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ORIGINAL ARTICLE

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Application of hydrochemical signatures to delineating portable groundwater resources in Ordos Basin, China

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Abstract The Ordos Basin of China encompasses Shaanxi, Gansu, and Shanxi provinces, Ningxia and Inner Mongolia autonomous regions. It lacks significant surface water resources. Among the water-bearing formations, the Luohe formation, with an area of 1.32×10^5 km^2, is the most prospective aquifer. Groundwater quality data collected at 211 boreholes drilled into the Luhe formation indicate a complex distribution of groundwater chemistry. The hydrochemical properties were used to study the recharge, runoff, and discharge conditions of the groundwater in Ordos Basin and to evaluate sustainable groundwater resources. In the northern part of the basin, the hydrochemistry types and the total dissolved solids (TDS) show a clear lateral transition from SEE to NWW, indicating that the groundwater gets recharge in the northwest region and discharges in the southeast region. In the southern part of the basin, maximum TDS occurs at the center of the Malian River valley, from which the TDS decreases radially. Therefore, the groundwater in the southern basin gets recharge from the southeast and southwest regions, and the Malian River valley is the discharge zone. As a result of this research, the areas with portable groundwater were delineated. They include most of the southeast region of the Sishili Ridge, east of the Ziwu Mountain, and the southwest corner of the basin. The TDS of the groundwater in these regions is less than 1 g/l, and the hydrochemistry type is either HCO_3 or $HCO_3{\cdot}SO_4$.

Keywords Ordos Basin · Hydrochemistry · Groundwater resource · Total dissolved solids · China

Introduction

Shortage of the water resource in Ordos Basin

The Ordos Basin is in northwestern China. It belongs to the middle reach of the Yellow River. The Basin encompasses Shaanxi, Gansu, and Shanxi provinces, Ningxia and Inner Mongolia autonomous regions. The total area of the basin is approximately 365,000 km^2. Many kinds of economic minerals have been discovered in this region, and there is a great potential for economic development.

However, one of the main factors restraining economic development in the Ordos Basin is the availability of water resources. The basin is known for scarcity of the surface water resources. In addition, the characteristics of the groundwater have not been fully understood. Most of the groundwater currently supplied to local people is either salty water or brackish water. The poor groundwater quality has also resulted

in high incidence of endemic disease among local populations.

Foreground of water supply from Luohe formation

Of the water-bearing formations in the Ordos Basin, the Cretaceous system is the largest aquifer (Li et al. 2004). The system is located in the middle and west of the basin and is bounded by the Wei River in the south and the Yellow River in all other directions. The Cretaceous system underlies Shaanxi, Gansu provinces, and Ningxia and Inner Mongolia autonomous regions, and stretches 265 km in the east–west direction and 640 km in the north–south direction, covering an area of 132,100 km^2.

The Cretaceous system is more than 1,000-m thick. From the top to the bottom, it can be divided into the Luohandong water-bearing formation, Huanhe water-bearing formation, and Luohe water-bearing formation.

Because of the extensive distribution and large thickness of the aquifer, the quantity of groundwater in the Cretaceous system is quite rich. The groundwater recharge in the Ordos Basin is made up of recharge from surface water such as precipitation, condensation water, irrigation, and percolation water. The lateral flow of groundwater is another recharge.

Suppose the total quantity of groundwater recharge is Q, according to the theory of the water-balance method (Fang et al. 1987), the following equation was established: $Q = Qp + Qn + Qc + Qb$ (1) where Qp is the recharge capacity of the precipitation, which is 6.1454×10^4 m^3/a, Qn, the recharge capacity of the condensation water, which is 4.782×10^8 m^3/a, Qc, the recharge capacity of the lateral flow of groundwater, which is 0.838×10^8 m^3/a, Qb, is the recharge capacity of the percolation of surface water, which is 0.153×10^8 m^3/a.

As a result, the total recharge capacity is $Q = 61.454 + 4.782 + 0.838 + 0.153 = 67.227\times10^8$ m^3/a (Wang 2004).

The above is the groundwater resource of the whole Cretaceous system in the Ordos Basin. Among the three water-bearing formations, the Luohe formation has the most extensive distribution and produces the most of the groundwater. The Luohe formation is present in almost all of the Cretaceous system in the areas, as shown in Fig. 1. The thickness of the Luohe formation varies from 250 to 742 m.

