Groundwater Quality Assessment in the Northern Part of Changchun City, Northeast China, Using PIG and Two Improved PIG Methods

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Abstract: As a numerical indicator, the pollution index of groundwater (PIG) has gained a great deal of popularity in quantifying groundwater quality for drinking purposes. However, its weight-determination procedure is rather subjective due to the absolute dependence on experts’ experience. To make the evaluation results more accurate and convincing, two improved PIG models (CRITIC-PIG and Entropy-PIG) that integrate subjective weights and objective weights were designed, and they were employed to appraise groundwater suitability for drinking purposes in the northern part of Changchun City. A total of 48 water samples (34 unconfined water samples and 14 confined water samples) with abundances of Ca2+ and HCO3− were collected and tested to obtain the data for the analyses. The results showed that 60.4%, 47.9% and 60.4% of the water samples manifested insignificant pollution and were marginally potable based on the values of the PIG, CRITIC-PIG and Entropy-PIG, respectively. Though 48% of the water samples had different evaluation results, their level difference was mostly 1, which is relatively acceptable. The distribution maps of the three sets of PIG values demonstrated that the quality of groundwater was the best in Dehui City and the worst in Nongan County. Groundwater contamination in the study area was mainly caused by the high concentrations of TDS, TH, Fe3+, F− and NO3−, which not only came from geogenic sources but also anthropogenic sources.

Keywords: PIG; CRITIC-PIG; Entropy-PIG; groundwater quality assessment

1. Introduction

Groundwater, as the premier and finite source of freshwater for human drinking purposes, is confronted with a more or less serious contamination status in many areas around the world on the grounds of the fast urbanization process and population growth, as well as the increase in anthropogenic activities (agricultural, industrial and domestic activities) [1–5]. Ample evidence has shown that a good correlation exists between the quality of groundwater and human health [6–12]. Therefore, the quantitative delineation of the regional groundwater contamination level for drinking purposes badly needs to be conducted for us to have an overall understanding of the water pollution status, which is helpful to carry out relevant and effective measures to maintain or improve water quality and ensure local inhabitants’ health.

The determination of each chosen parameter’s weight is an indispensable procedure in the process of the comprehensive evaluation of groundwater quality. The weight itself represents the importance of the evaluation parameter, and the larger the weight is, the
greater the impact it has on the groundwater-quality-appraisal result. All in all, the subjective weighting method, the objective weighting method and the integrated weighting method are commonly used to determine the weight values in recent research studies [13]. Compared with the other two methods, the integrated weighting method overcomes the subjectivity caused by the complete dependence on experts’ subjective judgment as well as the illogicality caused by the total dependence on groundwater-quality-analysis data to some extent [14].

Initially proposed by N. Subba Rao [15], the pollution index of groundwater (PIG) is a useful and effective numerical indicator to quantify groundwater contamination for drinking purposes, and its application is widespread [16–22]. The subjective weighting method is employed in the process of determining the PIG value, and the calculation of the weight is based on subjective judgment and former experience. Several objective weight-determination methods, such as the Entropy-weighted model and the CRITIC (criteria importance through intercriteria correlation)-weighted model were integrated with TOPSIS and the WQI approach to evaluate water quality in different areas [23–31]. As for the integrated method, Zhang et al. integrated CRITIC (objective method) and AHP (subjective method) to calculate the index weight, aiming to comprehensively appraise the water-source vulnerability of Yuqiao Reservoir [32]. By integrating order relation analysis method and Entropy-weighted method, Gao et al. employed an additive model to evaluate the drinkability of groundwater in Xi’an city, Shaanxi Province [14]. Yan et al. improved the Entropy-weighting model by coupling the relative entropy theory to make the evaluation results more logical and reliable [33].

As a famous gold corn belt in China, from 70% to 80% of the population in the northern part of Changchun City (Dehui City, Yushu City and Nongan County) lives in rural areas, and groundwater is nearly the sole source for their drinking and irrigation aims [34]. Therefore, taking human health into consideration, it is worth carrying out groundwater quality assessment in the region to decide whether to take some measures to maintain or improve groundwater quality.

The present research study intends to: (1) propose two novel PIG models (the CRITIC-PIG model and the Entropy-PIG model) by integrating the traditional PIG with two objective weighting methods (the CRITIC method and the Entropy method, respectively); (2) employ the traditional PIG model and the two improved PIG models (the CRITIC-PIG model and the Entropy-PIG model) to evaluate the drinkability and obtain the overall pollution distribution of the groundwater in the northern part of Changchun City; (3) study the hydrochemical characteristics of groundwater in the study area by adopting graphical methods (Gibbs diagrams and Piper diagram). The result of the current study not only can provide the pollution status of groundwater for drinking purposes, which is helpful to carry out effective measures for the remediation and control of groundwater resources in Dehui City, Yushu City and Nongan County to guarantee the inhabitants’ health, but it can also offer two improved PIG models to assess the pollution levels of groundwater for drinking aims.

2. Overview of the Study Area
2.1. Study Area

Covering an area of 13,434 km², the study area (124°32′–127°05′ E, 43°54′–45°15′ N) is located in the northern part of Changchun city (Nongan County, Dehui City, Yushu City), the hinterland of Songliao Plain, as illustrated in Figure 1. Songhua River, Yitong River, Yinma River, Mushi River and Kacha River are the five principal rivers flowing through. Denudation-accumulation high plain and accumulation-mountain-valley plain are the two major landforms of the study area, with elevation ranging from 130 to 296 m.

