.54	13.84	45.41

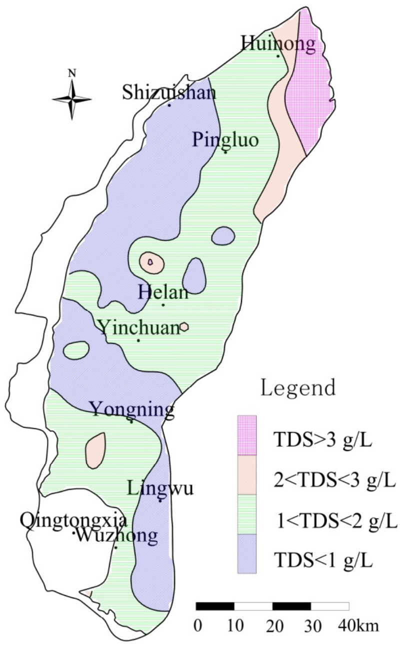

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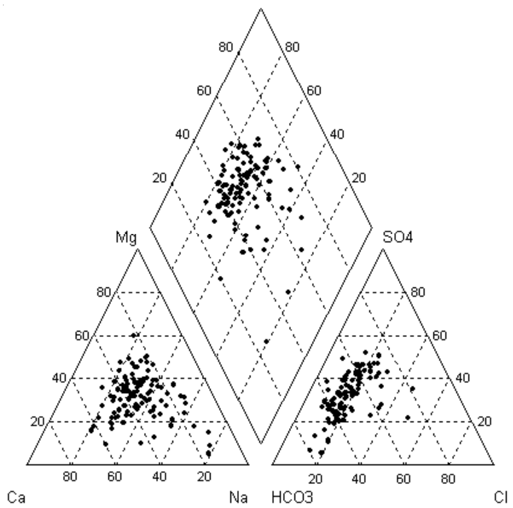
Fig. 4. Distribution of TDS in the Yinchuan Plain. (a) Phreatic water. (b) First confined water



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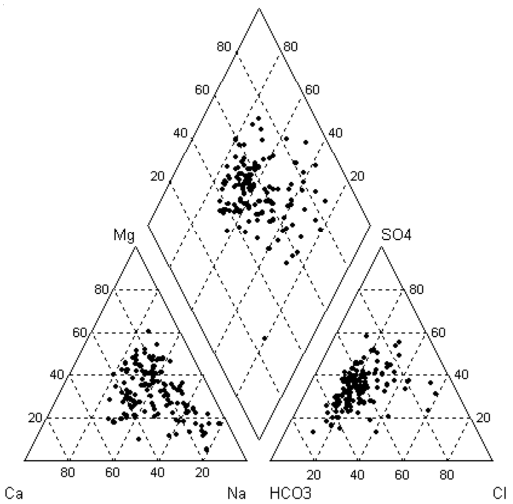

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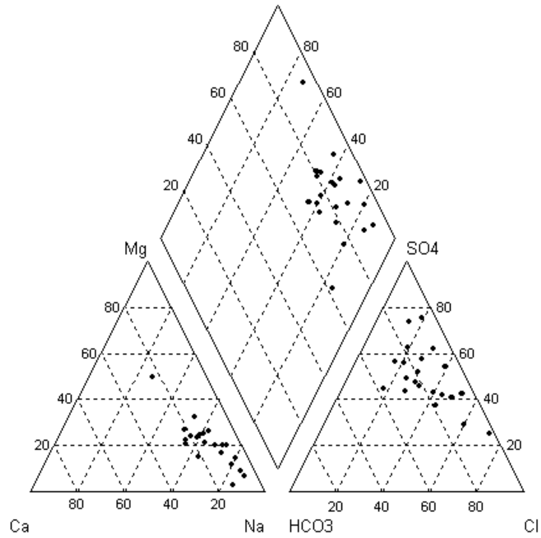

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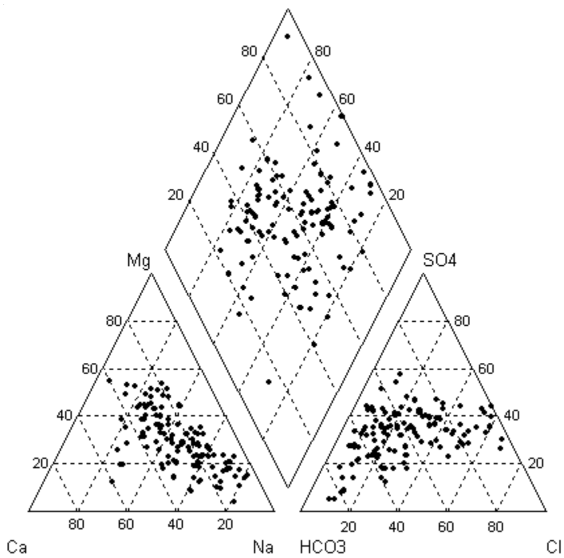
Fig. 5. Piper diagram of phreatic water. (a) TDS < 1 g/L (b) 1 g/L < TDS < 3 g/L (c) TDS > 3 g/L

