Hydrochemical Characteristics and Quality Assessment of Shallow Groundwater in Poultry Farming Sites in Suzhou City, China

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Abstract

In recent years, the impact of the excrement from large-scale poultry farms on the quality of shallow groundwater has attracted widespread attention. In the present study, the hydrogeochemical characteristics of shallow groundwater around poultry farming sites in the town of Zhuxianzhuang in Suzhou, Northern Anhui, China, were investigated using various statistical techniques, a Piper trilinear diagram, ion combination ratios, correlation analysis, and a fuzzy comprehensive evaluation method. The results show that the shallow groundwater in the area is dominantly of the HCO3–Ca type. The relative abundances of the major cations and anions in the groundwater are in the order Na+>Ca2+>Mg2+ >K+ and HCO3−>Cl−>SO42−>NO3−> F−, respectively. According to the concentrations and distribution of tri-nitrogen in the groundwater, pollution is mainly associated with domestic wastewater, followed by poultry farm waste. The most severe pollution involves NO2–N, and this adversely impacts the potability of the shallow groundwater. The leaching of rocks and silicate weathering are the principal processes responsible for the ionic composition of the shallow groundwater in the study area. Class I, II, and III waters account for 9.52%, 28.57%, and 61.90%, respectively, of the groundwater in the area. The shallow groundwater is suitable for high salinity-tolerant plants or soils associated with good leaching conditions. Future water management in the poultry farming area should prioritize the control of shallow groundwater nitrite pollution.

Keywords: poultry farming sites, shallow groundwater, hydrochemical characteristics, water quality assessment, Zhuxianzhuang Town of Suzhou City

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Introduction

Owing to the development of large-scale intensive poultry farms, the surrounding environment, especially the quality of shallow groundwater, is commonly affected. In fact, approximately 3.8 billion tons of manure associated with animals are produced in China annually [1]. In addition to the high organic matter content in undigested feed, including proteins, amino acids, and other nitrogen-containing substances, manure from poultry usually contains high concentrations of trace elements and agents of infection [2-3]. In the absence of effective management, the groundwater resources surrounding the source areas of such manure are susceptible to pollution [4]. Shallow groundwater, which is closest to the surface, is easily influenced by the superficial environment, however, it is a crucial resource utilized for irrigation, aquaculture, and domestic needs. Therefore, the pollution of shallow groundwater resources through the superficial environment directly affects the health of residents in the impacted areas. Thus, knowledge of the hydrogeochemical characteristics and quality of shallow groundwater is crucial for the preservation of this resource and the rational operation of poultry farming sites.

Several studies on groundwater and the pollution associated with poultry farming sites have been conducted previously. Cruz et al. [5], for example, reported that shallow groundwater quality degradation in northern Argentina was linked to poultry farming based on the monitoring of quality parameters, including microbiological aspects. Kim et al. [6] investigated the relationship between hydrochemical processes in shallow groundwater and poultry farms in Korea based on the relationship between the Ca\(^{2+}\)+Mg\(^{2+}\) and HCO\(_3\)\(^{-}\) concentrations and principal component analysis (PCA), and indicated that nitrate pollution from the farms enhanced the weathering of aquifers, which increased the salinity of the groundwater. In addition, studies on the environmental impact of poultry farms on surface water in areas around poultry farms [7] and the pollution characteristics of heavy metals, nitrogen, and phosphorus in poultry manure [8-9] have also been conducted.

In the present study, poultry farming sites in the town of Zhuxianzhuang in Suzhou, Anhui Province, China, were selected and the hydrogeochemical characteristics and quality of the shallow groundwater around these sites were investigated. Suzhou, which covers an area of 9,787 km\(^2\), is a major city in the north of Anhui Province and hosts a population of 6.58 million, with agriculture as one of the principal activities in the area. In fact, agriculture and poultry farming are the primary activities in the town of Zhuxianzhuang in Suzhou. The poultry farms involve mainly semi-industrial and industrial production systems, and degradation in septic tanks is the primary method for the treatment of poultry waste. Moreover, shallow groundwater is the main source for irrigation, poultry breeding, and domestic requirements in the area.

