Hydrochemical Characteristics and Water Quality Assessment of Groundwater in the Plain Area of the Turpan Basin (Postprint)

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Abstract

To investigate the hydrochemical characteristics and water quality status of groundwater in the plain area of the Turpan Basin, 44 sets of groundwater quality monitoring data (33 sets of phreatic water and 11 sets of confined water) were selected based on the comprehensive groundwater pollution survey data from 2015 (the most recent) in the Turpan region. Statistical analysis, Piper diagram, Gibbs diagram, and ion ratio method were employed to analyze the hydrochemical characteristics and genesis of groundwater in the study area, while the Nemerow index method, improved Nemerow index method, and fuzzy comprehensive evaluation method were used to assess groundwater quality. The results indicate that: (1) Groundwater in the plain area of the Turpan Basin is primarily weakly alkaline water with low mineralization, with hydrochemical types dominated by SO4 · Cl-Na · Ca and HCO3 · SO4-Na · Ca, followed by HCO3 · SO4 · Cl-Na · Ca; the hydrochemical composition in the study area is mainly influenced by the combined effects of evaporation concentration and rock weathering. (2) Ca2+ and Mg2+ in groundwater primarily originate from evaporite dissolution, Na+, K+, and Cl- mainly come from rock salt dissolution, while Na+ and K+ in a small portion of phreatic water are derived from silicate dissolution. (3) γ(Na+-Cl-)/γ [(Ca2++Mg2+)-γ(SO42-+HCO3-)=-1, showing a significant negative correlation, indicating that the formation of groundwater chemical components is influenced by cation exchange processes. (4) Water quality assessment results show that the proportion of Class III and above water quality exceeds 55% in all three evaluation methods, indicating relatively good overall groundwater quality; the fuzzy comprehensive evaluation method shows the lowest proportion of Class IV and V water at 27.3%, with Class IV and V water mainly distributed in Bostan Township of Toksun County and Railway Station Town and Qiketai Town east of Shanshan County.

Full Text

Hydrochemical Characteristics and Quality Evaluation of Groundwater in the Plains of the Turpan Basin

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Abstract

To investigate the hydrochemical characteristics and quality status of groundwater in the plains of the Turpan Basin, this study utilized the latest comprehensive groundwater pollution survey data from the Turpan area (2015). A total of 44 groups of groundwater quality test data were selected (33 groups of phreatic water and 11 groups of confined water). Mathematical statistics, Piper trilinear diagrams, Gibbs diagrams, and ion ratio methods were employed to analyze the hydrochemical characteristics and genesis of groundwater in the study area. The Nemerow index method, improved Nemerow index method, and fuzzy comprehensive evaluation method were used to assess groundwater quality. The results showed that: (1) Groundwater in the Turpan Basin plains is primarily weakly alkaline water with low mineralization, with hydrochemical types dominated by $SO_4 \cdot Cl\text{-}Na \cdot Ca$, followed by $HCO_3 \cdot SO_4\text{-}Na \cdot Ca$; (2) The chemical composition is mainly influenced by the combined effects of evaporation concentration and rock weathering; (3) Na^+ and K^+ in groundwater originate from rock salt dissolution, with a small amount in phreatic water coming from silicate dissolution; (4) Ca^{2+} and Mg^{2+} mainly come from evaporite dissolution; (5) The formation of groundwater chemical components is affected by cation exchange; (6) In all three evaluation methods, the proportion of grade III and higher water quality exceeded 55%, indicating generally good groundwater quality. The fuzzy comprehensive evaluation method yielded the lowest proportion of grade V water (27.3%), with grade V water mainly distributed in Bostan Township of Toksun County and Railway Station Town and Qiketai Town to the east of Shanshan County.

