

Hydrogeochemical characteristics of groundwater depression cones in Yinchuan City, Northwest China

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Abstract Groundwater in Yinchuan City has been heavily over-exploited, thus leading to the formation of depression cones in confined and phreatic groundwater environments. The depression cones have an important influence on the hydrodynamic and hydrochemical fields of groundwaters. The evolution of depression cones was analyzed on the basis of the monitoring data on groundwater level accumulated in the past 14 years. The ratio of $r\text{Cl}^-/r\text{Ca}^{2+}$ showed that phreatic water circulation was intensified, and confined groundwater was affected by external factors. Mass balance of Cl^- showed confined water mixed with about 11% phreatic water. It is shown that the alternative function of confined water was affected by external factors. At last, the evolution of groundwater hydrochemical field on the basis of groundwater chemical composition showed that phreatic water quality has been improved whereas confined water quality has been deteriorated. Saturation indices of minerals with respect to phreatic and confined waters were calculated by using PHREEQC.

Key words groundwater depression cone; hydrochemical field; groundwater cycle; saturation index

1 Introduction

Yinchuan City, the capital city of Ningxia Hui Autonomous Region, is the center of politics, economy and culture. It is located in the north of Ningxia (latitude: 38°20'–38°39'; longitude: 105°52'–106°34'), covering an area of about 1760 km² (Fig. 1). Owing to little precipitation and intensive evaporation, the local climate is a typical arid-semi-arid continental one. The average annual precipitation is 292.47 mm and evaporation is 2075.1 mm (Zhang Li et al., 2003). The evaporation is more than 7 times the precipitation.

The first confined aquifer is the main exploitation layer of water for drinking and industry in Yinchuan City. With increasing water demand and long-term underground water over-exploitation (Zhang Li et al., 2003), depression cones have been formed in aquifers in the past years. The formation of depression cones and the leakage of phreatic water to confined groundwater will cause the raise of TDS and major ions in confined water, and simultaneously the deterioration of water environmental quality.

Described in this paper are the hydrogeochemical characteristics of groundwater depression cones in Yinchuan City. In addition, further discussion is given to the evolution of groundwater depression cones, the

variation of hydrodynamic fields of phreatic and confined waters, the mixture ratio of groundwater and the evolution of hydrochemical fields.

2 The evolution of groundwater depression cones

Lithologically, the aquifers consist of fine sands, powder sands and silt. The clay layer between phreatic and confined waters is discontinuous. The water-level difference between phreatic and confined waters is about 1–3 meters. Due to long-term over-exploitation of groundwater, depression cones have been formed to different extents. The depression cones have a serious influence on water level, water quality, water recycle and hydrochemical field, which would enhance the risk of confined water contamination.

The analysis results, for confined water-level from 1991 to 2004, are shown in Figs. 2 and 3. The area of depression cones with the drawdown ≥ 10 m has been continuously increasing since 1991, and it reached the maximum in 1996. From the water column, it can be seen that the annual average increasing rate was 22 km² from 1991 to 1996 and the annual average decreasing rate was 11 km² from 1996 to 2004. The decreasing rate is half the increasing rate. The maximum drawdown of depression cones

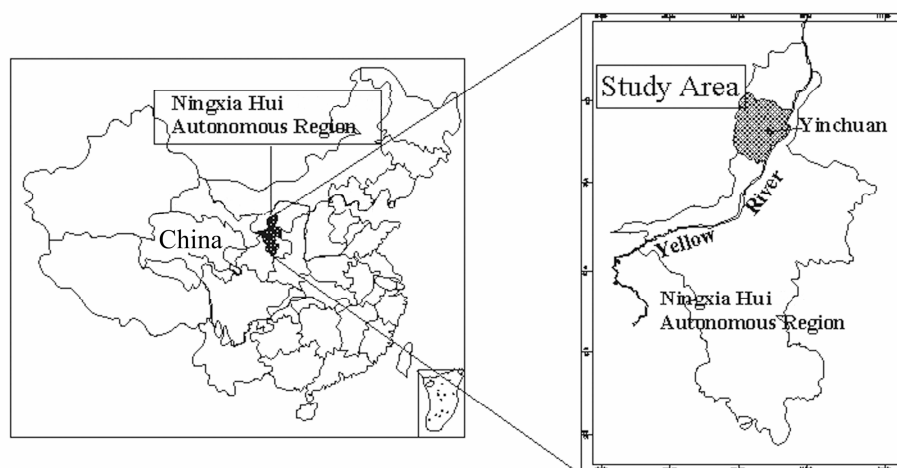


Fig. 1. Geographical location of the study area in Ningxia, China.