The major objectives of the present study were to: (1) determine the hydrochemistry of the shallow groundwater in the impact zones of poultry farming sites; (2) evaluate the water quality of the shallow groundwater at the poultry farming sites against recognized standards; and (3) investigate the tri-nitrogen characteristics of poultry farming and their relationship with groundwater quality.

Materials and Methods

Study Area

The poultry farming sites in Zhuxianzhuang are in the east of Suzhou (Fig. 1b), and these can be partitioned into two major farms (X00 and X05). The study area is between the longitudes 117°4′4" E and 117°10′44" E and latitudes 33°33′16" and 33°37′46" N. The X00 poultry farm covers an area of 30000 m\(^2\), and accounts for more than 15,000 chickens annually. The X05 poultry farm is approximately 2.4 km to the northeast of the X00 farm and covers an area of approximately 1000,000 m\(^2\); more than 10,000 chickens are produced by the farm annually.

The study area is characterized by a typical warm temperate semi-humid monsoon climate, involving a hot and rainy summer. The average, maximum, and minimum annual temperatures in the area are 14.6, 40, and –12.5°C, respectively, while the annual rainfall varies between 774 and 855 mm, and the annual mean evaporation is 832.4 mm [10].

Loose Quaternary sediments in the area are 200-300 m thick. These sediments host four aquifers from top to bottom. The first aquifer, which is the shallowest, exhibits a mean thickness of 30 m, and it comprises silty and fine sands as well as clay. The groundwater in this aquifer is referred to as “shallow groundwater” and occurs at depths of 3-5 m from the surface [10-11].

Sampling and Measurements

Water samples were collected from 21 household wells in the study area in August 2020. The sampling and preservation of the water samples were conducted in accordance with the procedures in the Groundwater pollution investigation and evaluation specifications (DD2008-01) and Water and wastewater detection and analysis methods (Fourth Edition). The wells were pumped for 5 min before sampling to collect fresh samples and the sampling bottles were washed thrice using the well water. After sampling, the bottles were sealed, transported to the laboratory, and stored at 4°C for subsequent testing. The electrical conductivity (EC), pH, and total dissolved solids (TDS) were measured in situ via a portable OHAUS instrument (Shanghai,
China), while the locations of the sampling sites were obtained using a GPS.

Twenty-one 50-mL polyethylene bottles were used to store filtered (0.22 μm Millipore membrane filter) water samples for the measurement of dissolved ions. Analyses of Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻, F⁻, SO₄²⁻ were performed using ion chromatography (ICS-600-900), while the HCO₃⁻ concentration was determined using acid–base titration. The oxygen (¹⁸O) and deuterium (D) isotope compositions of the groundwater samples were measured using an LGR-LWIA-45EP. The concentrations of nitrate (NO₃⁻N), nitrite (NO₂⁻N), and ammonium (NH₄⁻N) were analyzed using ultraviolet spectrophotometry, spectrophotometry, and Nessler’s Reagent Spectrophotometry, respectively. The total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) were determined using the potassium persulfate digestion ultraviolet spectrophotometry, ammonium molybdate spectrophotometry, and dichromate methods, respectively. Ten percent of the samples were analyzed in duplicate, and the associated errors were <5%.

Analytical Methods

Quality Assessment of Irrigation Water

The sodium percentage (%Na) is used to highlight the alkali hazard, because the replacement of calcium and magnesium with excess sodium in irrigation causes poor soil drainage [12]. The Na% was calculated based on the following expression:

\[
Na\% = \frac{Na^+}{Na^++Ca^{2+}+Mg^{2+}+K^+} \times 100
\]  

The sodium adsorption ratio (SAR) is employed to characterize the suitability of water for irrigation. It reflects the alkali/sodium hazard for crops [13], and is determined using the following equation:
where \( a_i \) is the normalized weight of indicator \( i \) and \( \sum_{i=1}^{n} W_i \) represents the sum of weights for all water quality indicators. The normalized results are listed in matrix \( A \), while the water quality evaluation was achieved through the fuzzy membership calculation of matrix \( B \), as expressed in Eqs (9) and (10)

\[
A = [ a_1 \ a_2 \ ... \ a_n ]
\]

\[
B = A \cdot R
\]

According to the values obtained from matrix \( B \), the class of the water quality is determined from the order of the maximum value.