Keywords: Turpan Basin; groundwater; hydrochemical characteristics; quality evaluation

1 Study Area Overview

The Turpan Basin is located in eastern Xinjiang, covering the Gaocheng District, Shanshan County, and Toksun County. The basin is approximately 240 km wide from north to south and 300 km long from east to west. It is bounded by the Kumtag Desert to the east, the Jueluotag Mountains to the south, and the Tianshan Mountains to the north. Urumqi City lies to the northwest of the basin. Ayding Lake, located in the central part of the basin, represents the lowest point at -154 m elevation. Situated in the interior of the Eurasian continent at mid-latitudes, the Turpan Basin has a continental warm temperate desert climate with scarce precipitation (approximately 16 mm annually) and intense evaporation (up to 3000 mm). Summer temperatures are extremely hot, with maximum temperatures exceeding 49.6°C, earning the region its historical reputation as the "Flaming Continent." The basin enjoys abundant sunshine with over 3000 hours of annual sunlight.

Geologically, the Turpan Basin is a Tianshan intermountain depression basin. The Flaming Mountains run east-west through the basin, dividing it into southern and northern sub-basins. The northern basin contains both phreatic and confined water. Phreatic water is primarily distributed in the loose rock pore water of the piedmont alluvial-pluvial fan groups, while confined water is mainly distributed in the Qiketai area of Shanshan County in the eastern part of the northern basin, occurring as multi-layered aquifers with alternating coarse and fine-grained sediments. In the southern basin, phreatic water is distributed in a ring-shaped pattern along the basin edge, with loose sand, gravel, and pebble constituting the main aquifer lithology. Confined water is mainly distributed within the alluvial-pluvial-lacustrine plain of the southern basin, typically forming multi-layered structures of medium-coarse sand, fine silt sand, and clay. Groundwater in the study area is primarily recharged by precipitation in the plain area, seepage from canal systems and irrigation water, and lateral runoff from bedrock fissure water in the mountains. Discharge occurs mainly through evapotranspiration and extraction from mechanical wells and karez systems.

2 Methods

2.1 Sample Collection

Groundwater sampling points were distributed across the plains of the Turpan Basin. Sampling was conducted in July 2015, covering a control area of approximately 50,000 km^2. The number and density of sampling points were strictly established according to the "Specification for Regional Groundwater Contamination Investigation and Evaluation" (DZ/T 0288–2015). A total of 44 groundwater samples were collected (33 phreatic water and 11 confined water), achieving a sampling density of 1 point per 1000 km^2, which meets the precision requirements for 1:250,000-scale regional groundwater pollution investigation and evaluation.

2.2 Sample Testing

Groundwater samples were collected, preserved, and transported in strict accordance with the "Technical Specifications for Environmental Monitoring of Groundwater" (HJ/T 146–2020). Field measurements included pH, water temperature, dissolved oxygen (DO), oxidation-reduction potential (Eh), and electrical conductivity (EC). Other indicators were analyzed at the laboratory of the Second Hydrogeological Brigade of the Xinjiang Bureau of Geology and Mineral Resources. Tested parameters included K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, ${SO_4}^{2-}$, ${HCO_3}^-$, ${CO_3}^{2-}$, total dissolved solids (TDS), total hardness (TH), and other inorganic indicators.

2.3 Research Methods

The absolute values of the anion-cation balance errors for all 44 water samples were less than 5%, confirming the data reliability for analysis. This study employed classical statistical methods, Piper trilinear diagrams, Gibbs diagrams, and ion ratio methods to analyze the hydrochemical characteristics and genesis of groundwater. The Nemerow index method, improved Nemerow index method, and fuzzy comprehensive evaluation method were subsequently applied to evaluate groundwater quality in the study area.