Fig. 6a is the Piper diagram of all water samples collected in the first confined aquifer and it shows that the first confined water contains relatively smaller sulfate and calcium. Fig. 6b and Fig. 6c are the Piper diagrams for water samples with TDS less than 1 g/L and greater than 1 g/L. It can be seen from the diagram that when the TDS is less than 1 g/L, chemical types of the first confined water are mainly HCO_3·SO_4-Mg·Na type and HCO_3·SO_4-Na·Mg type. When the TDS is greater than 1 g/L, the water chemistry types are HCO_3·Cl-Na·Mg type and Cl·SO_4-Na·Mg-type.

Spatial distribution of major constituents: Major constituents including Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and HCO_3^- account for over 90 % of the chemical contents in groundwater. Regional changes of major constituents in phreatic water are primarily controlled by topography, lithology of the aquifer and the recharge, runoff and discharge conditions of the groundwater. Contour maps of various major constituents in phreatic water and the first confined water are drawn with Surfer 9 in Figs. 7 and 8, respectively.



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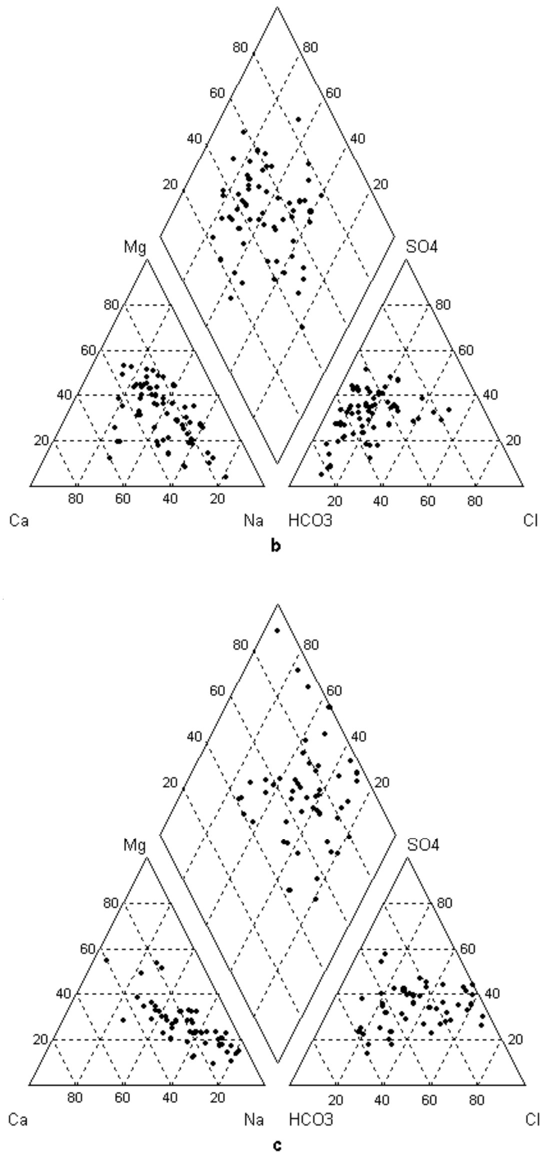

Fig. 6. Piper diagrams of first confined water. (a) All water samples (b) TDS <1 g/L (c) TDS > 1 g/L

The maximum and minimum concentrations of Cl^- in phreatic water are 4627.75 and 10.38 mg/L, respectively, with an average value of 177.86 mg/L. It can be seen from Fig. 7a clearly that from SW to NE, the concentration of Cl^- increases gradually. The water with Cl^- less than 100 mg/L is mainly in the south and west boundary of the study area and between Helan and Pingluo County. In Wuzhong and Lingwu cities, Xidatan Town, north of Pingluo County and east of Huinong County, the concentrations of Cl^- are usually high. The concentrations of Cl^- in the north-east corner of the study area and in Taole County are usually larger than 500 mg/L.

The maximum and minimum concentrations of Na^+ in phreatic water are 6800 and 23 mg/L, respectively, with an average value of 230.85 mg/L. The spatial change of the concentration of Na^+ has a similar trend to Cl^- (Fig. 7b). The low concentration area is mainly in the south and west boundary of the study area and between Helan and Pingluo County. In the north-east corner of the study area, the concentration of Na^+ is usually high.