According to the Köppen climate classification, the study area lies in the temperate climate zone and belongs to the hot summer–dry winter temperate climate class (Dwa) with the temperature of the hottest month being over 22 °C. The annual average temperature, precipitation and evaporation from 1962 to 2000 were 4.3 °C, 538.6 mm and 1629 mm,
respectively. Based on Figure 2, rainfall is mainly concentrated in the summer stage (from June to September), which accounts for approximately 78% of total annual rainfall, while evaporation mainly occurs from April to September, a period that accounts for around 80% of total annual evaporation.

![Figure 1](image1.png)

**Figure 1.** Location of the study area in the northern part of Changchun City (Nongan County, Dehui City, Yushu City) in Jilin Province, China. (a) Jilin Province, China; (b) the location of the study area in Jilin Province; (c) the terrain and sampling point distribution map of the study area.

![Figure 2](image2.png)

**Figure 2.** Monthly average values of precipitation, evaporation and temperature in the northern part of Changchun city from 1962 to 2000.

2.2. Geology

The study area lies in the southeastern uplift area of the Songliao fault basin of Jihai Fold System, where the Lower Cretaceous and Quaternary strata are well developed,
whereas most of the Cretaceous strata are covered by Quaternary loose deposits (sand, silt, subclay, gravel, pebbles). The lithology of the Cretaceous strata is dominated by mudstone, shale and silty sandstone of Nenjiang Formation (107–666 m), mudstone and sandstone of Yaojia Formation (35–220 m), mudstone and siltstone of Qingshankou Formation (32–196 m), clastic rock of Quantou Formation (29–2199 m) and mudstone and sandy conglomerate of Denglouku Formation (0–1082 m).

### 2.3. Hydrogeology

Groundwater in the study area is dominated by loose rock pore water (Quaternary) whose aquifer is mainly gravel, sand and loess, as well as clastic rock fissure–pore water (Cretaceous) whose aquifer is mainly sandy conglomerate, sandstone and mud rock [35]. The detailed hydrogeological information of each formation is listed in Table 1. Groundwater mainly receives recharge from the infiltration of atmospheric precipitation, and the major means of groundwater discharge are evaporation and artificial extraction for irrigation and drinking purposes.

| Aquifer System | Aquifer | Lithology of the Aquifer | Permeability (m/d) | Thickness (m) | Water Inflow (m³/d) | Type of Groundwater |
|----------------|---------|--------------------------|--------------------|---------------|---------------------|---------------------|
| Quaternary Porous Aquifer System | Holocene Aquifer | Medium and coarse sand, gravel sand and gravel | 30–100 | 5–20 | 500–3000 | unconfined |
| | Upper Pleistocene (Guxiang Formation) Aquifer | Fine sand, sand and loss-shaped subclay | 10–30 | 10–30 | 100–500 | unconfined |
| | Middle Pleistocene (Huangshan Formation) Aquifer | Sand and loss-shaped subclay | Average | 5–20 | <100 | unconfined |
| | Lower Pleistocene (Baitushan Formation) Aquifer | Sand, gravel and clay | 10–30 | 10–30 | 500–1000 | confined |
| | Nenjiang Formation and Yaojia Formation Aquifer | Sandstone and mud rock | Bad | 50–80 | <100 | confined |
| | Qingshankou Formation and Quantou Formation Aquifer | Sandstone, sandy conglomerate and mud rock | Bad | 50–80 | <100 | confined |

### 3. Materials and Methods

#### 3.1. Materials

A sum of 48 wells (Figure 1), including 34 Quaternary unconfined water wells and 14 Quaternary confined water wells, were sampled in November 2017 to investigate the groundwater quality situation of the study area. To obtain accurate and reliable water-quality-analysis results, each well was extracted for 5–10 min before sampling to minimize the influence of residual water in the suction pipe. Samples were gathered in polyethylene plastic bottles (350 mL), which were pre-cleaned three times by using deionized water. Two bottles of water were gained from each well, and 10% nitric acid solution was added to one of them to make the pH less than two in order to perform a cation analysis, while the other one was non-acidified. pH and alkalinity were tested and determined in situ using the calibrated HANNA (HI99131) portable pH analyzer and Gran titration, respectively [36].
The water samples were carefully gathered, strictly sealed, clearly labeled and immediately transported to Pony Testing International Group in Changchun City to be tested. The water quality testing technique was in accordance with Chinese Drinking Water Standard Examination Methods (GB5750-2006). ICP-AES (inductively coupled plasma atomic emission spectrometry) and ion chromatography were used to examine the major cations (K\(^+\), Na\(^+\), Ca\(^{2+}\) and Mg\(^{2+}\)) and anions (Cl\(^-\), NO\(_3^-\), SO\(_4^{2-}\), F\(^-\) and Fe\(^{3+}\)), respectively. TDS and TH (Total Hardness; CaCO\(_3\) Hardness) were measured using the vapor-drying method (an electric blast-drying oven and an electronic analytical balance) and the Na\(_2\)EDTA titrimetric method, respectively. All groundwater samples passed the reliability test (a charge-balance check), with the relative errors of the sum of anion and cation milliequivalent concentrations being less than 5%.

