Hydrochemical properties and groundwater quality evaluation in Suzhou City, lower Yangtze Delta, China

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Abstract. Detailed study of the chemical analysis results of 49 groundwater samples collected from the region’s second confined aquifer were carried out in an attempt to identify the samples’ hydrochemical properties and to assess the quality and usability of groundwater in Suzhou city, China. The results revealed that sodium, calcium and bicarbonate were the dominant ions in the groundwater samples. Na-HCO₃, mixed Na-Ca-HCO₃, Ca-HCO₃, and Na-Cl type were the four major hydrochemical facies identified by a Piper Trilinear diagram. It was observed that the concentration of ammonia and nitrite in most of the samples in study area exceeded the permissible limit values prescribed by the national (China) and international (WHO) drinking water guidelines. Anthropogenic activities have been shown to be largely responsible for groundwater contamination. Scatter diagrams and factor analysis suggest that natural weathering processes, along with anthropogenic activities, control the hydrogeochemistry of groundwater. On the basis of the analytical results of the 49 groundwater samples as compared to water quality standards, it was found that majority of groundwater samples were not suitable for drinking or for industrial uses directly. Toxic metals and high levels of ions must be removed to render the groundwater suitable for drinking and industrial purposes. However, salinity, sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and sodium percentage (Na%) values indicate that most of groundwater samples were suitable for irrigation purposes.

1. Introduction
The lower Yangtze River Delta, including Suzhou city, is well known in China for its dense population and intensive human activities. In the past few years, especially since the 1970s, groundwater extraction has steadily increased along with the rapid development of industry and population growth in Suzhou city; thus, groundwater has become a main water source for different purposes [1,2]. Due to the imbalances the occur among recharge and groundwater exploitation, irrational utilization, and pollutants emissions into soils and aquifers, the decline in water quality and groundwater levels are continuous and serious in the study area, and certain related geologic problems such as ground fissures, and land subsidence have occurred [2,3]. These problems have affected the quality of life and sustainable development of the local society and economy.

In recent years, much research has focused on water resource utilization and management in the lower Yangtze River Delta. Many reports have focused on water pollution and groundwater quality
[4,5], groundwater circulation mechanisms [6] and land subsidence [2,7]. However, little is known about the major hydrogeochemical processes that control the observed chemistry of groundwater and its suitability for different purposes in the region. In order to manage, utilize and protect precious groundwater resources, it is very important to fully understand and recognize the principal groundwater chemical processes and the main factors that contribute to groundwater pollution. The main purposes of this case study are: (1) to identify the hydrochemical properties and quality of groundwater in the lower Yangtze River Delta; (2) to recognize the dominant processes responsible for the observed groundwater chemistry; and (3) to identify water pollution parameters and evaluate the suitability of groundwater sources for different purposes.

2. Study area
The study area, Suzhou city, is located in the lower Yangtze River Delta in China, between 119°55'-121°20' E and 30°47'-32°02' N. The area has a total area of 8,488.42 km², including five counties (Wujiang, Kunshan, Taicang, Changshu and Zhangjiagang) and one urban planning area (figure 1).

![Figure 1. Map of sample collection in the study area.](image)

The study area is generally overlapped by quaternary sediments that come from rivers, lagoons, fluvial lakes and marine origins; the composite sediment layer has a thickness ranging from 150 to 300 meters [2,3]. According to their geological and hydrogeological characteristics, the quaternary sediments in Suzhou generally can be divided into three confined aquifers and one unconfined aquifer. The unconfined layer has large quantity of organic materials from Holocene continental deposits with a thickness of 10 to 20 meters [3]. The first confined aquifer consists of medium-sized and fine silty sand with an average thickness of 70 meters. The second confined aquifer consists of russet and grey clay, fine silty and medium-sized sands; these materials are distributed widely, although they are lacking in certain scattered regions and have an average thickness of 30 to 50 meters. The second confined aquifer has become the main recharge layer for groundwater due to its good water quality, moderate burial depth and large water storage capacity [7]. The third confined aquifer exists only in the eastern part of the city. It is mainly composed of middle sand and coarse sand from the Early Pleistocene era, and the thickness of the sand layer is about 20 to 30 meters [3,7]. Since the area is flat in terrain, the velocity of groundwater flow is relatively small.
3. Materials and methods

To evaluate and identify the groundwater quality and hydrochemical properties, 49 groundwater samples throughout the study area were collected from drinking wells and long-term observation wells located in the second confined aquifer (figure 1). Water samples were collected using a liquid sampler (SEBA, Germany); after being pumped for 10-15 minutes, all collected samples were stored in precleaned polyethylene bottles stored at a low temperature, and they were then immediately transported to the laboratory for testing and analysis.