The spatial changes of Ca^{2+} are relatively small (Fig. 7c). The maximum and minimum concentrations of Ca^{2+} are 386.5 and 27.33 mg/L, respectively, with an average value of 95.25 mg/L. In most part of the study area, the concentration of Ca^{2+} is less than 150 mg/L. In the middle and south part of the study area, the concentration of Ca^{2+} is between 50 and 100 mg/L and the distribution of Ca^{2+} is orderless. In the northern part of the study area, the concentration of Ca^{2+} is between 100 and 200 mg/L and in the north-east corner of the study area, the concentration of Ca^{2+} is greater than 200 mg/L.

The maximum and minimum concentrations of HCO_3^- are 1292.87 and 111.35 mg/L, respectively, with an average value of 415.74 mg/L. In the east foot of Helan Mountain, the concentration of HCO_3^- is usually smaller than 350 mg/L. In south-west of Lingwu County, north of Yinchuan city, east of Huinong County, north of Pingluo County, the concentrations of HCO_3^- are usually greater than 500 mg/L. The general trend of the concentration of HCO_3^- is low in south and west, high in east and north (Fig. 7d).

The distributions of Mg^{2+} and SO_4^{2-} in the phreatic water are similar. It can be seen from the Figs. 7e and 7f that both the concentrations of Mg^{2+} and SO_4^{2-} are relatively higher in the south and north of the plain than that in the middle where the distributions of the two indices are orderless.

The maximum and minimum concentrations of Cl^- in the first confined water are 2791.92 and 13.72 mg/L, respectively, with an average value of 212.12 mg/L, In the western region of the plain, concentration of Cl^- is generally less than 100 mg/L and in the northeast is larger than 500 mg/L. Overall, Cl^- has an increasing pattern northeastwards (Fig. 8a).

The maximum and minimum concentrations of Na^+ in the study area are, respectively, 1896 and 24 mg/L, with an average of 205.37 mg/L. Na^+ shows a similar distribution pattern to Cl^-, increasing gradually from southwest to northeast (Fig. 8b). The main difference between the two is the concentration of Na^+ in the southern part of the plain is relatively higher than that of Cl^-.

Ca^{2+} and Mg^{2+} show a similar distribution pattern in the plain, increasing from southwest to northeast (Fig. 8c and 8d). In most parts of the study area, the concentrations of the two are below 100 mg/L except in the northeast part of the study area where the concentrations of two are higher than 100 mg/L. The difference is that in the central and western regions of the plain, the concentration of Mg^{2+} is generally lower than that of Ca^{2+}.

The spatial distribution of HCO_3^- in the first confined water is slightly different from the foregoing ions. The high value point appears in Lijun town and the north and east of Helan County, while in the southwest corner of the plain, Yongning County and east part of Huinong County, the concentration of HCO_3^- is the lowest. On the whole, the concentration of HCO_3^- shows a decreasing trend from the southwest to the northeast (Fig. 8e).

The variation trend of SO_4^{2-} concentration in the plain is similar to that of Mg^{2+} or Ca^{2+} (Fig. 8f). The concentration of SO_4^{2-} in the central and western regions is the lowest, generally less than 150 mg/L. In the southern area, the concentration of SO_4^{2-} is generally higher than 200 mg/L and from the Helan