**Statistical Analysis**

ArcGIS 10.5 was used to produce a map of the study area indicating the locations of the water sampling sites. AqQA software (version 1.5) was utilized to construct the Piper diagrams, while the statistical analysis of the water chemistry data was performed using OriginPro 9.1 and R 4.0.3.

**Results and Discussion**

**Hydrogeochemical Characteristics**

Descriptive statistics were employed to highlight the characteristics of the water chemistry parameters. As presented in Table 1, the pH values for the water samples range from 7.39 to 9.37 (mean = 7.79), and these indicate an overall weakly alkaline character for the shallow groundwater in the region. The TDS values, which vary from 360 to 795 mg/L (mean = 558.16 mg/L), are within the limits recommended by the World Health Organization drinking water quality standard (1000 mg/L) [15] and Chinese national standard GB 5749-2006 (1500 mg/L) [16]. Therefore, the shallow groundwater in the study area is suitable for drinking. The concentrations of Ca\(^2+\), Mg\(^2+\), Na\(^+\), and K\(^+\) correspondingly range from 31.39 to 106.45 mg/L (mean = 56.63 mg/L), 20.11 to 75.14 mg/L (mean = 40.53 mg/L), 21.82 to 187.37 mg/L (mean = 86.05 mg/L), and 0 to 0.70 mg/L (mean = 0.09 mg/L). The concentrations of \( F^- \), \( Cl^- \), \( SO_4^{2-} \), \( HCO_3^- \), and \( NO_3^- \) range from 0.76 to 2.76 mg/L (mean = 1.37 mg/L), 4.88 to 181.54 mg/L (mean = 66.31 mg/L), 19.06 to 162.79 mg/L (mean = 46.30 mg/L), 382.06 to 700.44 mg/L (mean = 498.80 mg/L), and 0 to 102.63 mg/L (mean = 9.94 mg/L), respectively. In addition, the TN values range from 0 to 1801.78 mg/L (mean = 132.01 mg/L), while the COD values vary from 0 to 12.04 mg/L (mean = 4.44 mg/L).

Based on the average concentrations, the shallow groundwater in the study area is dominated by Na\(^+\) and HCO\(_3^-\). The measured data reveal that the major cations are in the order Na\(^+\)>Ca\(^{2+}\)>Mg\(^{2+}\)>K\(^+\), while the anions...
follow the order HCO₃⁻ > Cl⁻ > SO₄²⁻ > NO₃⁻ > F⁻. In general, Na⁺ in the groundwater is attributed to the dissolution of sodium-containing minerals and/or ion exchange [17].

Similar assessments of shallow groundwater quality at poultry farms sites have been conducted in other parts of the world [6, 18-20], and the results are listed in Table 2. Except for K⁺, the concentrations of other cations (Na⁺, Ca²⁺, and Mg²⁺) in this study are higher than those in Ordos Basin, Netherlands, South Korea, and Young-am City. The concentrations of HCO₃⁻, Cl⁻, and F⁻ in other areas are lower than those in this study, whereas the concentration of SO₄²⁻ in the Netherlands [19] is 3.5 times higher than that in this study. The concentrations of NO₃⁻ in Young-am City, South Korea [20], and South Korea [6] are 5.3 and 3.3 times that in this study, respectively. The concentration of NO₃⁻ in this study is 2.6 times that in the Netherlands [19]. The concentration of NO₃⁻ in the Ordos Basin is 4.7 times higher than that in this study. The concentration of NH₄-N in this study is different to that in the Netherlands [19], but higher than that in Young-am City [20] and the Ordos Basin [18]. This shows that the hydrochemical components of the shallow groundwater in this study are affected by human activities.