3.2. Methods

3.2.1. The Traditional PIG Method

As is shown in Table 2, a total of twelve chemical parameters (TDS, TH, Ca\(^{2+}\), Mg\(^{2+}\), Na\(^+\), K\(^+\), HCO\(_3^-\), Cl\(^-\), SO\(_4^{2-}\), NO\(_3^-\), F\(^-\), Fe\(^{3+}\)) were chosen to carry out drinking-water quality appraisal in the study area. The procedures for computing the traditional PIG are summarized briefly in Figure 3 [15]. In Step 1, the allotted weight (A\(_w\)) (numbers from 1 to 5) was assigned by taking their respective importance for human health into consideration. The number itself quantitatively indicated the extent of impact on human health, so the larger the number was, the greater the impact it had. Step 2 calculated the subjective weight (w\(_s_j\)) using the ratio of the allotted weight (A\(_w\)) of each parameter to the sum of all A\(_w\) values. The ratio of the measured concentration (C) to the drinking-water standard (D\(_s\)) of its corresponding index was the result of the status of concentration (S\(_c\)). Overall water quality (O\(_w\)) for drinking purposes was gained via the multiplication of the subjective weight (w\(_s_j\)) and the status of concentration (S\(_c\)) in Step 4. Then, in Step 5, after calculating the sum of O\(_w\) for each water sample, their respective PIG was obtained.

![Figure 3. Technical roadmap of the traditional PIG method.](image)

Table 2. Values of allotted weight, weight parameter and drinking-water quality standard as well as the units of the 12 chemical parameters [15,20,21,37].

| Chemical Parameters | Aw (Allotted Weight) | Wp (Weight Parameter) | Ds (Drinking-Water Quality Standard) | Unit   |
|---------------------|----------------------|-----------------------|-------------------------------------|--------|
| TDS                 | 5                    | 0.1136                | 500                                 | mg/L   |
| TH                  | 4                    | 0.0909                | 300                                 | mg/L   |
| Ca\(^{2+}\)         | 2                    | 0.0455                | 75                                  | mg/L   |
3.2.2. The Improved PIG Methods (the CRITIC-PIG Method and the Entropy-PIG Method)

Figure 4 shows the procedure of the determination of two distinct objective weights using the CRITIC [30] and Entropy [38,39] methods, respectively. $x_{ij}$, the element of Evaluation Matrix $X$, is the measured value of the $j$th parameter of the $i$th water sample. $m$ (48) is the number of water samples, and $n$ (12) is the number of parameters. $y_{ij}$ is the measured value after normalization, which ranges from 0 to 1. $\max(x_{ij})$ and $\min(x_{ij})$ refer to the maximum and the minimum of the $j$th parameter of the $i$th water sample, respectively. For the CRITIC method, information account $C_j$ is associated with $\delta_j$, the standard deviation of the $j$th parameter, as well as $r_{ij}$, the correlation coefficient of the $i$th and $j$th indicators. For the Entropy method, constant 0.0001 is used in the formula of $P_{ij}$, aiming to avoid meaninglessness when $y_{ij}$ is zero.

As is shown in Figure 5, the improved PIG methods (the CRITIC-PIG method and the Entropy-PIG method) were adopted to integrate subjective weights (listed in Table 2) and objective weights (CRITIC or Entropy method), which not only involve human subjective judgment but also objective calculation in Steps 1 and Step 2 [40], while the other procedures are essentially the same as the traditional PIG method. After calculation, the CRITIC-PIG value and the Entropy-PIG value were obtained. Based on the values of three PIG values, they were divided into five categories (Table 3).
Figure 4. Technical roadmap of objective weight determination using the CRITIC and Entropy methods, respectively.

As shown in Figure 5, the improved PIG methods (the CRITIC-PIG method and the Entropy-PIG method) were adopted to integrate subjective weights (listed in Table 2) and objective weights (CRITIC or Entropy method), which not only involve human subjective judgment but also objective calculation in Steps 1 and Step 2[40], while the other procedures are essentially the same as the traditional PIG method. After calculation, the CRITIC-PIG value and the Entropy-PIG value were obtained. Based on the values of three PIG values, they were divided into five categories (Table 3).

Figure 5. Technical roadmap of the improved PIG method.

Table 3. Five categories of water for drinking purposes according to three PIG values [15].

| PIG | Result                          |
|-----|---------------------------------|
| <1  | Insignificant Pollution         |
| 1–1.5 | Low Pollution                 |
| 1.5–2 | Moderate Pollution             |
| 2–2.5 | High Pollution                 |
| >2.5 | Very High pollution            |

4. Results and Discussion

4.1. Physicochemical Parameter

Based on the statistical analysis data (Table 4) of the main ion concentrations as well as the major water quality indexes of the 48 groundwater samples (confined water and unconfined water) in Dehui, Nongan and Yushu Districts, unconfined water and confined water manifested a weak alkaline environment, with pH ranging from 6.7 to 8.5 and from 7 to 7.8, respectively. The pH value was relatively stable due to the low S.D. value (0.4 and 0.3, respectively). On the whole, unconfined water in the study area was characterized by higher concentrations of Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, Cl$^-$, SO$_4^{2–}$ and HCO$_3^{–}$ than those in confined water. The box diagram of the eight major ions (except K$^+$) of the two distinct types of water shown in Figure 6 indicates their analogous abundance order: cations dominated by Ca$^{2+}$, followed by Na$^+$ and Mg$^{2+}$; anions dominated by HCO$_3^{–}$, followed by Cl$^-$, SO$_4^{2–}$ and NO$_3^{–}$.