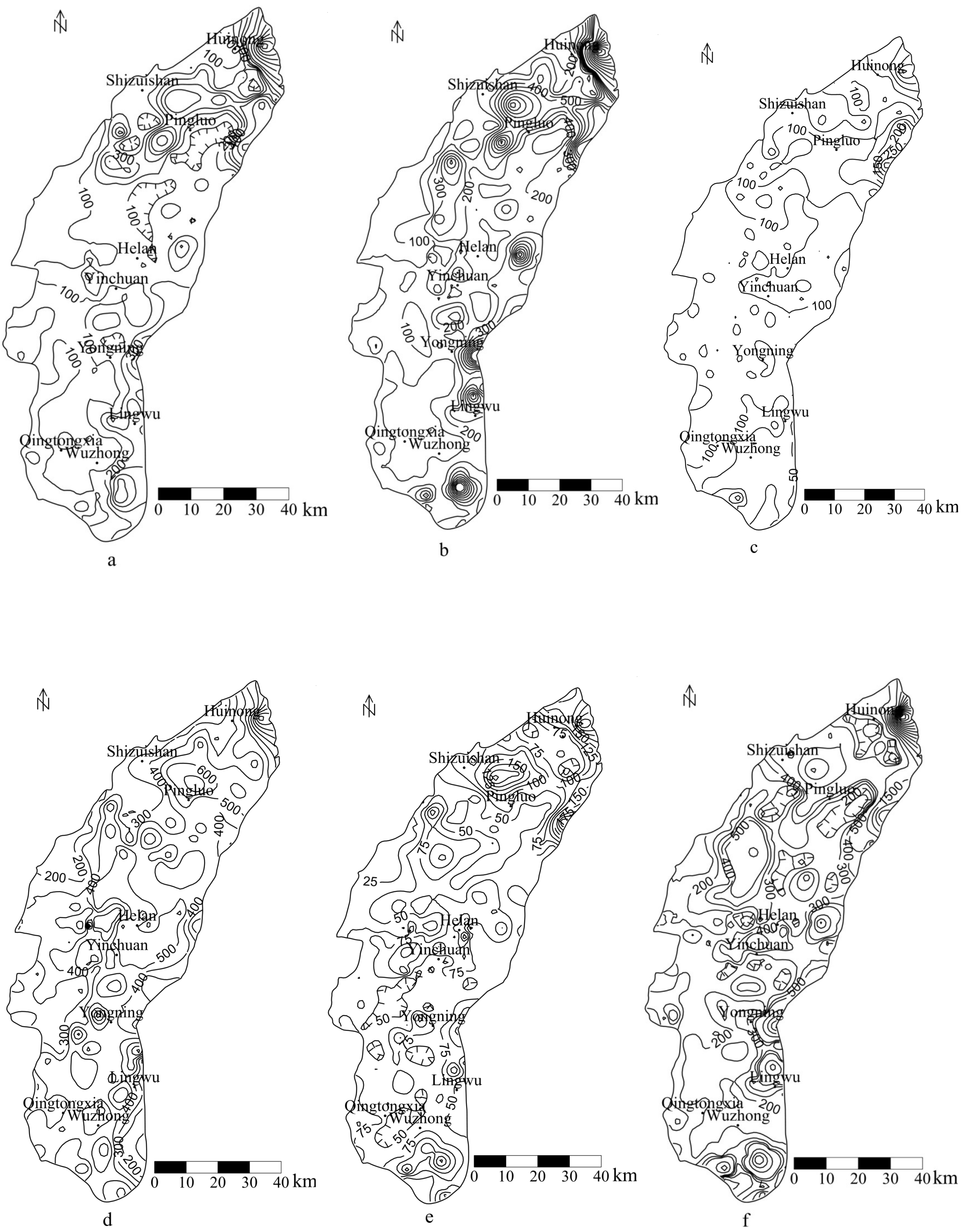

Fig. 7. Contour maps of various main constituents in phreatic water (a) Cl^-; (b) Na^+; (c) Ca^{2+}; (d) HCO_3^-; (e) Mg^{2+}; (f) SO_4^{2-}