3 Results

3.1 Hydrochemical Characteristics

3.1.1 Hydrochemical Component Content Statistical analysis revealed that the variation coefficients of confined water hydrochemical indices were significantly smaller than those of phreatic water, indicating greater spatial heterogeneity in phreatic water chemistry. Phreatic water pH ranged from 7.51 to 8.22 (mean 7.87), showing weak alkalinity. Total dissolved solids (TDS) ranged from 248.4 to 6616.6 $mg \cdot L^{-1}$ (mean 2482.0 $mg \cdot L^{-1}$). According to the TDS classification standard, groundwater can be categorized as freshwater (TDS < 1 $g \cdot L^{-1}$), brackish water (1 $g \cdot L^{-1}$ < TDS < 3 $g \cdot L^{-1}$), saline water (3 $g \cdot L^{-1}$ < TDS < 10 $g \cdot L^{-1}$), and saltwater (10 $g \cdot L^{-1}$ < TDS < 50 $g \cdot L^{-1}$). Among phreatic water samples, freshwater accounted for 6.1%, brackish water 57.6%, saline water 36.4%, and saltwater 0%. Total hardness (TH) ranged from 60.0 to 680.5 $mg \cdot L^{-1}$ (mean 519.59 $mg \cdot L^{-1}$), with classification showing extremely soft water (TH $\leq$ 75 $mg \cdot L^{-1}$) at 12.1%, soft water (75 $mg \cdot L^{-1}$ < TH $\leq$ 150 $mg \cdot L^{-1}$) at 33.3%, moderately hard water (150 $mg \cdot L^{-1}$ < TH $\leq$ 300 $mg \cdot L^{-1}$) at 15.2%, hard water (300 $mg \cdot L^{-1}$ < TH $\leq$ 450 $mg \cdot L^{-1}$) at 36.4%, and extremely hard water (TH > 450 $mg \cdot L^{-1}$) at 3.0%.

Confined water pH ranged from 7.87 to 8.38 (mean 8.11), also weakly alkaline. TDS ranged from 209.8 to 1067.2 $mg \cdot L^{-1}$ (mean 548.4 $mg \cdot L^{-1}$), with freshwater comprising 90.9% and brackish water 9.1% of samples. TH ranged from 80.1 to 680.5 $mg \cdot L^{-1}$ (mean 332.5 $mg \cdot L^{-1}$), with soft water, moderately hard water, and extremely hard water accounting for 27.3%, 54.5%, and 18.2% respectively. Comparative analysis of mean ion concentrations revealed that cations were dominated by Na^+, followed by Ca^{2+}, while anions were dominated by ${SO_4}^{2-}$, followed by ${HCO_3}^-$.

3.1.2 Groundwater Chemical Types Piper trilinear diagrams and GIS zoning maps were constructed using Origin and ArcGIS software to analyze groundwater chemical types. The results indicated that the primary hydrochemical type in the study area was $SO_4 \cdot Cl$-$Na \cdot Ca$, followed by $HCO_3 \cdot SO_4$-$Na \cdot Ca$. The $HCO_3 \cdot SO_4$-$Na \cdot Ca$ type was mainly distributed in areas north of Shanshan County seat, as well as in the southeastern parts of Dikan Township and Qiketai Town. The $SO_4 \cdot Cl$-$Na \cdot Ca$ type was predominantly found in Bostan Township and Xia Township of Toksun County, Daheyan Town, Hongliuhe Horticultural Farm, Ya' er Township, Putaogou Subdistrict, and Shengjin Township north of Gaocheng District, and in Sanbao Township and Erbao Township southeast of Gaocheng District. In Shanshan County, this type was mainly distributed in Railway Station Town and Qiketai Town. The secondary $HCO_3 \cdot SO_4 \cdot Cl$-$Na \cdot Ca$ type was primarily distributed in areas north of Toksun County seat and south of Gaocheng District, forming an east-west belt through Yilahu Township, Guolebuyi Township, Tuan Field, and Qiatekale Township.

3.2 Genesis Analysis

3.2.1 Evaporation Concentration Effect Gibbs diagrams can intuitively identify the major factors controlling groundwater chemical formation. When the ratio of $(Na^+ + K^+)/(Na^+ + K^+ + Ca^{2+})$ is plotted against TDS, points falling in the upper right indicate evaporation concentration dominance, while points in the lower left indicate rock weathering dominance. Most sampling points in the study area plotted in the middle and upper right portions of the Gibbs diagram, indicating that hydrochemical characteristics are influenced by both evaporation concentration and rock weathering. Atmospheric precipitation had negligible influence, consistent with the region' s arid climate with low rainfall and strong evaporation.