Distribution pattern of the groundwater quality in Luohe formation provides useful hydrochemical signature for studying groundwater flow conditions

The groundwater quality in the Luohe formation is very complex, and quality varies not only in the lateral directions but also in the vertical direction. Both fresh water with total dissolved solids (TDS) < 1 g/l and salt-water with TDS > 10 g/l exist. The distribution pattern of the groundwater quality in the Luohe formation provides a useful hydrochemical signature for studying groundwater flow conditions. The hydrochemical properties were used to delineate the recharge and discharge regions in the Ordos Basin and to evaluate the regional groundwater resource and its exploitation potentiality.

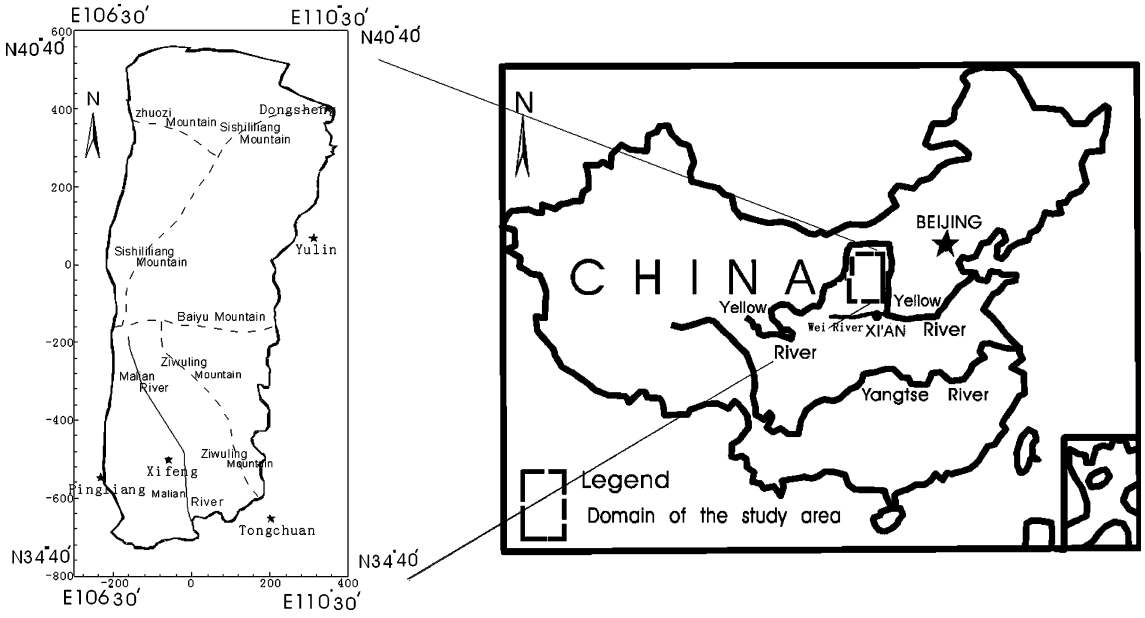

Fig. 1 The location figure of Luohe water-bearing formation in Ordos Basin of China. (Annotation: one scale in all the maps corresponds to 500 m on the spot)

Research methods

Most chemical parameters of the groundwater in Luohe Formation do not go beyond the standard for drinking water except exceptional ones. But the distribution signatures of them are not obvious due to the large area of the Ordos Basin. However, the mineral grade of the groundwater in this area has the obvious character of horizontal zonality. The mineral grade is also one of the most important factors to decide whether the groundwater can be used for drinking. So the mineral grade distribution properties, which reflect the degree of salt of the groundwater, are mainly discussed in this paper.

Water quality data in the Luohe formation were collected at 211 boreholes. Figure 2 shows the sampling locations. The TDS and hydrochemistry type were used to represent the hydrochemistry. Other factors considered in the hydrochemical studies include geomorphology, geologic build, geologic structure, and hydrogeology of the basin.