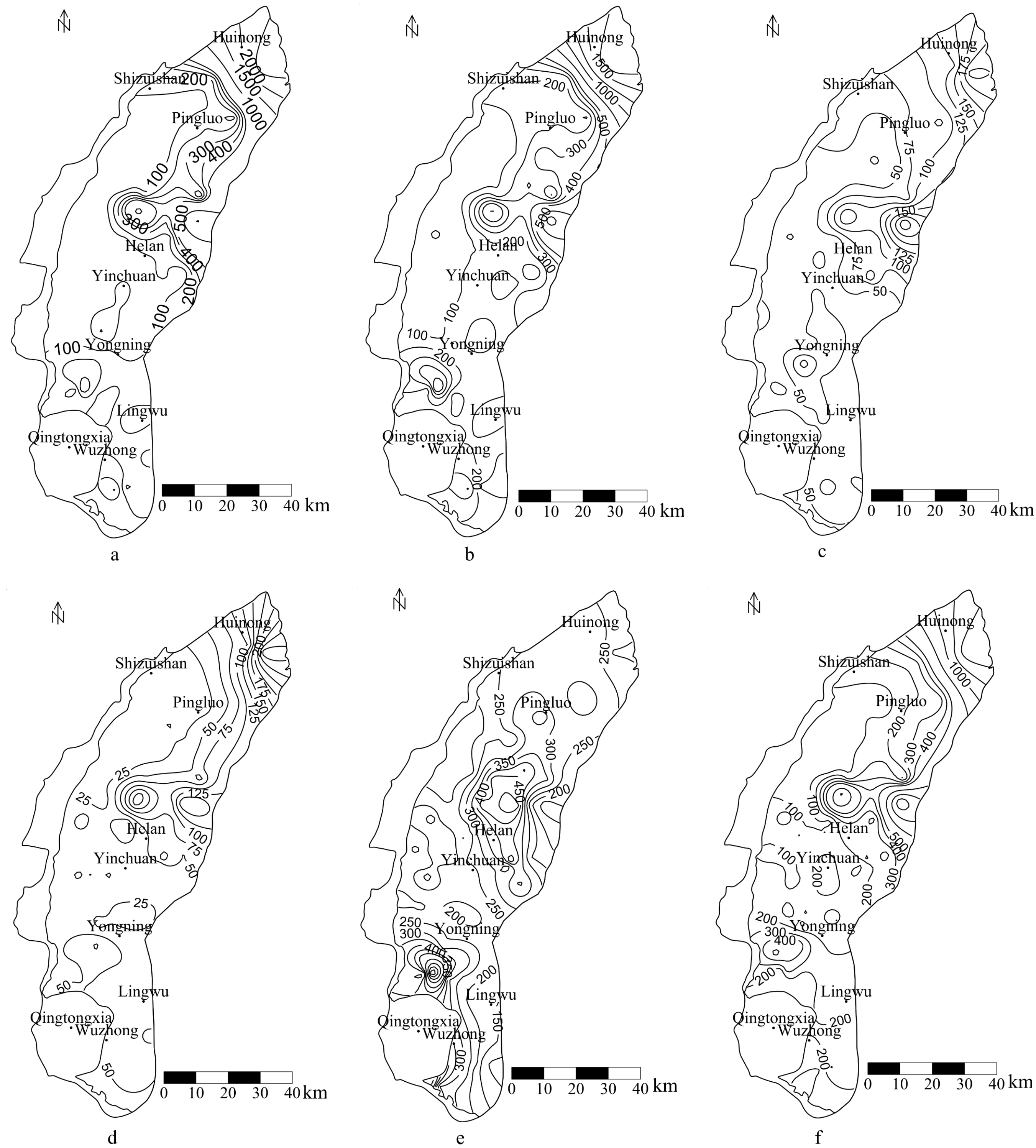

Fig. 8. Contour maps of various main constituents in first confined water. (a) Cl^-; (b) Na^+; (c) Ca^{2+}; (d) Mg^{2+}; (e) HCO_3^-; (f) SO_4^{2-}

County northeastwards, the concentration of SO_4^{2-} gradually increases, up to 1000 mg/L or more. SO_4^{2-} as a whole shows an increasing pattern from southwest to northeast.

Factors controlling hydrochemistry: Groundwater chemical compositions and their formations and distributions are the product of certain natural geographical and geological environment after a long geological history. Chebotarlev[12-14] analyzed more than 10,000 groundwater samples in Australia and proposed that along the groundwater flow path, the regional evolutionary trend of the predominant anions is: $HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$. In Yinchuan Plain, the chemical types of phreatic water varies in following sequences $HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-}$ in the groundwater flow direction from SW to NE, which is part of the sequences in Australia. Through comprehensive study and analysis, it is concluded that the main factors influencing and determining the chemical characteristics and evolution of groundwater in Yinchuan Plain are: (1) geological and hydrogeological conditions, (2) the chemical compositions of the recharge water,

(3) content of soluble salt in soil, (4) water-rock interaction and (5) evaporation of groundwater.

Geological and hydrogeological conditions: The geological and hydrogeological conditions play a key role in controlling the compositions of groundwater to some extent. This is reflected by the fact that when the topography, lithology, circulation and depth to groundwater table are different, the compositions of groundwater usually differ greatly.

In the pluvial-alluvial and alluvial-lacustrine plain, the spatial variations of the compositions of groundwater are large. In the south of Yongning County, the groundwater is mainly fresh water with TDS less than 1 g/L. The chemical type of groundwater is mainly HCO_3·SO_4. In the north of Yongning County, with the slowing down of the circulation of groundwater and the depth to water table becoming small, the quality of groundwater becomes worse. In the region between Liangtian-Pingjibu and Nuanquan-Yaofu, the water type is mainly HCO_3·Cl and SO_4·Cl with TDS ranging from 1-2 g/L. In the north region of Nuanquan-Yaofu, especially in the north of Pingluo County, the water type is mainly Cl·SO_4-Na·Mg with TDS between 1 and 3g/L, or even greater than 3g/L.

Chemical compositions of the recharge water: The recharge sources of phreatic water in Yinchuan Plain are multiple. In the decrease sequence, they are channel leakage, irrigation seepage, precipitation, underground inflow and infiltration of flood water, respectively.

Table-2 lists the chemical analysis results of rain and some surface water samples in Yinchuan Plain. It can be seen from the table, the major cation and anion in rain are Na^+ and HCO_3^-, respectively. The chemical types of water from Yellow River are mainly HCO_3·SO_4 or SO_4·HCO_3. For waters of drainage ditches, their TDS and concentrations of various species (especially Na^+, Cl^- and SO_4^{2-}) increased apparently compared to the channel waters and Yellow River water. Yellow River water, the main recharge source of phreatic water, is mainly fresh water with low TDS. Its effect on the compositions of phreatic water is primarily dilution. The Na^+, Cl^-, SO_4^{2-} in drainage ditches are mainly from soil and groundwater. This shows drainage ditch has the function of draining salt out of the soil.