3.2.2 Ion Ratio Analysis Ion ratio methods were further employed to identify sources of chemical components. When $\gamma(Na^+ + K^+)/\gamma Cl^-$ 1, Na^+ and K^+ are primarily affected by rock salt dissolution; values significantly less than 1 indicate silicate dissolution influence. Most sampling points plotted above the y = x line, indicating that Na^+ and K^+ in the study area groundwater mainly originate from rock salt dissolution, with a small amount in phreatic water coming from silicate dissolution.

When $\gamma(Ca^{2+} + Mg^{2+})/\gamma(HCO_3{}^- + SO_4{}^{2-})$ 1, Ca^{2+} and Mg^{2+} are mainly influenced by carbonate dissolution; values less than 1 indicate evaporite or silicate dissolution influence. Most sampling points plotted below the y = x line, with a few phreatic water points above, indicating that Ca^{2+} and Mg^{2+} in the study area groundwater mainly originate from evaporite dissolution, with some phreatic water Ca^{2+} and Mg^{2+} coming from carbonate dissolution.

When $\gamma(SO_4{}^{2-} + Cl^-)/\gamma HCO_3{}^- > 1$, groundwater chemistry is dominated by evaporite dissolution; values less than 1 indicate carbonate dissolution dominance. The ratio $\gamma(Na^+ + K^+ - Cl^-)/\gamma[(Ca^{2+} + Mg^{2+}) - (SO_4{}^{2-} + HCO_3{}^-)]$

showed a significant negative correlation, indicating that cation exchange affects the formation of groundwater chemical components in the study area.

4 Groundwater Quality Evaluation

4.1 Evaluation Process Example

Based on the 44 groundwater sample datasets from the Turpan Basin plains and using the "Standard for Groundwater Quality" (GB/T 14848–2017) as the benchmark, evaluation factors with high detection rates and exceeding-standard values were selected for groundwater quality assessment. The Nemerow index method and improved Nemerow index method involve relatively simple calculation processes and are therefore omitted here. The fuzzy comprehensive evaluation method involves more steps and complex calculations, so this section details its evaluation process using sampling point D7 (confined water) as an example.

4.1.1 Establishing Evaluation Factor Set and Evaluation Set The evaluation factor set is U = {TDS, TH, Na^+, SO_4^{2-}, Cl^-, Fe, Mn, NO_3^-, F^-, NH_4^+, COD}; the evaluation set is V = {I, II, III, IV, V}.

4.1.2 Establishing Weight Matrix A for Evaluation Factors Weight calculations for each evaluation factor are shown in Table 3. The weight matrix A for sampling point D7 is: A = [0.111 0.113 0.093 0.068 0.128 0.067 0.030 0.029 0.187 0.168 0.006]

4.1.3 Establishing Fuzzy Evaluation Matrix R This evaluation divided groundwater quality into five grades. The "Standard for Groundwater Quality" (GB/T 14848–2017) does not specify separate standard values for grade V, instead stipulating that values greater than the grade IV standard constitute grade V. Based on symmetry principles, the grade V standard value was defined as $S_5 = 2S_4 - S_3$. Membership functions for each grade were constructed according to the standard values. Using the D7 sampling point data, membership degrees for all five grades were calculated to establish the fuzzy evaluation matrix R. Although each evaluation factor requires calculation of membership degrees for all five grades—a process that is computationally intensive and tedious—Matlab software was used to calculate the fuzzy evaluation matrices for all 44 sampling points. The fuzzy evaluation matrix for the D7 sampling point is: R = [0 0 0 0.47 0.53; 0 0 0 0.38 0.62; 0 0 0 0.45 0.55; 0 0 0 0.40 0.60; 0 0 0 0.50 0.50; 0 0 0.20 0.80 0; 0 0 0.60 0.40 0; 0 0 0.30 0.70 0; 0 0 0 0.20 0.80; 0 0 0 0.30 0.70; 0 0 0.50 0.50 0]