Distribution of TDS

Total dissolved solids indicate the amount of minerals in groundwater. According to the commonly referred Manual of Hydrogeology (The Fourth Hydrogeology Team of Geology Bureau of Hebei Province 1978), groundwater in China is divided into five categories based on TDS values:

1. < 1 g/l, fresh water
2. 1–3 g/l, slightly salt water
3. 3–10 g/l, salt water
4. 10–50 g/l, brine water
5. > 50 g/l, halogenated water.

Because of the shortage of fresh water and the fact that people in many places of the basin have to drink poor quality water, the categorization into five types was modified as follows:

< 1 g/l, fresh water
1–2 g/l, slightly saltish water; water in this category can be used for irrigation and for drinking under special circumstances
2–3 g/l, heavily saltish water; water in this category cannot be used for drinking or routine irrigation
3–5 g/l, slightly salty water; water in this category cannot be used for irrigation of common crops. It can be used for irrigation of paddy
5–10 g/l, heavily salty water; water in this category cannot be used as irrigation water for crops. It can irrigate salt-resistant grazing
10–50 g/l, salt water
> 50 g/l, halogenated water.

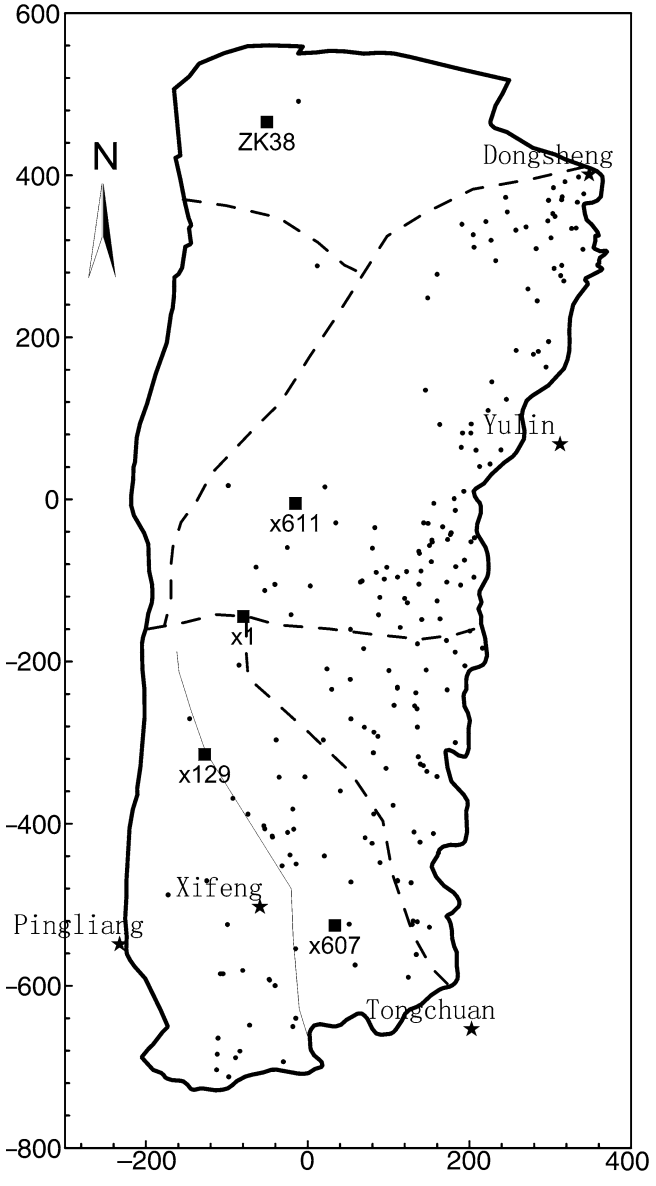

Fig. 2 Distribution figure of sampling drills of groundwater in Luohe formation of Ordos Basin

Groundwater hydrochemistry type

Designation of hydrochemistry type is based on Wang et al. (1995) in which only the major cations of groundwater are considered. The groundwater quality data revealed seven types of hydrochemistry in this area as follows:

HCO_3^-: The hydrochemistry of the water is dominated by HCO_3, which accounts for more than 25%.
SO_4^{2-}: The hydrochemistry of the water is dominated by SO_4^{2-}, which accounts for more than 25%.
Cl^-: The hydrochemistry of the water is dominated by Cl^-, which accounts for more than 25%.