The Piper diagram created to provide a hydrochemical classification [21-23] of the samples is shown in Fig. 2. The data for cations in the shallow groundwater samples from the study area are mainly in zone B, while the data for anions are plotted principally in zone E. Based on this diagram, the groundwater samples from the study area are mainly of the HCO₃⁻-Ca type (90.48%).

According to the coefficient of variation (CV), the water quality parameters are in the order TN>NO₃⁻>NO₃-N>K⁺, and their values of >00 indicate that these parameters are susceptible to external contributions [24]. Considering the paucity of natural NO₃⁻ in rocks, an NO₃⁻ concentration of >5 mg/L usually indicates pollution from animal waste, fertilizer, or wastewater [17]. NO₃-N generally originates from the sewage of poultry farms, municipal wastewater discharge, fertilizers, and the atmosphere [25].

Correlation Analysis of Ions

Correlation analysis is valuable for highlighting elements from identical or similar sources [26]. In Fig. 3, Ca²⁺ and Mg²⁺ exhibit strong positive correlations with SO₄²⁻, indicating that, in the groundwater in the study...
In the study area, these cations were probably derived from the same source. Moreover, the moderate correlation between $SO_4^{2-}$ and $NO_3^{-}$ suggests that the former originates from chemical fertilizers or pesticides. Conversely, the positive correlation between TP and $K^+$ indicates that, in the shallow groundwater in the study area, the former is probably derived from agricultural non-point source pollution.

Mechanisms Associated with Groundwater Composition

The principal mechanisms that control the composition of groundwater are weathering, atmospheric precipitation, and evaporation-crystallization [27]. According to the Gibbs diagram (Fig. 4), the primary mechanism responsible for the chemistry of the shallow groundwater in the study region is weathering, while dissolution enhances the concentrations of some ions. In addition, in Fig. 4a), the sample data are clustered where the $Na^+/(Na^+ + Ca^{2+})$ values generally exceed 0.5. These results suggest that the shallow groundwater in the study area is significantly impacted by the cation exchange process [28].

The molar ratios of major ions are commonly utilized to identify chemical processes associated with groundwater and evaluate the sources of dissolved ions [30-32]. For example, $Na^+/Cl^-$ close to unity indicates that the dissolution of rock salt is the main source of $Na^-$.
in groundwater [30]. Conversely, a ratio of 1 implies that Na+ is principally introduced to groundwater through the weathering of silicates [30, 33]. In the present study, the Na+ + K+/Cl− ratios are mostly >1 (Fig. 6a), indicating that, in addition to the dissolution of rock salt, the weathering of silicates (e.g., albite and K-feldspar) is another important source of Na+ + K+ in the shallow groundwater. Ca2+/HCO3− ratios close to or less than 1 suggest that the weathering of calcite is the main source of these ions in groundwater [21, 33]. As shown in Fig. 6b), the data for most of the samples studied are near the 1:2 line, which indicates that the weathering of dolomite is the main contributor of Ca2+ and HCO3− in the shallow groundwater. Similarly, the dissolution of gypsum produces a Ca2+/SO42− ratio close to 1 for groundwater [31]. In the present study, the correlation

Fig. 3. Correlation chart involving 13 variables for shallow groundwater samples from the poultry farming sites.