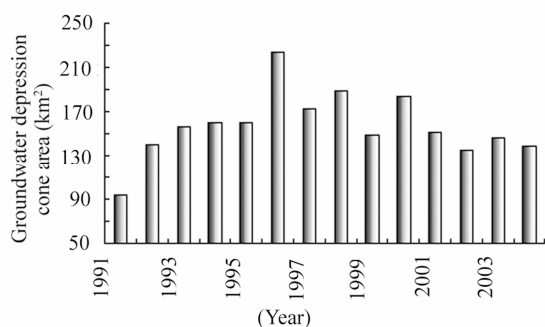


Fig. 2. The depression cone area of 10-m drawdown.

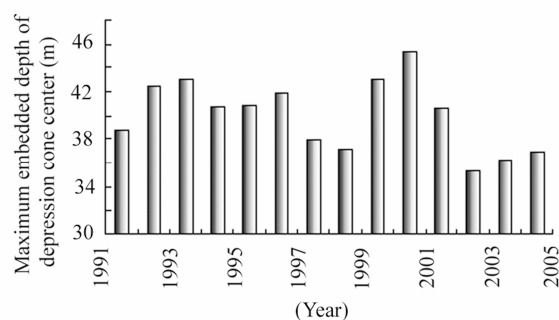


Fig. 3. Maximum embedded depth of the depression cone.

changes with the exploitation volume of groundwater, and correlates with the depression cone area. The groundwater depression cones display that the water level is controlled by the exploitation volume rather than by natural factors (Dong Zhifeng et al., 2005). Variations in groundwater area of depression cones and maximum drawdown reflect that the depression cones are in relatively stable state in recent several years.

3 Geochemical characteristics of the groundwater dynamic field

3.1 Groundwater cycle

The groundwater depression cone affects the groundwater cycle and converts natural runoff to an exploitation depression cone. The parameter rCl/rCa^{2+} can indicate groundwater flow and alternation degree and a bad hydrodynamic condition. (Wang Li, 2003). The average ratios of rCl/rCa^{2+} for phreatic and confined waters are 5.7 and 2.89, respectively, which indicates the hydrodynamic condition of confined water is better than that of

phreatic water. Obviously, the rapid circulation of confined water could be ascribed to the over-exploitation of groundwater. As seen from Fig. 4, the circulation of phreatic and confined waters experienced obvious variations from 1991 to 2004, which may be caused by varying-degree water exploitation. The flow rate at the depression cone center is estimated at 3.91–11.10 m/a, which exceeds the lateral replenishment rate (1.38 m/a) (Su Xiaosi and Lin Xueyu, 2004).

3.2 Mixing ratio of groundwater

Groundwater in Yinchuan City originates from ancient groundwater formed in geological times. In the depression cone region, the average value of tritium in confined water is about 5TU in 2003, indicating that phreatic water mixed with confined water and the latter became younger in age. According to the principle of mass balance of $\delta^{18}O$, the mixing ratio of phreatic water is usually 10%–20%, but 11.54% in the low water period (Su Xiaosi and Lin Xueyue, 2004). On the basis of the principle of mass balance of Cl⁻ (Guo Yonghai et al., 1997), the mixing