Besides Yellow River and rain, the other source of recharge is the underground inflow from groundwater in the hard rocks of Helan Mountain. The groundwater in the mountain is recharged by precipitation and the rocks are mainly metamorphic and carbonate rocks with low solubility, so the TDS of groundwater is usually low, which makes the phreatic water at the foot of Helan Mountain be the fresh water.

Content of soluble salt in soil: Fig. 9 is the zoning map of soluble salts content in soil in Yinchuan Plain based on

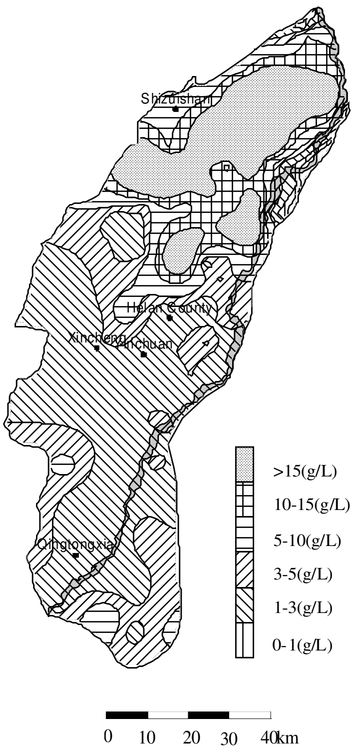

Fig. 9. Zoning map of soil salt content in Yinchuan Plain

analysis results. At the same time, according to the remote sensing (RS) data in year 2003, the distribution of different saline soil in Yinchuan Plain is extracted (Fig. 10). It can be seen from the two figures, the soil salinization mainly develops in the northern part of Yinchuan Plain. By comparing Figs. 9, 10 and Fig. 4, it can be seen that in the regions where soil salinization developed, the hydraulic gradient and the depth to phreatic water level are usually small, the movement of groundwater is slow and the TDS of phreatic water is large. In Fig. 11, the chemistry of phreatic water and soluble salts in soils are shown in the same Piper diagram. The figure indicates the cations in soil nearly cover the cations in phreatic water. For the anions, only Cl^- and SO_4^{2-} in soils cover the corresponding ions in phreatic water. There is obvious difference for HCO_3^-, which may reflect the exchange of CO_2 between phreatic water and atmosphere.

Water-rock interaction: Saturation index (SI) is a widely used indicator in hydrogeochemical study which reflects the saturation state of minerals in water. Saturation index is calculated by the following formula:

$$SI = \log \frac{IAP}{K}$$

TABLE-2
ANALYSIS RESULTS OF RAIN AND SURFACE WATER IN YINCHUAN PLAIN (UNIT mg/L)

Water sample	TDS	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	HCO_3^-	Chemical type
Rain	13.84	1.52	1.61	0.17	1.0	0.35	0.91	7.46	HCO_3-Mg·Ca
Yellow River	472.59	51.61	21.86	2.83	52.28	50.76	90.95	190.6	HCO_3·SO_4-Ca·Na·Mg
Tanglai channel	681.4	99.55	17.76	4	80	93.42	159.13	210.3	HCO_3·SO_4·Cl-Ca·Na
Xigan channel	443.7	40.74	30.6	3	36	38.84	60.44	215.2	HCO_3-Mg·Ca·Na
Huinong channel	775.5	70.27	50.91	4.1	91	100.34	234.82	191.8	SO_4·HCO_3·Cl-Mg·Na·Ca
4'th Drainage Ditch	1930.1	83.94	81.7	28.2	396	411.74	399.29	525.8	Cl·HCO_3·SO_4-Na
2'th Drainage Ditch	1543.44	70.27	95.9	9.2	264	328.61	278.39	476.3	Cl·HCO_3·SO_4-Na·Mg