Samples were measured for temperature, pH, and electrical conductivity (EC) in the field. Major anions and cations were analyzed using standard methods [8]. The temperature and pH were measured by a pH-meter (model 6010, Jenco, USA). EC and TDS (total dissolved solids) were measured by a conductivity meter (Model HQ14d, Hach, USA). The anions—including nitrates, nitrites, chloride and sulfate—were analyzed using a modular ion chromatograph (Shimadzu, Japan), and the anion bicarbonate was analyzed by titration (pH 4.8 alkalinity). The metals were analyzed by plasma emission spectrograph from a spectrometer (Thermo, USA). The cations—including K, Na, Mg and Ca—were analyzed by ICP-MS (Thermo, USA), and the ammonia was analyzed using a Nessler reagents spectrophotometer. All analytical equipment was regularly calibrated.

The groundwater quality results were evaluated in accordance with the standards for drinking water quality given by the MHC (Ministry of Health of China) and by WHO [9,10]. Calculations were analyzed using Statistica6.0.

4. Results and discussion

4.1. Hydrochemical properties of groundwater

4.1.1. General hydrogeochemistry. The physical and chemical parameters of groundwater samples and drinking water standards are shown in Table 1. The temperature variation of groundwater samples ranged from 18.7°C to 24.9°C, with a mean value of 20.03°C. The pH values ranged from 7.04 to 8.48, with a mean of 8.06, indicating the alkaline nature of the groundwater. The TDS variation of groundwater ranged from 62.85 to 2,082 mg/l, with an average value of 504.24 mg/l.

Table 1. Summary statistics of physical and chemical parameters of groundwater samples.

| Parameters | This study | WHO (2008)MHC (2006) |
|------------|-----------|---------------------|
|            | Min       | Max     | Ave  | S.D  |            |         |
| T          | (°C) 18.7 | 24.9    | 20.03| 0.89 | –         | –       |
| pH         | 7.04      | 8.48    | 8.06 | 0.36 | 6.5-8.5   | 6.5-8.5 |
| EC         | (µS/cm) 44.89 | 1628 494.14370.84 | –     |
| TDS        | (mg/l) 62.85 | 2082 504.24338.51500 | 1000  |
| NH₄⁺       | (mg/l) 0.02 | 6.78   | 0.86 | 1.76 | –         | 0.5     |
| K⁺         | (mg/l) 0.04 | 6.95   | 1.77 | 1.18 | 12        | –       |
| Na⁺        | (mg/l) 2.95 | 214.689.58 | 53.71 | 200  |
| Mg²⁺       | (mg/l) 2.62 | 97.1    | 22.85| 19.72 | 50          | –       |
| Ca²⁺       | (mg/l) 7.56 | 229.960.62 | 49.12 | 75   |
| NO₃⁻       | (mg/l) 0.04 | 9.27   | 1.74 | 2.00 | 50        | 20      |
| NO₂⁻       | (mg/l) 0.00023.66 | 0.31 | 0.82 | 0.2  | 0.2       |
| Cl⁻        | (mg/l) 6.9 | 1208 111 | 206.00250 | 250  |
| HCO₃⁻      | (mg/l) 42.3 | 568 318.05135.09 | –     |
| SO₄²⁻      | (mg/l) 0.2 | 116 20.18 31.41 | 250  |
| Fe²⁺       | (mg/l) 0.006 | 16.9 2.50 | 3.93 | 0.3  | 0.3       |
| Mn²⁺       | (mg/l) 0.00051.0350.16 | 0.20 | 0.4  | 0.1  |
| COD        | (mg/l) 0.5 | 4.87   | 1.65 | 1.03 | –         | 3       |
| T H        | (as CaCO₃, mg/l) 32.6 | 947 245.54188.33500 | 450  |
| Alkalinity (as CaCO₃, mg/l) 34.7 | 466 254.29106.17 | –     |
According to the chemical analysis of the main anions and cations, it was found that the hydrochemical types of groundwater could be divided into three major types and nine facies using Piper Trilinear diagram (figure 2). The diagram shows that samples fall into the following types: Na-HCO₃, mixed Na-Ca-HCO₃, Ca-HCO₃, Na-Cl, mixed Ca-Na-HCO₃, mixed Na-SO₄-HCO₃, Ca-Cl, mixed Mg-Ca-HCO₃, and mixed Mg-Na-Cl type, according to their order of dominance. Na-HCO₃, mixed Na-Ca-HCO₃, Ca-HCO₃, Na-Cl type, and mixed Ca-Na-HCO₃ type each represented 26.53%, 18.37%, 18.37%, 12.24%, and 10.20%, respectively, of the total number of groundwater samples analyzed, while mixed Na-SO₄-HCO₃, Ca-Cl, mixed Mg-Ca-HCO₃ type, and mixed Mg-Na-Cl represented 4.08%, 4.08%, 4.08%, and 7% of the groundwater samples analyzed.