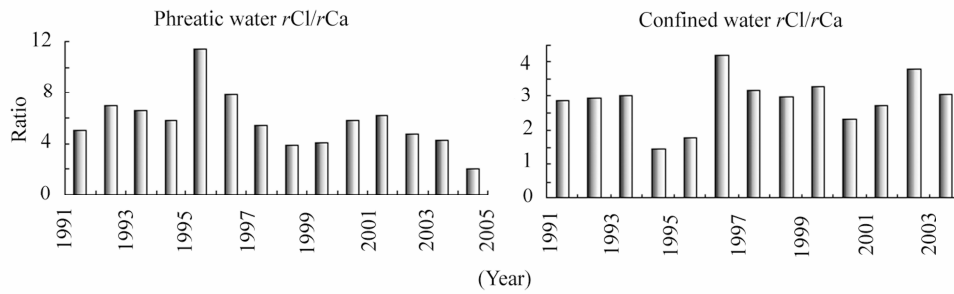


Fig. 4. rCl/rCa^{2+} ratios in phreatic and confined groundwaters.

ratio of phreatic water is 10.8% in the low water period. Obviously, the results are consistent with each other very well. The mixing ratio of phreatic water is about 11% in the depression cone center. The depression cones can make phreatic water become a supplier to confined water.

In conclusion, the depression cones have effects on groundwater cycle, groundwater flow and groundwater alternation, and can also enhance the mixing ratio of phreatic to confined water in the depression cone region. By analyzing the hydrodynamics data, it can be seen that the flow and alternation of groundwater are affected by depression cones, which is related to the depression cone area and maximum drawdown. The depression cones make phreatic water become a supplier to confined water. At present, the mixing ratio of phreatic water is about 11% in the depression cone center.

4 Geochemical characteristics of groundwater chemical field

4.1 Hydrogeochemical characteristics of phreatic water

By analyzing the available data, the hydrogeochemical characteristics of phreatic water are described as follows. The pH value varies from 7.7 to 8.16, and this indicates that phreatic water is alkaline. Such phreatic water belongs to the brackish type according to its TDS ranging from 1049.765 to 2305.16 mg/L ($TDS > 1000$ mg/L). The concentrations of HCO_3^- , SO_4^{2-} and Cl^- vary from 387.65 to 866.44, 153.7 to 433.49 and 103.8 to 331.48 (mg/L), and those of Ca^{2+} , Mg^{2+} and Na^+ range from 56.36 to 117.77, 75.33 to 113.02 and 77.67 to 484.9 (mg/L), respectively. The quality of phreatic water is greatly affected by the salinization of soil due to extensive irrigation and strong evaporation. As shown in Fig. 5, the concentrations of dissolved ions in phreatic water tended to decrease gradually from 1995 to 2004, TDS decreased annually by 120 mg/L on average, and the concentrations of SO_4^{2-} and Cl^- decreased annually by 129.5 and 227.68 mg/L, respectively.

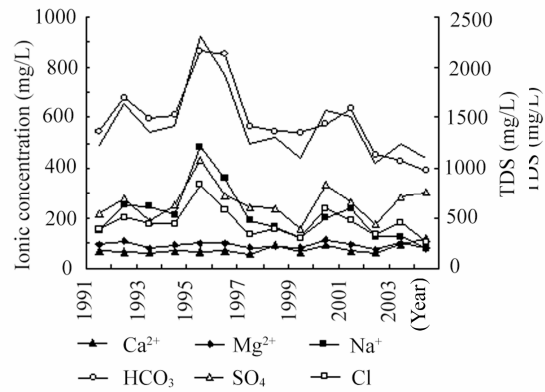


Fig. 5. Dynamic curve of phreatic water quality in the depression cones.

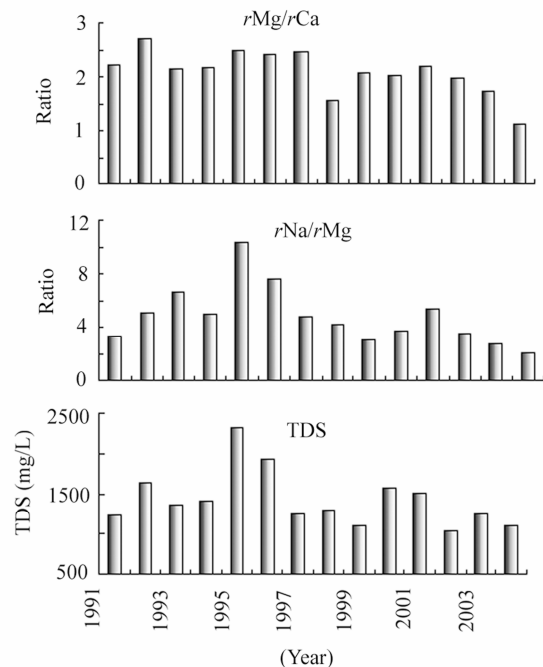


Fig. 6. rMg/rCa and rNa/rMg ratios and TDS of phreatic water.