Fig. 4. Gibbs diagrams highlighting the hydrochemical processes responsible for the compositions of shallow groundwater from the poultry farming sites based on a) cations and b) anions.
between Ca$^{2+}$ and SO$_4^{2-}$ is weak ($R^2 = 0.40$), and the data for all samples are plotted above the 1:1 line (Fig. 6c). These results demonstrate that the dissolution of gypsum and anhydrite is not the principal mechanism responsible for the presence of these ions in the studied shallow groundwater. In addition, the dissolution of dolomite causes the Ca$^{2+}$/Mg$^{2+}$ ratio to fall near the 1:1 line, while ratios close to 2 indicate higher contributions from calcite [34]. In the present study, data for only a few samples are plotted between the 1:1 and 1:2 lines (Fig. 6d). The excessive Mg$^{2+}$ in the samples shows that, although the dissolution of dolomite contributes, it is not the main process responsible for the concentrations of Mg$^{2+}$ in the shallow groundwater. According to Lin et al. [33], the dissolution of carbonates and sulfates produces a Ca$^{2+}$+Mg$^{2+}$/HCO$_3^-$+SO$_4^{2-}$ ratio close to 1. Data for few samples in the present study are plotted near the 1:1 line, while most fall under the 1:1 line (Fig. 6e). These results rule out the dissolution of sulfate as the main process responsible for these ions in the groundwater, although the dissolution of carbonate certainly contributed [35]. The data for most samples are plotted between the 1:1 and 1:2 lines (Fig. 6f), confirming that the dissolution of carbonate is not the primary source of the Ca$^{2+}$ and Mg$^{2+}$ in the studied groundwater.

The ion exchange reaction can be inferred from the relationships between the Ca$^{2+}$+Mg$^{2+}$–SO$_4^{2-}$+HCO$_3^-$ and Na$^+$+K$^+$ ions. If cation exchange reactions are involved, these ions are expected to exhibit ratios close to –1 [37]. In the present study, the strong positive correlations ($R^2 = 0.95$) between these ions (shown in Fig. 6g) indicate that cation exchange reactions are involved. The chlor-alkali index (CAI) reflects direct or reverse cation exchange reactions. In Fig. 6h, the data for most water samples are in the area characterized by CAI values of <0, which indicates that the Mg$^{2+}$ and Ca$^{2+}$ in the shallow groundwater are associated through ion exchange reactions with the Na$^+$ and K$^+$ in rocks [35], with minimal occurrence of the opposite process. Consequently, the concentrations of Na$^+$ and K$^+$ in the groundwater are increasing, while those of Mg$^{2+}$ and Ca$^{2+}$ are decreasing.

Analysis of the Composition of Stable Isotopes

The δD values for the samples presented in Table 1 vary from −56.27 to 46.29‰ (−51.63‰), while those for δ$^{18}$O range from −8.41 to 6.49‰ (−7.50‰). The relationship between δ$^{18}$O and δ$^2$H for water in the atmosphere varies within a range near the global meteoric water line (GMWL), which is expressed as δ$^2$H = 8δ$^{18}$O + 10 (Craig 1961). Conversely, the local meteoric water line (LMWL) is expressed as δ$^2$H = 7.8δ$^{18}$O + 8.2 [36]. According to the relationship between δ$^{18}$O and δ$^2$H shown in Fig. 7, the water sample data are mostly under the GMWL and LMWL, which illustrates that precipitation is the main large-scale recharge source for the shallow groundwater in the study area [37-39]. In addition, the fitting of data for the water samples produced good results ($R^2 = 0.64$), and this further indicates that other sources contributed to the groundwater in the study area [40]. In fact, the data for samples X02, X12, and X16, which are plotted far from the GMWL and LMWL, suggest that the groundwater in these sites involves significant contributions from another source.

Overall, the relationship between the δ$^{18}$O and δ$^2$H for the shallow groundwater in the poultry farming sites in Zhuxianzhuang can be expressed as follows:

$$\delta^2H = \frac{4.46 (\pm 0.74)}{\delta^{18}O - 18.19}$$

$$\left(\pm 5.55\right); \ R^2 = 0.64$$  (11)
Fig. 6. Relationships between the major ions in shallow groundwater samples from poultry farming sites.
Water Quality Assessment

Assessment of the Water Quality for Drinking

The shallow groundwater in the study area is mainly exploited as a drinking water resource by the local residents. According to the groundwater quality standard (GB/T 14848-2017) [41] and drinking water quality standard (GB/T 5749-2006) [16], the data for the groundwater samples produce five classes (Table 3). The fuzzy comprehensive assessment (Eqs (3)–(10)) shows that the samples are categorized into Classes I, II, and III, which account for 9.52%, 28.57%, and 61.90%, respectively, of the total shallow groundwater samples (Fig. 8). This indicates that the shallow groundwater in the study area is suitable for landscape entertainment, and industrial and agricultural water use. Overall, the shallow groundwater in the study area is suitable for drinking.