HCO_3–SO_4: The hydrochemistry of the water is dominated by HCO_3 and SO_4, which accounts for more than 25%.
HCO_3–Cl: The hydrochemistry of the water is dominated by HCO_3 and Cl, which accounts for more than 25%.
SO_4–Cl: The hydrochemistry of the water is dominated by SO_4 and Cl, which accounts for more than 25%.
HCO_3–SO_4–Cl: The hydrochemistry of the water is dominated by HCO_3, SO_4, and Cl, which accounts for more than 25%.

The distribution of mineral grade of groundwater in Luohe formation

In the Ordos Basin Cretaceous system, the groundwater hydrochemistry can be obviously divided into two regions by the north foot of the Baiyu Mountain. The dividing line of the north region and south region is along Ertuok Former Mongolia to the north of Jingbian County, near N37°40′,whose vertical coordinate is −70.5 in the iconograph.

Distribution of the mineral grade of groundwater in Luohe formation in north region

The groundwater in Luohe formation in the north region of the basin is mostly fresh water with TDS < 1 g/l, as shown in Fig. 3. The fresh water accounts for more than 80% of the distribution area of the Luohe formation. Generally the TDS value of the groundwater in the north region of the basin gradually ascends from southeast to northwest. The groundwater changes from fresh water in the southeast to slightly saltish water near the boundary in the northwest. The TDS reaches 1.95 g/l at the northwest corner (Dill ZK38).

The maximum TDS occurs at the north foot of Baiyu Mountain (Dill ×611)—in the northeast of Yanchi County. It reaches 2.49 g/l, belonging to ''heavily saltish water''.

In the north region of the basin, the groundwater TDS value gradually ascends from southeast to northwest. It appears that the groundwater travels through the watershed, Sishili Ridge, divide of surface water.

Distribution of mineral grade of groundwater in Luohe formation in south region

Distribution of the mineral grade of groundwater in the south region is much more complex than that in the north region. The TDS value ascends from the east and west to the middle where the Malian River is located. The closer to the Malian River valley, the higher the TDS value tends to be. Lastly, the Malian River valley forms a strip-shaped zone of TDS peak values in the NW–SE direction of its east bank. The mineral grade of the groundwater is low in the east and in the west, and the groundwater is fresh water. As the groundwater flows towards the Malian River Valley, it changes progressively from fresh water, gradually to slightly saltish water, heavily saltish water, slightly salt water, heavily salt water, and finally to brine water.

The TDS value in this region is all above 3 g/l. i.e., the mineral grade of the groundwater belongs to at least ''slightly salt water''. South of the peak value strip-shaped zone, the TDS of the groundwater is