Table 4. Statistical analysis results of physico-chemical parameters of unconfined water and confined water.

| Parameter | Unit | Ds | Unconfined Water | Confined Water |
|-----------|------|----|------------------|----------------|
|           |      |    | Min   | Max   | Mean   | S.D.  | CV     | Min   | Max   | Mean   | S.D.  | CV     |
| pH        | /    | 6.5–8.5 | 6.7   | 8.5   | 7.5    | 0.4   | 6      | 7     | 7.8   | 7.4    | 0.3   | 4      |
| TDS       | mg/L | 500 | 182   | 2280  | 880.7  | 454   | 52     | 189   | 813   | 478.1  | 238   | 50     |
| TH        | mg/L | 300 | 90.8  | 1200  | 555.8  | 269   | 48     | 120   | 522   | 297.9  | 137   | 46     |
| Ca$^{2+}$ | mg/L | 75  | 24.2  | 401   | 170.3  | 89    | 53     | 37.2  | 200   | 96.3   | 52    | 54     |
| Mg$^{2+}$ | mg/L | 30  | 3.9   | 84.8  | 28.1   | 22    | 77     | 4.25  | 24.9  | 12.3   | 7     | 60     |
| Na$^+$    | mg/L | 200 | 12.9  | 360   | 84.2   | 88    | 105    | 10.3  | 94.6  | 30.7   | 27    | 86     |
| K$^+$     | mg/L | 12  | 0.268 | 106   | 4.2    | 18    | 430    | 0.396 | 11.2  | 1.6    | 3     | 178    |
| Cl$^-$    | mg/L | 300 | 2.5   | 434   | 112.8  | 89    | 79     | 3.4   | 124   | 47.3   | 42    | 88     |
| SO$_4^{2–}$ | mg/L | 250 | 1.55  | 298   | 102.3  | 86    | 84     | 5.77  | 163   | 42.8   | 46    | 108    |
| HCO$_3^{–}$ | mg/L | 200 | 93    | 881   | 376.6  | 173   | 46     | 67.7  | 415   | 228.8  | 102   | 44     |
| NO$_3^{–}$ | mg/L | 45  | 0.01  | 143   | 36.3   | 38    | 105    | 0.4   | 59.5  | 22.3   | 21    | 93     |
### Table 4. Cont.

| Parameter | Unit   | Ds  | Unconfined Water | Confined Water |          |          |          |          |          |          |
|-----------|--------|-----|------------------|----------------|----------|----------|----------|----------|----------|----------|
|           |        |     | Min         | Max           | Mean     | S.D.     | CV       | Min        | Max       | Mean     | S.D.  | CV   |
| F−        | mg/L   | 1.5 | 0.09          | 6.8           | 1.6      | 1.0      | 157      | 0.12        | 0.67      | 0.3      | 0.1   | 47   |
| Fe3+      | mg/L   | 0.3 | 0.0045        | 20.3          | 1.6      | 4.1      | 263      | 0.0045     | 4.97      | 0.5      | 1.3   | 247  |

S.D., standard deviation; CV, coefficient of variation; Ds, drinking-water quality standard.

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**Figure 6.** Box diagram of 7 main ion concentrations in confined water and unconfined water.

### 4.2. Spatial-Distribution Characteristics of TDS, TH, NO₃⁻-N, Fe³⁺ and F⁻ in the Study Area

Figure 7 vividly presents the spatial distributions of TDS, TH, NO₃⁻, Fe³⁺ and F⁻ in the area of consideration. TDS varied from 182 to 2280 mg/L, and Nongan County tended to have a higher concentration of TDS than Yushu City and Dehui City. Areas with high TDS were mainly located in the south and northeast of Nongan County. The spatial distributions of TH and NO₃⁻ were similar to that of TDS, varying from 90.8 to 1200 mg/L and from 0.01 to 143 mg/L, respectively. As for Fe³⁺, a majority of areas had low Fe³⁺ content, except for the northeastern parts of Nongan Country and Yushu City. The presence of high Fe concentrations is closely associated with the Fe-rich matters in the reducing environment of the aquifer, the formation of organic complexes, which lead to the dissolution of Fe, and poor groundwater run-off conditions; however, the influence of pH on Fe in the study area is negligible according to Oluwafei Adeyeye’s quantitative analysis [41], which can explain the existence of elevated values of Fe under neutral–alkaline pH conditions. The content of F⁻ was relatively low in Yushu City and Dehui City, but Nongan country had the tendency of having high levels of F⁻, especially in the middle part.
reducing environment of the aquifer, the formation of organic complexes, which lead to the dissolution of Fe, and poor groundwater run-off conditions; however, the influence of pH on Fe in the study area is negligible according to Oluwafei Adeyeye's quantitative analysis [41], which can explain the existence of elevated values of Fe under neutral–alkaline pH conditions. The content of $F^-$ was relatively low in Yushu City and Dehui City, but Nongan country had the tendency of having high levels of $F^-$, especially in the middle part.