The ratios of rMg/rCa and rNa/rMg can indicate the TDS of groundwater. When Ca^{2+} is dominant in groundwater with low TDS; with increasing TDS, the concentrations of Mg^{2+} tend to increase. With further

increasing TDS, Na^+ will become dominant (Wang Li, 2003). The ratios of $r\text{Mg}/r\text{Ca}$ and $r\text{Na}/r\text{Mg}$ for phreatic water are shown in Fig. 6, illustrating the evolution of groundwater quality with time. From 1991 to 2004, the $r\text{Mg}/r\text{Ca}$ ratio decreased slightly, and the variation of $r\text{Na}/r\text{Mg}$ ratio is well corresponding to that of TDS. It is suggested that the irrigation of the Yellow River and the variation of underground water flow in the depression cone region led to a continuous decrease in TDS of phreatic water.

As can be seen from Fig. 7, the evolutionary trend of hydrochemical type shows that phreatic water belongs to the HCO_3^- type, and the major cations vary in sort from Na^+ to Ca^{2+} and Mg^{2+} . The hydrochemical type evolves from HCO_3^- -Mg-Na toward HCO_3^- -Na-Mg and HCO_3^- -Mg-Ca with time in the rhomboid area of the Piper diagram.

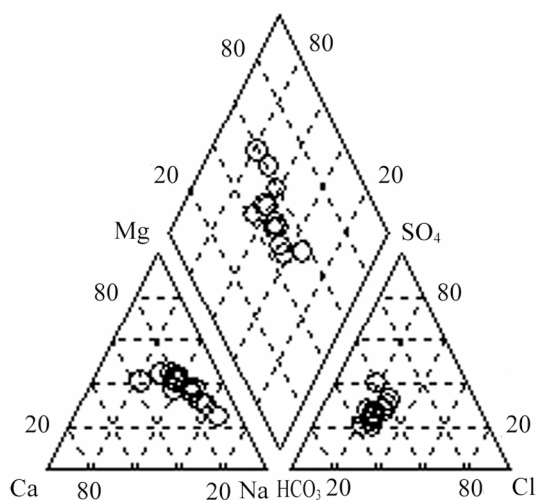


Fig. 7. Piper diagram of phreatic water.

4.2 Hydrogeochemical characteristics of confined water

The hydrogeochemical characteristics of confined water are described as follows. The pH values of confined water vary from 7.69 to 8.61, and this indicates confined water is also alkaline. TDS, a measure of water quality, ranges from 410.83 to 694.78 mg/L. Obviously, the confined water belongs to fresh water (TDS < 1000 mg/L). The concentrations of HCO_3^- , SO_4^{2-} and Cl^- vary from 192.21 to 369.15, 30.02 to 179.18 and 24.815 to 115.67 (mg/L), respectively; those of Ca^{2+} , Mg^{2+} and Na^+ range from 36.32 to 62.38, 22.94 to 61.19 and 43.3 to 123.7 (mg/L), respectively. Confined aquifers are the main exploitation layers in Yinchuan City. Because of its serious over-exploitation, the quality of confined water tends to deteriorate gradually. As seen from Fig. 8, the concentrations of ions in confined water

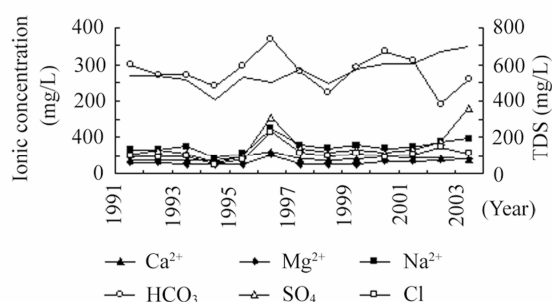


Fig. 8. Dynamic curve of confined water quality for the depression cones.