![Figure 2. Piper trilinear diagram for groundwater samples.](image)

### 4.1.2. Chemical properties of major ions.

The average chemical characteristics of groundwater based on the concentration of major anions and cations were evaluated and are shown in figure 2. The results show that the concentrations of K⁺, Na⁺, Ca²⁺, and Mg²⁺ ranged from 0.01% to 4.45%, 10.18% to 79.51%, 6.45% to 71.14% and 9.76% to 49.41%, respectively, with average values of 0.72%, 44.52%, 34.37%, 20.39%, respectively. According to the molar means, the order of the cations was Na⁺ > Ca²⁺ > Mg²⁺ > K⁺. The concentrations of HCO₃⁻, Cl⁻ and SO₄²⁻ ranged from 9.73% to 97.18%, 2.32% to 90.16%, and 0.02% to 43.10%, with mean values of 68.64%, 24.58% and 6.78%, respectively. The relative order of the anions based on their mean molar concentrations was HCO₃⁻ > Cl⁻ > SO₄²⁻. As can be seen in figure 2, alkalis (Na⁺ and K⁺) exceeded the other cations, while HCO₃⁻ exceeded other anions.

### 4.2. Properties and factor analysis of chemical processes

#### 4.2.1. Major cation chemistry.

Compared with the concentration of potassium ions shown in table 1, the concentration of calcium, magnesium, and sodium ions was relatively high. The concentration ranges of sodium and potassium ions in the groundwater were 2.95 to 214.6 mg/l, 0.04 to 6.95 mg/l, respectively, with mean values of 89.58 mg/l and 1.77 mg/l.

Generally, if sodium ions were released from the halite dissolution process, then the ratio of sodium to chlorine (Na/Cl ratio) should be approximately 1; a ratio greater than 1 usually indicates that the silicate weathering process is responsible for the sodium ions [11]. On the other hand, if the sodium ions were released by silicate weathering, then the occurrence of HCO₃⁻ in the water samples will be the most abundant anion other than sodium [12] (equation (1)). In this study, the Na/Cl ratio generally varied from 0.13 to 19.7, with an average value of 3.42. The Na/Cl ratio of about 60% of the groundwater samples was greater than 1, as shown in figure 3(a). Therefore, the sodium in the majority of samples with an Na/Cl ratio greater than 1 and values of HCO₃⁻ that were higher than the values of

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*Figure 2. Piper trilinear diagram for groundwater samples.*

*Figure 3(a). Sodium and chloride ratio for groundwater samples.*
Na\(^+\) (shown in figure 3(b)) suggests that the source of sodium in the majority of the samples from the inland area was silicate weathering, and that the potassium also come from the above process. Whereas, the Na/Cl ratio of samples (0.129 to 0.759) from the coastal area near the Yangtze River indicates that ion exchange process or salinization caused by saltwater intrusion was the dominant factor.

\[
2\text{NaAlSi}_3\text{O}_8 + 2\text{H}_2\text{CO}_3 + 9\text{H}_2\text{O} = 2\text{Na}^+ + \text{Al}_2\text{Si}_2\text{O}_3(\text{OH})_4 + 4\text{H}_4\text{SiO}_4 + 2\text{HCO}_3^- \quad (1)
\]

![Figure 3. Scatter diagram of Na\(^+\) versus Cl\(^-\) and HCO\(_3\)\(^-\) versus Na\(^+\).](image)