4.3. Graphical Methods

Proposed by Piper [42], the Piper diagram is a commonly used tool to show the main hydrochemical types of a large number of groundwater samples from a specific area. As is shown in Figure 8, three major cation and anion types as well as a mixed type (non-dominant type) are listed as 1–7 in the bottom two triangles. Five categories of hydrochemical types are labeled A–E in the middle diamond. The bottom-left triangle indicates that the dominant cation in the vast majority of samples was Ca$^{2+}$, and in the minority of samples, this was Na$^+$ or a mixed type (non-dominant cations). The bottom-right triangle indicates that the dominant anion in the vast majority of samples was HCO$_3^-$, while some had no dominant anions (mixed type), and three water samples abounded in Cl$^-$. Based on the diamond in the middle, the hydrochemical type of groundwater in the study area was relatively diverse as a whole, with the dominance of the HCO$_3^-$-Ca type, as well as some Cl-Ca type, mixed type and a few HCO$_3^-$-Na type.

Gibbs diagrams were initially proposed by Gibbs [43] to study the hydrochemical evolution characteristics of surface water, and their usage is extended to the field of groundwater studies nowadays [44–46]. Though this widely used and mainstream method remains controversial in the interpretation of groundwater chemistry [47], it roughly provides the overall tendency of the evolution of groundwater chemistry when combined with the Piper diagram, as in this study. Based on the relationships between TDS and Na$^+/$(Na$^+$ + Ca$^{2+}$), and TDS and Cl$^-/$(Cl$^-$ + HCO$_3^-$), respectively, three genres of mechanisms affecting the chemical composition of natural water could be determined: precipitation dominance, rock
(lithology) dominance and evaporation dominance [43]. According to Figure 9, a great quantity of groundwater samples were in the “rock dominance” section, indicating that water–rock interaction (rock weathering and leaching) was the major factor controlling the chemical types of groundwater. In addition, a small amount of unconfined water samples had a tendency towards evaporation dominance with the characteristics of high Cl\(^-\) and TDS levels. This is mainly caused by the arid and semi-arid climate with little precipitation and relatively intensive evaporation effects.

![Gibbs diagrams of 48 groundwater samples in the study area.](image)

**Figure 8.** Piper diagram of 48 groundwater samples in the study area.

![Gibbs diagrams of 48 groundwater samples in the study area.](image)

**Figure 9.** Gibbs diagrams of 48 groundwater samples in the study area. (a) TDS vs. \([\text{Cl}^-/\text{(Cl}^- + \text{HCO}_3^-)]\). (b) TDS vs. \([\text{Na}^+/(\text{Na}^+ + \text{Ca}^{2+})]\).

### 4.4. Results of PIG, CRITIC-PIG and Entropy-PIG

According to 12 groundwater quality indexes (TDS, TH, Ca\(^{2+}\), Mg\(^{2+}\), Na\(^+\), K\(^+\), HCO\(_3^-\), Cl\(^-\), SO\(_4^{2-}\), NO\(_3^-\), F\(^-\) and Fe\(^{3+}\)) and their respective drinking-water standards listed in Table 2, the groundwater quality appraisal for drinking purposes was completed using the PIG model and the two improved PIG models (CRITIC-PIG and Entropy-PIG). The results are listed in Tables 5 and 6, including 34 unconfined water samples and 14 confined water samples, respectively. The PIG values ranged between 0.204 and 7.114, with an
average of 1.162, and based on the traditional PIG model, using which those 48 samples
could be classified into five categories, among them, 60.4%, 18.8%, 8.3%, 6.25% and 6.25%
showed insignificant, low, moderate, high and very high pollution, respectively. As for the
two improved PIG models, the CRITIC-PIG values were between 0.294 and 2.795, and the
average was 1.216. It was calculated that 47.9%, 20.8%, 18.8%, 6.25% and 6.25% of them
indicated insignificant, low, moderate, high and very high pollution, respectively, with
respect to the results. The results of the Entropy-PIG model indicated that the minimum and
maximum of the Entropy-PIG values were 0.229 and 3.985, respectively, with an average of
1.081. The percentages of water samples showing insignificant, low, moderate, high and
very high pollution were 60.4%, 18.8%, 10.4%, 8.3% and 2.1%, respectively.

Obviously, the confined water samples showed better quality for human drinking than
the unconfined ones as a whole, as can be seen by comparing Tables 5 and 6, which can
be proved by the percentage of the “Insignificant Pollution” ones (overall, 92.8%, 85.71%
and 100% of confined water samples manifested insignificant-pollution status, which is
suitable for human drinking, using the traditional PIG model, the CRITIC-PIG model and
the Entropy-PIG model, respectively, while these values were 33.3%, 22.9% and 31.3% for
unconfined water).