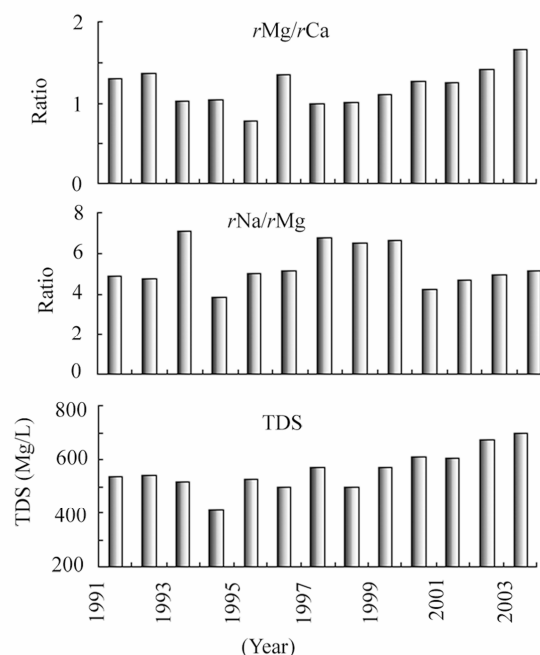


Fig. 9. Histograms of $r\text{Mg}/r\text{Ca}$ and $r\text{Na}/r\text{Mg}$ and TDS of confine water.

increased from 1991 to 2003, and the TDS and the concentrations of SO_4^{2-} and Cl^- increased by 160.18, 128.41 and 7.78 (mg/L), respectively.

The ratios of $r\text{Mg}/r\text{Ca}$ and $r\text{Na}/r\text{Mg}$ can indicate the mineralization degree of confined water. As seen from Fig. 9, the ratio of $r\text{Mg}/r\text{Ca}$ displays an increasing trend, which has been in accordance with the TDS since 1995. The ratio of $r\text{Na}/r\text{Mg}$ was variable from 1991 to 2003. That is because the phreatic water is mixed with confined water.

The type of confined water is shown in Fig. 10. The confined water belongs to the HCO_3^- type. The cations are dominated by Na^+ and Mg^{2+} . The evolutionary process of the hydrochemical type is from HCO_3^- -Na-Mg to HCO_3^- -Ca-Na and to HCO_3^- -Na-Mg, which is presented in the rhomboid area of the Piper diagram. In addition, the hydrochemical type is still controlled by natural processes in sediments.

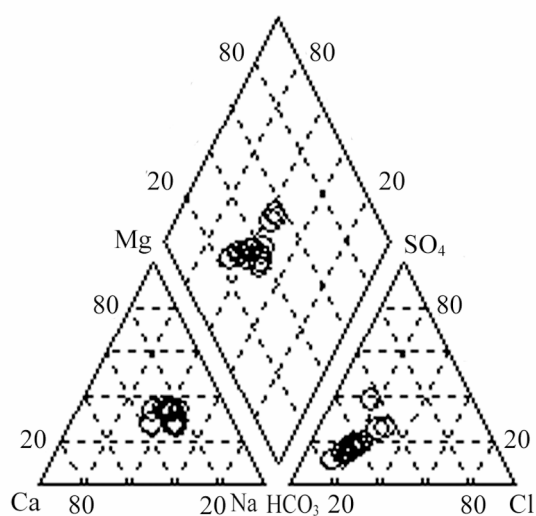


Fig. 10. Piper diagram of confined water.

In general, the pH of confined water is higher than that of phreatic water. The average value of TDS for phreatic water is 1430.93 mg/L, and that of confined water is 557.51 mg/L. The quality of confined water is better than that of phreatic water. The decrease of TDS of phreatic water may be attributed to groundwater over-exploitation, water level drop, evaporation decrease and reduction of salinization degree, so the hydrochemical type evolves from $\text{HCO}_3\text{-Mg-Na}$ toward $\text{HCO}_3\text{-Na-Mg}$ and $\text{HCO}_3\text{-Mg-Ca}$ with time, the quality of water has been obviously improved. On the contrary, owing to the over-exploitation of groundwater and the leakage of phreatic water, the TDS of confined water increases with time, and the water quality deteriorates gradually. The ratios of $r\text{Mg}/r\text{Ca}$ and $r\text{Na}/r\text{Mg}$ reflect that the TDS of phreatic water tends to decrease gradually, but that of confined water tends to increase with time. Therefore, the results are almost the same.