In general, calcium and magnesium ions in groundwater come from the leaching of gypsum, dolomite, limestone and anhydrite, and the cation exchange process is another main source of calcium ions [13]. In this study, the concentrations of Ca\(^{2+}\) and Mg\(^{2+}\) were 7.56 to 229.9 and 2.62 to 97.1 mg/l, respectively, with an average concentration of 60.62 and 22.85 mg/l (table 1). Compared with magnesium ion, the concentration of calcium was relatively high. Further study of the Ca/Mg molar ratio, (Ca\(^{2+}\) + Mg\(^{2+}\)) versus the (HCO\(_3\)\(^-\) + SO\(_4\)\(^{2-}\)) ratio can reveal the origin of the calcium and magnesium ions. That is to say, if the Ca/Mg molar ratio points closer to a straight line (i.e., the ratio is 1), then the dissolution of dolomite should generally occur, and when the ratio is larger, calcite contributes more [14], and if Ca/Mg molar ratio is greater than 2, then the silicate minerals play a greater role. Generally, if the reactions of the dissolution of gypsum, dolomite and calcite are dominant in a system, then the scatter ratios of (Ca\(^{2+}\)+Mg\(^{2+}\)) versus (HCO\(_3\)\(^-\) + SO\(_4\)\(^{2-}\)) will be close to the 1:1 line. If the ion exchange process is dominant in a system, then the scatter ratios tend to move to the right [15,16]. If the reverse ion exchange process is dominant, then the scatter ratios will shift to the left. In this study, the Ca/Mg ratios were mostly between 1.16 and 2.25, which indicates that the calcium and magnesium ions occurred in the groundwater mostly due to the dissolution of dolomite, calcite and silicate minerals in the alluvium (figure 4(a); equation (2)). Figure 4(b) shows that most of the scatter ratios were concentrated near and below the isoline, excepting some samples from coastal areas near the Yangtze River. The anomaly points indicate that the reverse ion exchange in some areas was very small. This shows that silicate weathering and ion exchange were the main processes responsible for calcium and sodium ions in groundwater.

\[
\text{CaMg(CO}_3\text{)}_2 + 2\text{H}_2\text{O} + 2\text{CO}_2 = \text{Mg}^{2+} + \text{Ca}^{2+} + 4\text{HCO}_3^- \quad (2)
\]

Trace metals such as Fe, Cu, Mn, Cd, As, Cr, Pb and Zn in groundwater samples were also studied. Iron and manganese concentrations in most samples were relatively high throughout the aquifer, with an average of 2.5 and 0.16 mg/l, respectively (table 1; figure 5). Concentrations of other metals such as Cu, Cd, As, Cr, Pb and Zn were low, below the limits of the WHO and MHC standards. The main reason for the high concentration of iron and manganese ions is that the redox environment of the aquifer (equations (3) and (4)) was beneficial to the dissolution of iron and manganese mineral
nodules and to the corrosion of drilling materials in the groundwater environment. The concentration of ammonia ions in most samples was also very high (table 1), which can be explained by the fact that the environment is controlled by strong redox and by the reduction of these iron and manganese mineral nodules.

Figure 4. Scatter diagram of Ca/Mg ratio, (Ca$^{2+}$+Mg$^{2+}$) versus (HCO$_3^-$ + SO$_4^{2-}$).

$$2\text{MnO}_2 + 3\text{H}^+ + \text{CH}_2\text{O} = 2\text{Mn}^{2+} + \text{HCO}_3^- + 2\text{H}_2\text{O}$$

(3)

$$2\text{Fe}_2\text{O}_3 + 7\text{H}^+ + \text{CH}_2\text{O} = 4\text{Fe}^{3+} + \text{HCO}_3^- + 4\text{H}_2\text{O}$$

(4)

Figure 5. Scatter diagram of Fe$^{2+}$ and Mn$^{2+}$.

Figure 6. Scatter diagram of SO$_4^{2-}$ versus Cl$^-$.

4.2.2. Major anion chemistry. In this study, the bicarbonate ion was usually dominant as compared with other anions as shown in figure 3. The concentration ranges of bicarbonate, chloride, sulfate, nitrate and nitrite ions in the groundwater samples were: 42.3 to 568.0 mg/l, 44.3 to 514 mg/l, 0.2 to 116.0 mg/l, 0.04 to 9.27 mg/l and 0.0002 to 3.66 mg/l, respectively, with a mean value of 318.05, 184.7, 20.18, 1.74 and 0.31 mg/l, respectively.