| Sample Number | PIG  | Evaluation Result | CRITIC-PIG | Evaluation Result | Entropy-PIG | Evaluation Result |
|---------------|------|-------------------|------------|-------------------|-------------|-------------------|
| D1            | 0.670 | Insignificant Pollution | 1.213 | Low Pollution | 0.782 | Insignificant Pollution |
| D2            | 2.552 | Very High Pollution | 1.778 | Moderate Pollution | 1.950 | Moderate Pollution |
| D3            | 0.577 | Insignificant Pollution | 0.765 | Insignificant Pollution | 0.615 | Insignificant Pollution |
| D4            | 4.109 | Very High Pollution | 1.635 | Moderate Pollution | 2.340 | High Pollution |
| D5            | 0.891 | Insignificant Pollution | 1.329 | Low Pollution | 1.059 | Low Pollution |
| D6            | 1.841 | Moderate Pollution | 2.584 | Very High Pollution | 2.091 | High Pollution |
| D7            | 0.452 | Insignificant Pollution | 0.708 | Insignificant Pollution | 0.545 | Insignificant Pollution |
| D8            | 1.033 | Low Pollution | 1.650 | Moderate Pollution | 1.281 | Low Pollution |
| D9            | 1.453 | Low Pollution | 2.195 | High Pollution | 1.766 | Moderate Pollution |
| D10           | 1.132 | Low Pollution | 1.615 | Moderate Pollution | 1.338 | Low Pollution |
| D11           | 1.233 | Low Pollution | 1.746 | Moderate Pollution | 1.443 | Low Pollution |
| D12           | 2.050 | High Pollution | 2.135 | High Pollution | 2.028 | High Pollution |
| D13           | 1.229 | Low Pollution | 1.769 | Moderate Pollution | 1.446 | Low Pollution |
| D14           | 1.906 | Moderate Pollution | 1.785 | Moderate Pollution | 1.703 | Moderate Pollution |
| D15           | 1.033 | Low Pollution | 1.509 | Moderate Pollution | 1.226 | Low Pollution |
| D16           | 0.593 | Insignificant Pollution | 0.881 | Insignificant Pollution | 0.688 | Insignificant Pollution |
| D17           | 1.368 | Low Pollution | 2.138 | High Pollution | 1.637 | Moderate Pollution |
| D18           | 2.282 | High Pollution | 2.795 | Very High Pollution | 2.447 | High Pollution |
| D19           | 0.859 | Insignificant Pollution | 1.232 | Low Pollution | 0.983 | Insignificant Pollution |
| D20           | 0.528 | Insignificant Pollution | 0.808 | Insignificant Pollution | 0.588 | Insignificant Pollution |
| D21           | 1.037 | Low Pollution | 1.399 | Low Pollution | 1.161 | Low Pollution |
| D22           | 7.114 | Very High Pollution | 2.568 | Very High Pollution | 3.985 | Very High Pollution |
| D23           | 2.267 | High Pollution | 0.649 | Insignificant Pollution | 1.164 | Low Pollution |
| D24           | 1.070 | Low Pollution | 1.036 | Low Pollution | 0.955 | Insignificant Pollution |
| D25           | 0.856 | Insignificant Pollution | 1.204 | Low Pollution | 0.953 | Insignificant Pollution |
| D26           | 1.931 | Moderate Pollution | 1.847 | Moderate Pollution | 1.681 | Moderate Pollution |
| D27           | 0.927 | Insignificant Pollution | 1.371 | Low Pollution | 1.072 | Low Pollution |
| D28           | 0.444 | Insignificant Pollution | 0.762 | Insignificant Pollution | 0.537 | Insignificant Pollution |
| D29           | 0.570 | Insignificant Pollution | 0.884 | Insignificant Pollution | 0.679 | Insignificant Pollution |
| D30           | 0.570 | Insignificant Pollution | 0.502 | Insignificant Pollution | 0.422 | Insignificant Pollution |
| D31           | 0.561 | Insignificant Pollution | 0.776 | Insignificant Pollution | 0.524 | Insignificant Pollution |
| D32           | 0.520 | Insignificant Pollution | 0.726 | Insignificant Pollution | 0.584 | Insignificant Pollution |
| D33           | 0.447 | Insignificant Pollution | 0.747 | Insignificant Pollution | 0.507 | Insignificant Pollution |
| D34           | 0.936 | Insignificant Pollution | 1.132 | Low Pollution | 0.987 | Insignificant Pollution |
### Table 6. Three PIG values and evaluation results of 14 confined groundwater samples.

| Sample Number | PIG  | Evaluation Result | CRITIC-PIG | Evaluation Result | Entropy-PIG | Evaluation Result |
|---------------|------|-------------------|------------|-------------------|-------------|-------------------|
| C1            | 0.204| Insignificant Pollution | 0.294 | Insignificant Pollution | 0.229 | Insignificant Pollution |
| C2            | 0.291| Insignificant Pollution | 0.461 | Insignificant Pollution | 0.331 | Insignificant Pollution |
| C3            | 0.282| Insignificant Pollution | 0.443 | Insignificant Pollution | 0.326 | Insignificant Pollution |
| C4            | 0.690| Insignificant Pollution | 0.963 | Insignificant Pollution | 0.781 | Insignificant Pollution |
| C5            | 0.630| Insignificant Pollution | 0.850 | Insignificant Pollution | 0.716 | Insignificant Pollution |
| C6            | 0.601| Insignificant Pollution | 0.697 | Insignificant Pollution | 0.532 | Insignificant Pollution |
| C7            | 0.819| Insignificant Pollution | 1.190 | Low Pollution | 0.926 | Insignificant Pollution |
| C8            | 0.552| Insignificant Pollution | 0.853 | Insignificant Pollution | 0.626 | Insignificant Pollution |
| C9            | 0.837| Insignificant Pollution | 0.948 | Insignificant Pollution | 0.850 | Insignificant Pollution |
| C10           | 0.350| Insignificant Pollution | 0.472 | Insignificant Pollution | 0.365 | Insignificant Pollution |
| C11           | 0.354| Insignificant Pollution | 0.609 | Insignificant Pollution | 0.435 | Insignificant Pollution |
| C12           | 1.697| Moderate Pollution | 0.549 | Insignificant Pollution | 0.904 | Insignificant Pollution |
| C13           | 0.622| Insignificant Pollution | 0.925 | Insignificant Pollution | 0.718 | Insignificant Pollution |
| C14           | 0.825| Insignificant Pollution | 1.226 | Low Pollution | 0.959 | Insignificant Pollution |