4.3 Geochemical characteristics of saturation index

The over-exploitation of groundwater results in the formation of depression cones which could give rise to variations in hydrochemical field and water circulation. In order to further study the characteristics of groundwater, the saturation indices of minerals with respect to phreatic and confined waters were calculated in terms of the chemical data available. The results are presented in Tables 1 and 2. The PHREEQC was used to analyze the saturation indices of the minerals calcite, dolomite and gypsum.

In Tables 1 and 2, it can be seen that calcite and dolomite are oversaturated relative to phreatic or confined water, and gypsum is unsaturated. Interaction between groundwater, which contains saturated calcite and dolomite and sufficient amounts of Ca^{2+} and CO_3^{2-} , with the gypsum layer would lead to the dissolution of gypsum (Feng Qiyan and Han Baoping, 2002). According to the common-ion effect, calcite would inevitably be deposited to keep the balance of calcite dissolution. The saturation indices of calcite and dolomite in phreatic water are higher than those of confined water, and this can be ascribed to evaporation which gives rise to the increase of constituent concentrations, thus making the minerals in groundwater reach thermodynamic instability, i.e., over-saturation. The saturation index of gypsum in confined water is lower than that of adjacent phreatic water, indicating that the dissolution of gypsum in confined water is weaker than that in phreatic water.

5 Conclusions

(1) The maximum drawdown of groundwater depression cones and 10-m drawdown area have decreased in recent 14 years. Depression cones have an influence on water circulation and hydrochemical field, and can reduce the risk of confined water contamination.

(2) The ratio of $r\text{Cl}/r\text{Ca}^{2+}$ indicates that the flow and alternation degree of groundwater are affected by depression cones, and the extent of influence correlates with the evolution of the depression cone

Table 1. Saturation indices of phreatic water minerals

Year	Calcite	Dolomite	Gypsum	Year	Calcite	Dolomite	Gypsum
1991	0.59	1.47	-1.74	1998	0.68	1.5	-1.6
1992	0.57	1.52	-1.71	1999	0.77	1.8	-1.87
1993	0.74	1.75	-1.86	2000	0.93	2.11	-1.5
1994	1.01	2.3	-1.7	2001	0.8	1.89	-1.69
1995	0.99	2.33	-1.59	2002	0.52	1.27	-1.83
1996	0.8	1.92	-1.7	2003	0.74	1.67	-1.5
1997	0.83	1.99	-1.78	2004	0.95	1.89	-1.37

Table 2. Saturation indices of confined water minerals

Year	Calcite	Dolomite	Gypsum	Year	Calcite	Dolomite	Gypsum
1991	0.58	1.22	-2.42	1998	0.41	0.77	-2.33
1992	0.45	0.98	-2.33	1999	0.72	1.43	-2.32
1993	0.66	1.28	-2.37	2000	0.63	1.31	-2.3
1994	0.95	1.87	-2.61	2001	0.7	1.44	-2.26
1995	0.94	1.72	-2.32	2002	-0.01	0.08	-2.14
1996	0.68	1.44	-1.84	2003	0.27	0.71	-1.9
1997	0.79	1.53	-2.25				

area and the variation of maximum drawdown. The depression cones may make phreatic water become a supplier to confined water. At present, confined groundwater at the depression cones mixes with 11% phreatic water in the study area.

(3) The TDS of phreatic water tends to decrease and the water quality has been improved. On the contrary, the TDS of confined water increases and the water quality deteriorates. The ratios of rMg/rCa and rNa/rMg have further verified that confined water has been mineralized.

(4) Calcite and dolomite are oversaturated and gypsum is undersaturated. The mineral saturation indices of confined water are lower than those of phreatic water.

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