Usually, during the process of the infiltration of irrigated water and rainwater into aquifers through a surface unsaturated zone, carbonate minerals obtained along the way will be dissolved depending on the ionizability of the carbonic acid and dissolved carbon dioxide [12] (equation (5)). With the recharge of groundwater, bicarbonate and calcium will be released into the water-bearing stratum (equation (6)). Meanwhile, the silicate weathering process can also increase the bicarbonate ions concentration in the groundwater (figures 3(b) and 4(b)). Therefore, the bicarbonate and carbonate ions in the study samples came mainly from carbonate minerals in the recharge areas, the silicate
weathering process and the dissolution of carbonic acid in the aquifers.

$$\text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^- \quad (5)$$

$$\text{CaCO}_3 + \text{H}_2\text{CO}_3 = \text{Ca}^{2+} + 2\text{HCO}_3^- \quad (6)$$

The chloride concentration in most of the samples was below the limits of MHC and WHO standards, except for a few samples from the coastal area near the Yangtze River (table 1; figure 3(a)). The chloride ions in the groundwater may come from rain water, weathering, dissolution of salt deposits and the back-flow of irrigation drainage [12]. The chloride concentration in the groundwater in sampling wells near the Yangtze River has generally been found to be high. These anomalies clearly indicate that the recharge of river water and salt water may increase the chloride concentration in groundwater.

The concentrations of sulfate in the majority of the samples were low throughout the area. Generally speaking, the dissolution of gypsum-bearing sedimentary rocks and the weathering of sulfates may be the main sources of sulfate ions in groundwater [12] (equation (7)). Another possible source of sulfate concentration is due to pyrite or acid rain, which can also deliver sulfates into the groundwater. Generally, high chloride levels with low sulfate concentration and low $\text{SO}_4^{2-}/\text{Cl}^-$ ratios in the groundwater indicate sulfate reduction [15]. In the present study, most samples were observed to have low sulfate concentration and low $\text{SO}_4^{2-}/\text{Cl}^-$ ratios (figure 6)). Therefore, sulfate reduction may be responsible for the low sulfate concentration in the groundwater of the area.

$$\text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{H}_2\text{O} = \text{Ca}^{2+} + \text{SO}_4^{2-} + 3\text{H}_2\text{O} \quad (7)$$

The nitrate concentration in all of the study samples was below the limits of MHC and WHO standards, but samples with high ammonia and nitrite concentrations were detected in most sites. The products of anthropogenic activities—such as chemical fertilizers, sewage, waste from extensive agricultural, industrial activities and urbanization—can introduce sizable amounts of inorganic or organic nitrogenous compounds into the surface water and groundwater. It seems probable that the occurrence of high concentrations of ammonia and nitrite concentrations in most of the study samples was the result of anthropogenic activities and a reduction in the environment of the alluvium and aquifers.

4.2.3. Factor analysis. Two partial contributions may be responsible for the concentration of each compound, one is related to the chemical weathering process, and the other is related to anthropogenic or atmospheric inputs [11,17]. R-mode factor analysis was applied to distinguish partial contributions and to extract the factors (figure 7).

![Figure 7. R-mode factor analysis for variables of samples.](image-url)
The extracted factor results indicate that these factors account for 75.68% of the total groundwater quality variance. The variables TDS, Ca$^{2+}$, Mg$^{2+}$ and Cl$^-$ have high positive factor loadings on Factor 1, Na$^+$ and HCO$_3^-$ shows high positive loadings on Factor 2; and NH$_4^+$ and Fe$^{2+}$ have high positive values on Factor 3. The factor variables of three different factor loads indicate that the determination of the geochemical composition of groundwater involves three different contributions (figure 7). The association of Ca$^{2+}$, Mg$^{2+}$, and Cl$^-$ denotes that they may originate from various water-rock interaction processes, and it may also reflect the influence of saltwater characteristics and weathering processes on groundwater quality. Na$^+$ and HCO$_3^-$ have good positive factor loadings, indicating that the ions mainly come from the same sources, including carbonate, weathering and gypsum dissolution processes. The association of ammonium and iron with strong negative loadings of pH indicated that a reducing environment influences the groundwater chemical compositions in the area. Therefore, it is assumed that three factor variables with different factor loads represent the natural process of groundwater, along with anthropogenic activities, and are responsible for the variations in the geochemistry of groundwater in the area.