By applying those three models, the classification results were not totally consistent with each other, with 25 of 48 water samples having the same evaluation results. Considering their respective consistency, between the PIG model and the two improved PIG models, the consistency values were 56.3% (CRITIC-PIG) and 79.2% (Entropy-PIG) and between the two improved models, this was 62.5%. As for those samples having divergent evaluation results, the level difference was mostly 1, which demonstrated the relatively convincing and correct results.

#### 4.5. Distribution Map of Three PIG Values

The spatial-distribution maps of PIG, CRITIC-PIG and Entropy-PIG are plotted in Figure 10. Compared with Yushu City and Nongan County, the groundwater pollution level in Dehui City was relatively low, with the predominance of insignificantly polluted areas and lowly polluted areas based on the three models. Yushu City showed a progressive increase in the pollution level from the southwestern part to the northeastern part and large, while this tendency was not obvious in the distribution map of the CRITIC-PIG values. Combined with Figure 7, it was concluded that the high level of pollution resulted from the high concentration of Fe$^{3+}$ in the northeast. As for Nongan County, lowly and moderately contaminated regions occupied a large proportion, and highly and very highly polluted areas were spread in the northeastern and southern parts, which was due to the high levels of TDS, TH, NO$_3^-$ and F$^-$ contents, as can be seen in Figure 7.

#### 4.6. Sources of Pollution

Judging whether the $O_w$ (overall water quality) value is over 0.1 provides a means to determine the general source of pollution [15,48]. If the value is below 0.1, pollution mainly comes from geogenic sources, while if the value is over 0.1, pollution caused by anthropogenic activities could not be negligible. Considering the five pollution-level zones, Tables 7–9 list the average $O_w$ values of the 12 chemical indexes obtained using the PIG, the CRITIC-PIG and the Entropy-PIG models. The results showed that the $O_w$ value of the 12 chemical indexes generally tended to increase from the insignificant-pollution level to the moderate-pollution level, while for the high and very high levels, this tendency was not noticeable because the total number was relatively limited and they had some very high values of certain indexes. It was concluded that the higher the pollution level was, the greater impact human activities had on the deterioration of groundwater quality. From the analyses using the PIG, CRITIC-PIG and Entropy-PIG models, 87.5%, 97.9% and 91.7% of the water samples, respectively, had at least one parameter’s $O_w$ value over 0.1, indicating that the pollution contribution in the study area was not only ascribable to geogenic sources but also to anthropogenic sources. Considering the results of the Gibbs diagrams, geogenic
sources were mainly the weathering and dissolution of rocks and minerals. Based on the background of the study area, anthropogenic sources were mainly agricultural activities such as the excessive use of chemical fertilizers and pesticides, industrial activities and domestic waste. As a well-known corn belt zone, the intense use of agrochemical products, especially phosphate and nitrogen fertilizers, in the study area significantly elevates the concentrations of NO$_3^-$, which can be seen from Figure 7, and is likely to be associated with the occurrence of potentially toxic elements in groundwater (e.g., As, Cd, Cr, Cu, Zn), according to cutting-edge research [49], which thus degrade groundwater quality and affect human health.

![Image](image_url)

**Figure 10.** Distribution maps of PIG values, CRITIC-PIG values and Entropy-PIG values in the study area: (a) PIG values; (b) CRITIC-PIG values; (c) Entropy-PIG values.

**Table 7.** Average values of the overall water quality of each chosen parameter in five pollution-level zones obtained using the PIG model.

| TDS   | TH   | Ca$^{2+}$ | Mg$^{2+}$ | Na$^+$ | K$^+$ | HCO$_3^-$ | Cl$^-$ | SO$_4^{2-}$ | NO$_3^-$ | F$^-$ | Fe$^{3+}$ | PIG   | Pollution Level |
|-------|------|-----------|-----------|--------|-------|-----------|--------|------------|----------|-------|-----------|------|-----------------|
| 0.126 | 0.105| 0.067     | 0.022     | 0.020  | 0.002 | 0.066     | 0.021  | 0.024      | 0.058   | 0.033 | 0.057     | 0.602| Insignificant  |
| 0.237 | 0.228| 0.147     | 0.054     | 0.034  | 0.002 | 0.098     | 0.051  | 0.077      | 0.118   | 0.060 | 0.071     | 1.177| Low           |
| 0.249 | 0.198| 0.119     | 0.048     | 0.058  | 0.002 | 0.082     | 0.072  | 0.070      | 0.135   | 0.150 | 0.661     | 1.844| Moderate      |
| 0.317 | 0.170| 0.085     | 0.077     | 0.098  | 0.068 | 0.082     | 0.053  | 0.105      | 0.202   | 0.243 | 0.699     | 2.200| High          |
| 0.199 | 0.193| 0.110     | 0.050     | 0.027  | 0.004 | 0.092     | 0.044  | 0.111      | 0.001   | 0.041 | 3.720     | 4.592| Very High     |