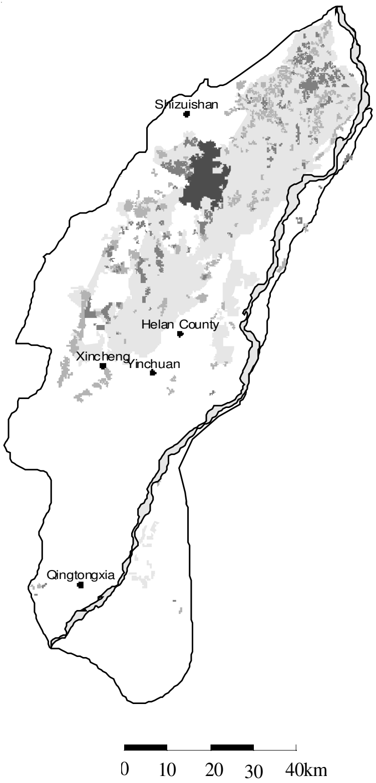

Fig. 10. Distribution of saline soil in Yinchuan Plain

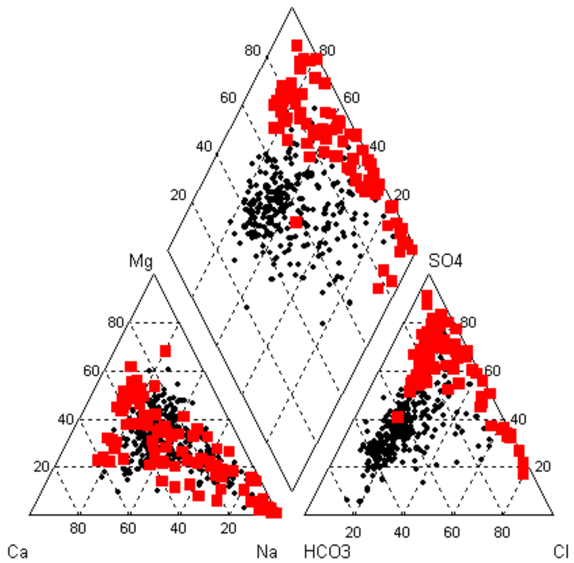

Fig. 11. Piper diagram of phreatic water and soluble salts. (● phreatic water, ■ soluble salts)

where, SI is the saturation index, IAP is the relevant ion activity product in a mineral dissolution reaction, which can be obtained by multiplying ion activity coefficient γ_i and composition concentration m_i; K is the equilibrium constant of mineral dissolution at certain temperature. Obviously, when SI = 0, the minerals in the aqueous solution is in equilibrium status; when SI < 0, the indicator shows that minerals in the aqueous solution has not reached saturation and has a dissolution trend; when SI > 0, a supersaturated status of minerals in the aqueous solution is indicated and mineral deposition will occur[15,16].

The saturation indices of calcite, dolomite and gypsum with respect to the 364 water samples collected in year 2003 were calculated using the method of Crerar[17], Plummer[18]. Fig. 12 shows the changes of saturation indices with TDS for the phreatic water in Yinchuan Plain.

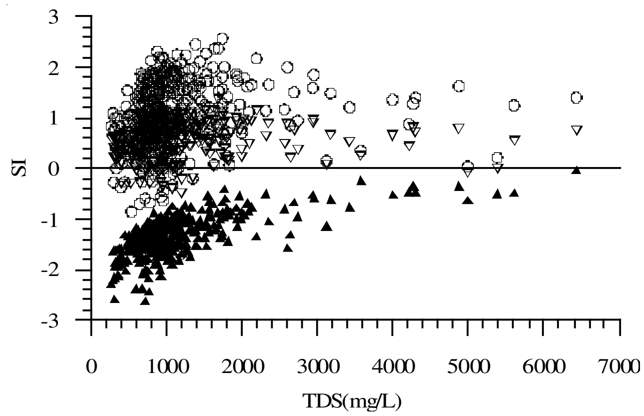

Fig. 12. Changes of saturation indices of minerals with TDS (▽ calcite, ○ dolomite, ▲ gypsum)

It can be seen from the figure, except a few water samples with TDS < 1.5 g/L, almost all the groundwater are supersaturated with calcite and dolomite. For gypsum, all the water samples are undersaturated with respect to the mineral, although the saturation index increases continually with TDS. This indicates in most part of Yinchuan Plain, the precipitation of calcite and dolomite is the main reaction for the two minerals, dissolution only occurs in local parts of the plain. Contour maps of SI were drawn in Fig. 13 with surfer 9. It can be seen from the contour maps that the precipitation of calcite and dolomite occurred mainly in the first confined water in the southeast part of the plain and in other parts of the study area, the precipitation of calcite and dolomite occurred locally.

By comparison, gypsum dissolves in the whole plain. Because all the phreatic waters are undersaturated with respect to salt (NaCl), the dissolution of salt is undoubted. This can also be seen by the scatter plots for the major ions in phreatic water (Fig. 14). In the figure, Ca^{2+} and SO_4^{2-}, Na^+ and Cl^- have a clear positive correlation. That is, the concentration of Ca^{2+} increases with the concentration of SO_4^{2-} and the concentration of Na^+ increases with the concentration of Cl^-. This indicates to some extent the dissolution of gypsum and salt in the phreatic water. For Ca^{2+}, Mg^{2+} and HCO_3^-, their relationships are complicated, which can not be explained by the dissolution of calcite and dolomite. For example, the dissolution of gypsum can lead to the precipitation of calcite and dolomite, the dissolution or release of CO_2 can result in the changes of concentration of HCO_3^-, *etc*. Under the influences of the above dissolution/ precipitation reactions, the concentrations of Ca^{2+}, SO_4^{2-}, Na^+ and Cl^- of phreatic water increase along the flow direction. The composition of phreatic water changes according to definite rules.