4.3. Groundwater quality evaluation
Understanding groundwater quality and contamination is essential to determining the water’s suitability for drinking, domestic, irrigation and industrial purposes [18]. The groundwater quality was appraised for its suitability for the classified usage purposes based on the MHC and WHO standards.

4.3.1. Suitability for drinking and domestic purposes. The suitability of groundwater sources for domestic and drinking purposes was evaluated by comparing different water quality parameters with drinking water quality standards in China [9]. Among the samples, about 67%, 43%, 33%, 33%, 14%, 14%, 14%, and 6% of them, respectively, were found to exceed the standard limit values for iron, manganese, ammonia, nitrite, chloride, total hardness, COD and TDS. It was found that high iron and manganese concentrations are the major problem that exist in the study area, as is evident from the iron and manganese concentrations for which 67% and 43% of samples are showed values higher than their permissible limits, respectively. It was found that the high concentrations of iron and manganese were the main problems in the study area, and that the concentrations of iron and manganese for about 67% and 43% of the samples were higher than their allowable limits values, respectively. The second problem was nitrogen pollutants, including ammonia and nitrite derived from the reduction of organism remains reduction in the strongly redox-controlled environment of the alluvium and the aquifer. COD indirectly reflects the influence of the organic reducing environment on the groundwater chemical compositions. TDS is also very important for evaluating drinking water [19]. Based on the TDS results, it was found that about 93.9% of the samples were fresh in nature (TDS<1,000 mg/l), and only three samples were brackish (TDS>1,000 mg/l). Other cations and anions were between or below the ideal and permissible limits. According to the chemical results, the main samples of groundwater were not suitable for direct domestic drinking purposes; toxic and high concentration of ions should be removed before such use.

4.3.2. Suitability for irrigational purposes. A large number of studies have shown that if agricultural irrigation water contains excessive soluble ions such as sodium, carbonate and bicarbonate, irrigation water will significantly affect plant uptake and agricultural soil structure, thereby reducing agricultural productivity [20]. SAR (sodium absorption ratio), RSC (residual sodium carbonate) and Na% (sodium percentage) were calculated to evaluate the harmful effects of calcium, sodium, carbonate and bicarbonate on water quality. The SAR, RSC and Na% were calculated using the following formula (equations (8)-(10)).

\[
SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \tag{8}
\]
\[RSC = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+})\]  
\[\text{Na} \% = \frac{(\text{Na}^+ + \text{K}^+)}{(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+)}\]

where all the concentrations of the samples are represented in meq/l.

The calculated SAR, RSC and Na\% values are classified in Table 2. Sodium ions play an important role in evaluating the quality of irrigation groundwater, because sodium can increase soil hardness and decrease soil permeability [21]. A salinity diagram proposed by the US Salinity Laboratory Staff was plotted for the groundwater in the study area [22], and the graph was based on the analytical SAR and EC values (Figure 8). Based on a USSL diagram, most samples were found to fall in the C2-S1 (medium salinity with low sodium) category, and a few samples fell in the C1-S1 (low salinity with low sodium) and C3-S1 (high salinity with low sodium) categories. This indicates that these samples had low to high salinity hazards levels along with low alkali hazard levels. The plot illustrates that most samples can satisfy irrigation requirements with low risk of exchangeable sodium. According to a Wilcox diagram [23], forty samples fell in the field of excellent to good, eight samples were good to permissible, and only one sample was permissible to doubtful (Figure 9).

| Parameters | Classification | Numbers of samples | Percentage of samples |
|------------|----------------|--------------------|-----------------------|
| SAR (sodium absorption ratio) | <10 | Excellent | 49 | 100% |
| RSC (residual sodium carbonate) | <1.25 | Excellent | 24 | 48.98% |
| | 1.25–2.5 | Doubtful | 6 | 12.24% |
| | >2.5 | Unsuitable | 15 | 30.61% |
| Na\% (sodium percentage) | <20% | Excellent | 5 | 10.20% |
| | 20–40% | Good | 18 | 36.73% |
| | 40–60% | Permissible | 12 | 24.49% |
| | 60–80% | Doubtful | 13 | 26.53% |
| | >80% | Unsuitable | 1 | 2.04% |

Figure 8. US salinity diagram for irrigation water quality classification.