Assessment of the Water Quality for Irrigation

In the study area, the shallow groundwater is also the main source of water for the irrigation of farms. Therefore, the electrical conductivity, SAR, and Na% data for the samples were plotted in USSSL (Fig. 9a) [41] and Wilcox (Fig. 9b) [43] diagrams to assess the suitability of the groundwater for irrigation. According to the data in these diagrams, 21.9% (X08, X13, and X00) of the water samples are rated excellent to good for irrigation. These water samples, which fall in the C2–S1 (medium salinity and low sodium content) category, indicate that the quality of the shallow groundwater studied is suitable for plants that grow under moderate leaching conditions or possess moderate salinity tolerance [13]. The percentage representing good to permissible is 65.85%, and these samples are in the C3–S1 (high salinity and low sodium content) category. This suggests that the groundwater could be used to irrigate soils with leaching and good drainage.

Table 3. Groundwater quality classification for drinking and irrigation.

<table>
<thead>
<tr>
<th>Class</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>NH₄-N</th>
<th>NO₂⁻N</th>
<th>NO₃⁻N</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>50</td>
<td>50</td>
<td>0.02</td>
<td>0.01</td>
<td>2</td>
<td>Drinking, Irrigation</td>
</tr>
<tr>
<td>II</td>
<td>150</td>
<td>150</td>
<td>0.10</td>
<td>0.10</td>
<td>5</td>
<td>Drinking, Irrigation</td>
</tr>
<tr>
<td>III</td>
<td>250</td>
<td>250</td>
<td>0.50</td>
<td>1.00</td>
<td>20</td>
<td>Drinking, Irrigation</td>
</tr>
<tr>
<td>IV</td>
<td>350</td>
<td>350</td>
<td>1.50</td>
<td>4.80</td>
<td>30</td>
<td>Irrigation</td>
</tr>
<tr>
<td>V</td>
<td>&gt;350</td>
<td>&gt;350</td>
<td>&gt;1.50</td>
<td>&gt;4.80</td>
<td>&gt;30</td>
<td>Not suitable</td>
</tr>
</tbody>
</table>

Units: Ion concentration (mg/L), TDS (mg/L).
Plants that can tolerate high salinity are required in this soil to minimize the occurrence of a salinity hazard. In general, the salinity of the groundwater in the study area requires reduction before its utilization for irrigation.

Evaluation of the Tri-nitrogen Data

Characteristics of the Tri-nitrogen Data

The concentrations of tri-nitrogen in groundwater are useful for highlighting the contribution of anthropogenic activities to the pollution of shallow groundwater in poultry farming areas. Nitrate, ammonia, and nitrite formation are associated with the decomposition of protein-containing organic matter in groundwater. Therefore, the presence of protein in groundwater indicates contamination from anthropogenic activities [31]. According to the data in Fig. 10, the NO₃⁻-N concentrations for the samples are ≤17.98 mg/L (mean = 1.91 mg/L), while

Fig. 10. Box charts of tri-nitrogen in water samples from the study area. The dotted lines in blue, red, and green represent the limits of the NH₄-N, NO₂-N, and NO₃⁻-N concentrations, respectively, for the national standard (GB/T 14848-2017).
the concentrations of NO$_2$–N and NH$_4$–N range from 0.45 to 2.73 mg/L (mean = 1.33 mg/L) and 0.05 to 0.63 mg/L (mean = 0.25 mg/L), respectively. The concentrations of NO$_3$–N in the water samples are within the acceptable limits stated in the Chinese national standard (20 mg/L; GB/T 14848-2017), while the NO$_2$–N concentrations of 14 samples (>66.7%) exceed the acceptable limit of the standard (1.00 mg/L). Additionally, 9.52% of the samples show NH$_4$–N concentrations higher than the acceptable limit defined in the national standard (0.50 mg/L). Therefore, the most serious tri-nitrogen pollutant in the shallow groundwater of the poultry farming sites in Zhuxianzhuang is NO$_2$–N, followed by NH$_4$–N, and NO$_3$–N.