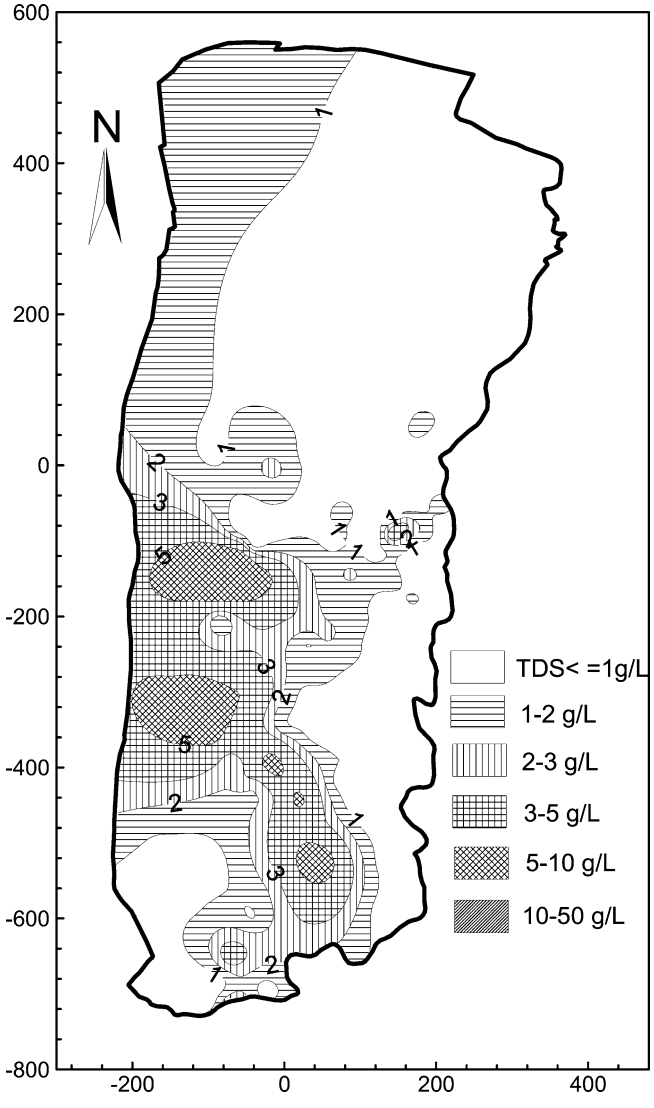

Fig. 3 The partition figure of mineral grade groundwater in Luohe formation

more than 6 g/l in the region between Ning County, Zhengning County, and Heshui County (TDS = 6.11 g/l at Dill ×607), belonging to "heavily salt water". In the middle and north of the peak value strip-shaped zone, the TDS of the groundwater is more than 6 g/l in Huan County (TDS = 7.04 g/l at Dill ×129), also belonging to "heavily salt water". The maximum TDS is more than 10 g/l (TDS = 10.45 g/l at Dill ×1), occurring at the top of Baiyu Mountain, in the north of the "axis", reaching the "brine water" classification.

Hydrochemistry type of groundwater in Luohe formation

Distribution of hydrochemistry type of groundwater in Luohe formation in north region

Generally, in the north region of the basin, the hydrochemistry type of the groundwater in Luohe formation is

$$\mathrm{HCO3} \rightarrow \mathrm{HCO3 \cdot SO4} \rightarrow \mathrm{HCO3 \cdot SO4 \cdot Cl} \rightarrow \mathrm{SO4 \cdot Cl}$$

from east (southeast) to west (northwest). Figure 4 shows the hydrochemistry type of the groundwater in Luohe formation. From the figure, we can find out that the hydrochemistry type is consisted with the distribution of the mineral grade of the groundwater in Luohe formation.

Distribution of hydrochemistry type of groundwater in Luohe formation in south region

Distribution of the hydrochemistry type of groundwater in the south region is much more complex than that in the north region. Similarly with the distribution of mineral grade of groundwater, the hydrochemistry type of groundwater is simple in the east and west of Malian River. The closer to the Malian River valley, the more complex the hydrochemistry type becomes. As a result, the Malian River valley forms a strip-shaped zone of TDS peak values in the NW–SE direction. The hydrochemistry type in the east and west belongs to HCO_3, and gradually changes to $HCO_3{\cdot}SO_4$ type towards the Malian River valley, where the hydrochemistry type can be $SO_4{\cdot}Cl$ type.

Distribution of major negative ion of Luohe formation in the whole basin

1. Distribution feature of SO_4^{2-} and Cl^-: In the whole basin, the change trends of SO_4^{2-} and Cl^- are similar. Their concentrations are generally low in the southeast, high in the northwest, and low at the southwest corner. The highest concentration occurs at the west end of Baiyu Mountain. In addition, the secondary higher concentrations occur at the south end of the basin, near Lingtai County and Changwu County.
2. Distribution feature of HCO_3^-: In the basin, the concentration of HCO_3^- is high along Wuqi County to Jingbian County, and descends towards northwest and southeast. Another high concentration zone is along Yanchi County to Jingbian County. The concentration descends towards northeast and southwest.