Evaporation of phreatic water: Evaporation is one of the important modes of discharge for phreatic water in Yinchuan Plain. The discharge by evaporation exceeds 45 %

Fig. 13. Contours maps of SI. (a) SI of calcite in phreatic water, (b) SI of dolomite in phreatic water, (c) SI of gypsum in phreatic water, (d) SI of calcite in confined water, (e) SI of dolomite in confined water, (f) SI of gypsum in confined water

of the total discharging groundwater. The evaporation mainly occurs in the northern part of the plain where the depth to water table is small. In the process of evaporation, water dissipate into the atmosphere, salts remain in the soil and residual water. Under the influence of this evaporation, large amount of salts accumulated in the phreatic water, the quality of groundwater becomes worse and soil salinization occurs. Therefore, the too shallow depth to groundwater table and the

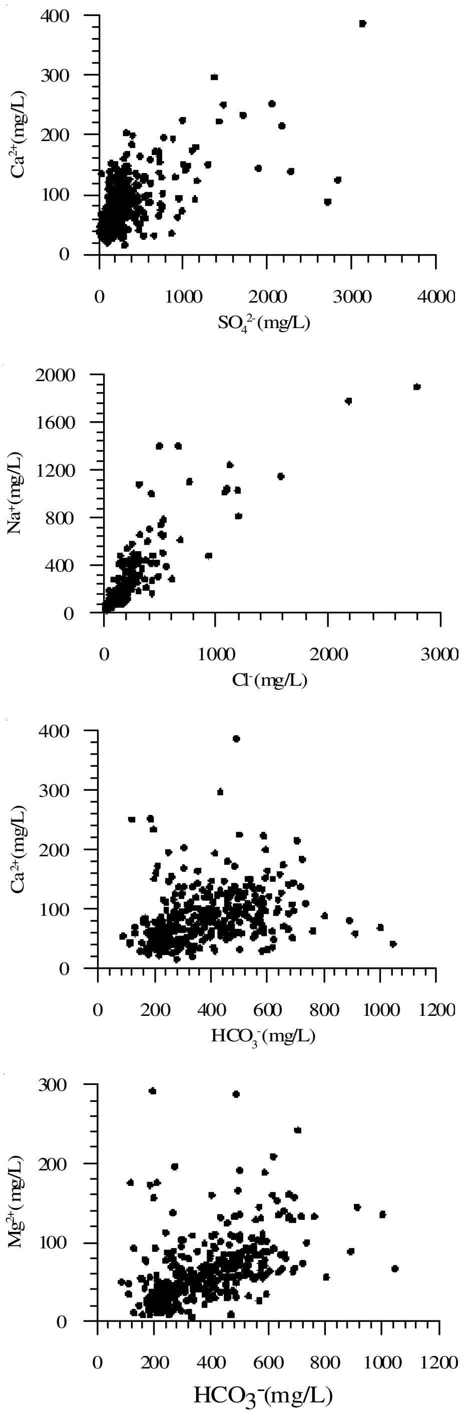

Fig. 14. Scatter plots for the major ions in groundwater in Yinchuan Plain

intensive evaporation are the essential causes leading to the large TDS and bad quality of phreatic water in northern Yinchuan Plain.

Conclusion

After comprehensive study and analysis, the following conclusions were reached: Groundwater is one of the important sources for agricultural irrigation, industry and drinking in Yinchuan Plain. Compared with the confined groundwater, the quality of phreatic water is worse and its composition is more complicated[22]. The changes of TDS, concentrations of Na^+ and Cl^- of phreatic water in Yinchuan Plain have similar trend. They generally increase along the flow direction from SW to NE. The phreatic water with TDS less than 1 g/L is mainly in the west and south-west parts of the plain. The phreatic water in the middle part of the plain usually has TDS between 1 and 2 g/L. The phreatic water in the northern part of Pingluo County, the eastern part of Huinong County and Taole County is mainly salt water with TDS greater than 3 g/L. (3) Water quality of the first confined water is hardly affected by the external environment due to the large aquifer depth. Total dissolved solid in the first confined water shows a zonation characteristic from west to east. The chemical types shows a similar distribution to phreatic water. In the Midwest of the plain, TDS of the first confined water is less than 1 g/L, east of Pingluo-Xidatan-Yinchuan-Yongning, the TDS is generally 1-3 g/L. Area where TDS is greater than 3 g/L mainly distributes in the northeast of the area. (4) In Yinchuan Plain, the chemical types of groundwater varies in following sequences $HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-}$ in the flow direction from SW to NE. The factors controlling and affecting the compositions of groundwater include geological and hydrogeological conditions, the compositions of recharge water, soluble salt in the soils, water-rock interactions and evaporation of shallow groundwater.

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