**Distribution Characteristics of Tri-nitrogen**

To further assess the contamination of shallow groundwater caused by the poultry farms, maps showing the distributions of the concentrations of NO$_3$–N, NO$_2$–N, and NH$_4$–N in the study area were created (Fig. 11). The concentrations of NO$_3$–N for most sampling sites were low (<20 mg/L), while those for NO$_2$–N were generally >1 mg/L. The irregular variation in the pollution involving NO$_2$–N originates mainly from the indiscriminate treatment and disposal of domestic wastewater, followed by the waste from the poultry farms. The concentrations of NH$_4$–N in groundwater in the farm sites are relatively high, and these suggest significant contamination of groundwater from the poultry farms.

The results of the drinking water quality assessment were compared with those for the spatial distribution of the tri-nitrogen concentrations. This revealed that samples X07 and X20 belong to Class I, while samples X10, X13, X15, X16, X17, and X19 are in Class II. The concentrations of NO$_2$–N in samples X15, X16, and X17 exceed that of the standard. All other samples fall into Class III, mainly because the concentrations of NO$_2$–N in samples X01, X02, X03, X04, X06, X08, X09, X11, X12, X14, and X18 exceed that of the standard. Sample X08 in Class III also exhibits an NH$_4$–N concentration that is higher than that of the standard. Therefore, the water quality indicators that commonly showed values higher than the limits in the standard are NO$_2$–N and NH$_4$–N. Similarly, at the site of sample X08, the reaction of carbonate and silicate rocks with NH$_4^+$ to produce Ca$^{2+}$ and Mg$^{2+}$ reduces the SAR value (see Eqs (14)), improving the quality of the shallow groundwater for irrigation.

\[
\text{Ca}_{(1-x)}\text{Mg}_x\text{Al}_2\text{Si}_2\text{O}_8 + \text{NH}_4^+ + 2\text{O}_2 = (1-x)\text{Ca}^{2+} + x\text{Mg}^{2+} + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + \text{NO}_3^- \quad (14)
\]

**Conclusions**

In the present study, shallow groundwater in Suzhou, China, was investigated, and the main findings are summarized as follows:

(1) The shallow groundwater in the study area was dominantly of the HCO$_3$–Ca type. Data for the concentrations of the major cations produced the order Na$^+$ >Ca$^{2+}$ >Mg$^{2+}$ >K$^+$, while the those of the anions yielded the order HCO$_3^-$ >Cl$^-$ >SO$_4^{2-}$ >NO$_3^-$ >F$^-$. The assessment of tri-nitrogen data revealed that the
most severe pollution was associated with NO$_3$–N, and this was attributed to the indiscriminate disposal of domestic wastewater. The NH$_4$–N pollution was closely linked to the discharge of waste from the poultry farms.

(2) The composition of the shallow groundwater in the study area was mainly affected by the leaching of rocks and weathering of silicates. Na$^+$ and K$^+$ were attributed mainly to the weathering of silicates, while Ca$^{2+}$ was attributed to the dissolution of dolomite, and Mg$^{2+}$, SO$_4^{2–}$, and HCO$_3^–$ originated mainly from the dissolution of sulfate. The ion exchange reactions between the Ca$^{2+}$ and Mg$^{2+}$ in the shallow groundwater and Na$^+$ and K$^+$ in rocks in the area also impacted the composition.

(3) The fuzzy comprehensive assessment showed that the quality of the shallow groundwater from the study area was good, and the water was suitable for landscape entertainment, and industrial and agricultural water use. Based on the quality for irrigation, the groundwater samples were in the C2–S1 (medium salinity, low Na$^+$ content) and C3–S1 (high salinity, low Na$^+$ content) categories. To prevent eventual hazards, measures to control the salinity of the groundwater are needed. The groundwater is suitable for plants with high salinity tolerance or soils with good drainage.

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Conflict of Interest

The authors declare no conflict of interest.

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