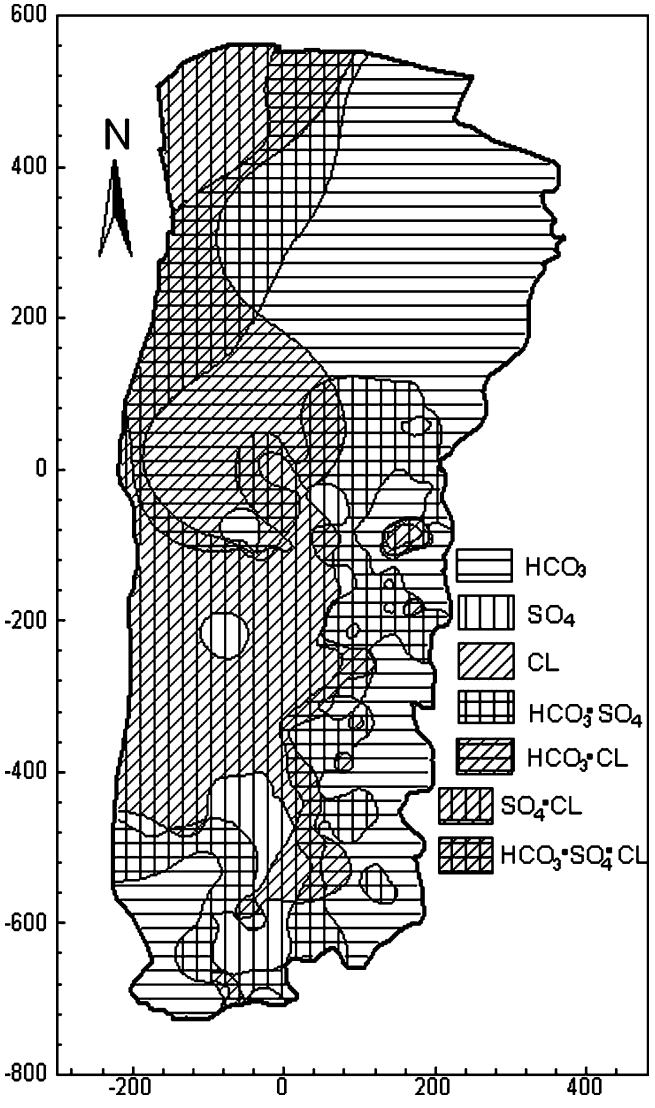

Fig. 4 Partition figure of the hydrochemistry type of groundwater in Luohe formation

In the north region of the basin, the zone along Ertuok Former Mongolia to the axis of SW to NE

direction of Dongshi City has the secondary higher concentration.

In the south region of the basin, the zone along Chongxin to Xifeng City has secondary higher concentration; to the south, the lowest point occurs at Lingtai County, and to the north it occurs at Huan County.

Factors controlling hydrochemistry in Luohe formation

The hydrochemical characteristics of the groundwater in Luohe formation are closely connected with the topography, geology build, geology structure, and hydrogeology condition in the Cretaceous system of the basin (Hou et al. 2004).

Upheaval in the middle of the basin

One reason for the differences of hydrochemistry value between the south region and north region is that an east–west upheaval occurs in the middle of the basin. This upheaval divides the basin into two secondary basins, the south and the north. The structure and bottom shape of the two secondary basins control the sediment facies type and distribution features of the Cretaceous system, the thickness and variety of the formation, and the configuration of water storage. They have a significant influence on the storage, and movement of groundwater and its hydrochemistry field.

Facies structure of Cretaceous system

The second reason for the differences between the north and south regions is the facies structure of Cretaceous system. Rock facies of the Cretaceous system in the whole basin are diversified. The lithology is complex, formed by two big sediment gyrations from the top down in a vertical direction. The Cretaceous system here is a multilayered structure with frequent alternation of coverage of sandstone, siltstone, and mudstone.

However, the differences between the south and north regions is quite great. The good stratification in horizontal direction and poor connectivity of vertical formation in the south region make groundwater flow mainly along the bedding planes. On the other hand, the poor stratification and good connectivity of up and down formations in the north region make the formations connect in the vertical direction and consequently the Cretaceous system functions as one thick aquifer in this area.