Figure 9. Sodium percentage vs EC values plot.
Based on the calculated SAR, RSC values and sodium percentages, the sodium hazards of most sampling sites were low, and most samples were found to be suitable for irrigation and agricultural purposes.

4.3.3. Suitability for industrial purposes. Normally, if water is neither scaly nor corrosive, then it is considered safe for industrial purposes and usage. It is very important to evaluate the corrosiveness of groundwater by carrying out the studies on the precipitation or dissolution trend of calcium carbonate [24]. In order to understand the corrosive nature of groundwater in Suzhou city in detail and decide whether groundwater used for industrial purpose will precipitate or dissolve calcium carbonate, SI (the Langley saturation index) and LnR (Larson Ratio) were calculated[25]. The SI and LnR were calculated using the following formulas (equations (11)-(13)).

$$ SI = p\text{H}_w - p\text{H}_s $$  \hspace{1cm} (11)

$$ p\text{H}_s = (9.3 + A + B) - (C + D) $$  \hspace{1cm} (12)

where $p\text{H}_w$ is the actual measured pH of the water; alkalinity (as CaCO$_3$ in mg/L); $p\text{H}_s$ is the pH at saturation in calcium carbonate, as calculated by equation (12) that takes into account calcium hardness (CH, mg/L), total dissolved solids (as CaCO$_3$ in mg/L) and temperature (T) of the water.

$$ A = (\log_{10}(\text{TDS}) - 1)/10 \hspace{1cm} B = -13.12 \times \log_{10}(T + 273) + 34.55 \hspace{1cm} C = \log_{10}(\text{CH}) - 0.4 \hspace{1cm} D = \log_{10}(\text{Alkalinity}) $$

$$ \text{LnR} = \left[\frac{\text{Cl}^- + (2 \times \text{SO}_4^{2-})}{\text{HCO}_3^-}\right] $$  \hspace{1cm} (13)

Generally, a positive value for SI usually indicates that water has a tendency to form scale, while a negative value indicates that water has a tendency to dissolve calcium acetate. If the LnR value is greater than 1, a strong corrosion potential is indicated; a value of 1 to 0.2 indicates a slight corrosion potential, and a value of less than 0.2 often indicates no corrosion potential.

In this study, the results shown in figure 10 indicate that most of the samples (92%) were deposited by calcium carbonate, while a few (8%) were dissolved naturally. Based on the LnR values, around 25%, 41% and 34% of the samples belong to the categories of strong potential toward corrosion (LnR>1), slight potential to be corrosive (LnR=0.2–1) and no potential (LnR<0.2), respectively. Most samples were deposited by calcium carbonate naturally, which is consistent with the results available by referring to the SI values.

![Figure 10. SI and LnR values for groundwater samples.](image)

5. Summary and conclusions

The present study describes the hydrochemical properties, water quality and usability of groundwater
in Suzhou city, 49 groundwater samples throughout the study area were collected from the region’s second confined aquifer, and the groundwater quality was assessed for its suitability for drinking, domestic (household), irrigation and industrial purposes. Based on our results, the hydrochemical properties and quality of groundwater used for different purposes were comprehensively discussed, and we obtained the following conclusions:

- Generally, sodium, calcium and bicarbonate were the dominant ions in the groundwater in the study area. Na-HCO$_3$, mixed Na-Ca-HCO$_3$, Ca-HCO$_3$, and Na-Cl type were the four major hydrochemical facies.
- The most abundant cation in the collected water samples was Na$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > K$, while that the most abundant of anions was HCO$_3^-$ > Cl$^-$ > SO$_4^{2-}$.
- Scatter diagrams and factor analysis suggest that natural weathering processes, such as silicate weathering, the ion exchange process and carbonate weathering, along with anthropogenic activities control the hydro-geochemistry of groundwater.
- The majority of groundwater samples in the study area were not suitable for drinking, domestic purposes or industrial uses. Toxic metals and high levels of ions (such as ammonia, iron, manganese, nitrite, chloride, COD and total hardness) should be removed if groundwater is to be prepared for drinking and industrial purposes.
- Salinity, SAR, RSC and Na% values indicate that most of the groundwater samples were suitable for irrigation and agricultural purposes.

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