4.1.4 Establishing Evaluation Result Matrix B Using the fuzzy mathematical model $B = A \cdot R$, the evaluation matrix B was calculated. The water quality grade corresponding to the maximum membership degree in B represents the fuzzy comprehensive evaluation grade. For the D7 sampling point, B = [0

0 0.018 0.412 0.570], indicating grade V water quality. The same method was applied to calculate water quality grades for all other sampling points (Table 4).

5 Results and Analysis

The evaluation results from the three methods are presented in Table 5. The Nemerow index method identified 27 grade III and above water quality points, accounting for 61.3% of total samples, and 17 grade V points (38.7%). The improved Nemerow index method identified 25 grade III and above points (56.8%) and 19 grade V points (43.2%). The fuzzy comprehensive evaluation method identified 32 grade III and above points (72.7%) and 12 grade V points (27.3%). These results demonstrate certain differences among the three methods. The improved Nemerow index method and fuzzy comprehensive evaluation method show better alignment with the recommended Nemerow index method (single-factor scoring method) in the "Standard for Groundwater Quality" (GB/T 14848–93), with a consistency of 52.3%. The improved Nemerow index method and Nemerow index method show the highest consistency, but the Nemerow index method overemphasizes the impact of the maximum single component value when calculating the comprehensive score, assuming all evaluation factors equally affect groundwater quality. The improved Nemerow index method assigns different weights to evaluation factors, weakening the maximum value influence, resulting in a reduced grade V proportion of 43.2% compared to the Nemerow index method. The fuzzy comprehensive evaluation method yielded the lowest grade V proportion (27.3%) because it comprehensively reflects water quality by constructing membership functions that consider the proximity to each water quality standard and incorporating evaluation factor weights.

Based on the fuzzy comprehensive evaluation results, a groundwater quality zoning map was prepared (Figure 7). Most groundwater in the Turpan Basin plains is grade III or better, with grade V water mainly distributed in Bostan Township of Toksun County and Railway Station Town and Qiketai Town to the east of Shanshan County.

6 Conclusions

(1) Both phreatic and confined water in the Turpan Basin plains are weakly alkaline. The proportions of freshwater and soft water in confined water are higher than in phreatic water. Cations are dominated by Na^+, followed by Ca^{2+}; anions are dominated by $SO_4{}^{2-}$, followed by $HCO_3{}^-$. The main hydrochemical types are $SO_4 \cdot$Cl-Na$\cdot$Ca and $HCO_3 \cdot SO_4$-Na$\cdot$Ca, followed by $HCO_3 \cdot SO_4 \cdot$ Cl-Na $\cdot$ Ca.

(2) Groundwater hydrochemical characteristics in the study area are primarily influenced by the combined effects of evaporation concentration and rock weathering, with negligible influence from atmospheric precipitation. Na^+ and K^+ in groundwater mainly originate from rock salt dissolution, with a

small amount in phreatic water coming from silicate dissolution. Ca^{2+} and Mg^{2+} mainly come from evaporite dissolution. Additionally, groundwater in the study area is affected by cation exchange processes.

(3) According to the three water quality evaluation methods, the proportion of grade III and above water quality exceeds 55%, indicating generally good groundwater quality. The improved Nemerow index method and Nemerow index method show the highest consistency (56.8%). The fuzzy comprehensive evaluation method yielded the lowest grade V water proportion (27.3%), as it comprehensively considers the proximity to each water quality standard and incorporates evaluation factor weights. Grade V water is mainly distributed in Bostan Township of Toksun County and Railway Station Town and Qiketai Town to the east of Shanshan County.

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Note: Figure translations are in progress. See original paper for figures.