Tianhuan syncline

In the south region of the basin, where the stratification is good and groundwater flow is mainly along the bedding planes, the hydrochemistry field is greatly influenced by the Tianhuan syncline. The Tianhuan syncline, which travels through the basin from north to south, is asymmetrical, with a wide and gently dipping east limb and a narrow and steep west limb. The east limb, 350-km wide, is the main water storage area. It controls the distribution of the fresh water field, where the TDS of groundwater is less than 1 g/l. The hydrochemistry type belongs to HCO_3 or $HCO_3{\cdot}SO_4$. The west limb, however, is 20-km wide, where the TDS of the groundwater is 1–3 g/l, belonging to $HCO_3{\cdot}SO_4$–Na and $SO_4{\cdot}$Cl–Na types of water. Because of the Influence of the deposit environment, structure condition, and physiognomy character, the hydrochemistry field in the west limb is very complex. The axis of the syncline, influenced by the zone of fracture, forms the drainage zone of groundwater. The hydrochemistry type is various and all the three main negative ions appear here. The hydrochemistry type belongs to $SO_4{\cdot}$Cl–Na. In the south region, where the groundwater is controlled by the Tianhuan syncline and the flow is mainly along the bedding planes, the recharge zone of stream influence and the discharge zone have clear borderlines. A horizontal transition zone of hydrochemistry exists from east and north, west to the basin center. This horizontal line of demarcation is in accord with the axis of the Tianhuan syncline in the south.

In the north region, the storage and flow of groundwater in the huge thick aquifer and the hydrochemistry field are not controlled by the Tianhuan syncline. In most of the area in the east of Dongsheng to Sishili Ridge, the mineral grade of groundwater is low, belonging to HCO_3^-. Groundwater here is similar in character to the first horizontal hydrochemistry zone. The majority of data shows that the flow is from west to east, contrary to the east limb of Tianhuan syncline. It is difficult to confirm the direction of the discharge and recharge of the groundwater.

Lithofacies and paleo-geography

The hydrochemistry field in Luohe formation of the basin is closely related with the lithofacies and paleogeography. From individual lithofacies and paleogeography of early Cretaceous in the basin, the zone of high mineral grade and the zone of the most complex hydrochemistry type are accordant with the sedimentation center, shallow lakeshore facies, and medium-deep lake facies. In early Cretaceous period, the lake facies in the basin distributed in the middle and south. In the northern part of the south region, the horizontal zone division reached to west end of the Baiyu Mountain. The formation shown from lake facies had low-lying topography at that time. The horizontal division passes through the bottom of Baiyu Mountain

and connects to the south foot and north foot of Baiyu Moutain. The low-lying topography of the lake lithofacies and paleo-geography of Luohe formation coincides with the axis of the Tianhuan syncline. As a result, the groundwater flows towards the axis of the Tianhuan syncline from both sides. The syncline is also a low-lying topography of lake facies and has formed a runoff-discharge zone where the groundwater in the Luohe formation converges. Therefore, the groundwater has high TDS value and complex mineralization-grade zones and hydrochemistry types. For example, the area of the Huan County to Ning County in the south region of the basin was a low-lying deposit center in every period of early Cretaceous. It is now the drainage center of the south region, where the groundwater has the highest TDS values and the hydrochemistry is the most complex.

Conclusions

1. The Ordos Basin is short of surface water and its groundwater quality is complex. The extensive Luohe water-bearing formation is a very hopeful area for supply water. But its groundwater quality is complex. Therefore, research and mastery of the distribution features of groundwater hydrochemistry in Luohe formation is very significant for determining the recharge, flow, and, discharge features of the groundwater in Ordos Basin and evaluating regional prospective groundwater resources and exploitation potential.
2. Partition figures of groundwater mineralization grade and chemistry type show the distribution pattern of groundwater chemistry of Luohe water-bearing formation. The distribution feature of water chemistry is analyzed and realized by combining the physiography, geologic characteristic, formations, and hydrogeology of the basin.
3. This research indicates that the distribution of water chemistry can be summarized as follows:
    1. In the north region of the basin, the hydrochemistry types and mineral grade of Luohe formation have a clear horizontal zone in the direction from SEE to NWW. This shows that the southeast region is the discharge zone and the northwest region is the recharge zone.
    2. In the south region of the basin, there is a peak value zone of mineralization grade of Luohe formation at the center of Malian River valley. A horizontal zone exists from the east to the west in the east and from the southwest to the northeast in the west. This shows the southeast and southwest regions in the south are the recharge zones and the Malian River valley is the discharge zone.
4. The following regions are identified as hopeful distribution regions for water resources: most sectors of the southeast region of Sishiliang Girder in the north basin, the east region of Ziwu Mountain in the south basin, and the southwest corner of the basin. The TDS of the groundwater in these regions is less than 1 g/l; the hydrochemistry type is HCO_3 or $HCO_3{\cdot}SO_4$, belonging to fresh water.

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