**Table 8.** Average values of the overall water quality of each chosen parameter in five pollution-level zones obtained using the CRITIC-PIG model.

| TDS   | TH   | Ca$^{2+}$ | Mg$^{2+}$ | Na$^+$ | K$^+$ | HCO$_3^-$ | Cl$^-$ | SO$_4^{2-}$ | NO$_3^-$ | F$^-$ | Fe$^{3+}$ | CRITIC-PIG | Pollution Level |
|-------|------|-----------|-----------|--------|-------|-----------|--------|------------|----------|-------|-----------|------------|-----------------|
| 0.211 | 0.164| 0.080     | 0.008     | 0.015  | 0.002 | 0.157     | 0.010  | 0.012      | 0.013    | 0.004 | 0.033     | 0.708      | Insignificant  |
| 0.405 | 0.330| 0.182     | 0.012     | 0.016  | 0.001 | 0.174     | 0.033  | 0.024      | 0.037    | 0.003 | 0.015     | 1.233      | Low           |
| 0.497 | 0.429| 0.205     | 0.025     | 0.038  | 0.002 | 0.268     | 0.039  | 0.046      | 0.032    | 0.012 | 0.111     | 1.704      | Moderate      |
| 0.708 | 0.550| 0.248     | 0.036     | 0.066  | 0.002 | 0.356     | 0.048  | 0.070      | 0.050    | 0.027 | 0.002     | 2.162      | High          |
| 0.843 | 0.582| 0.290     | 0.025     | 0.054  | 0.054 | 0.224     | 0.073  | 0.083      | 0.082    | 0.010 | 0.329     | 2.649      | Very High     |
Table 9. Average values of the overall water quality of each chosen parameter in five pollution-level zones obtained using the Entropy-PIG model.

| Parameter | Pollution Level |
|-----------|----------------|
| TDS       | 0.055          |
| TH        | 1.243          |
| Ca^{2+}   | 0.657          |
| Mg^{2+}   | 0.142          |
| Na^{+}    | 0.188          |
| K^{+}     | 0.030          |
| HCO_{3}^- | 0.002          |
| Cl^-      | 0.021          |
| SO_{4}^{2-}| 0.010          |
| NO_{3}^-  | 0.004          |
| F^-       | 0.018          |
| Fe^{3+}   | 0.018          |

5. Conclusions

Considering the subjectivity of the traditional PIG values, the two improved PIG methods, which combine the subjective weight and the objective weight, were utilized to determine the groundwater suitability for drinking purposes in the northern part of Changchun City. In addition, graphical methods (Piper diagram and Gibbs diagrams) were employed to study the hydrochemical characteristics of groundwater. The major conclusion are listed below.

(1) Showing to be weakly alkaline, groundwater in the study area abounded in the HCO_{3}^-Ca type. According to the Gibbs diagrams, the chemical composition of groundwater was dominated by water–rock interaction, with a small fraction of water samples being controlled by evaporation processes.

(2) The values of the PIG, CRITIC-PIG and Entropy-PIG ranged from 0.204 to 7.114, from 0.294 to 2.795 and from 0.229 to 3.985, respectively, and classified 60.4%, 47.9% and 60.4% of the water samples into insignificant pollution; 18.8%, 20.8% and 18.8% of the water samples into low pollution; 8.3%, 18.8% and 10.4% of the water samples into moderate pollution; 6.25%, 6.25% and 8.3% of the water samples into high pollution; and 6.25%, 6.25% and 2.1% of the water samples into very high pollution. In total, 52% of the water samples had the same evaluation results based on the three methods, and the same evaluation results occurred in the percentages of 56.3%, 79.2% and 62.5% between PIG and each of the two methods, and between CRITIC-PIG and Entropy-PIG, respectively. The level difference among the samples having different results using the three models was mostly one, which indicated that the results were relatively convincing.

(3) Pollution came not only from geogenic sources (weathering and dissolution of rocks and minerals, evaporation) but also anthropogenic sources (agricultural activities, industrial activities and domestic waste) based on the O_{w} (overall water quality) index.

(4) The distribution map of the three PIG values demonstrated that groundwater in Dehui City was the most suitable for drinking, with the dominance of insignificantly and lowly contaminated regions. Yushu City showed a progressive increase in the pollution level from the southwestern part to the northeast by and large, and the high-pollution areas were mainly affected by the high concentrations of Fe^{3+} in the northeast. Occupying a large area of lowly and moderately polluted regions, groundwater quality in Nongan County was worse than that in the other two cities. High levels of TDS, TH, NO_{3}^- and F^- contributed to highly and very highly polluted groundwater in the northeastern and southern parts.

(5) The results of the present research study provided an overall groundwater pollution status for drinking purposes in the north of Changchun City, which could be useful for the relevant authorities to take some protective and remedial measures for the guarantee of high-quality drinking groundwater for the people. However, due to the lack of sufficient water samples, a further groundwater quality investigation needs to be carried out in the study area, especially in those places whose PIG, CRITIC-PIG or Entropy-PIG values were over 1, aiming to obtain more accurate results.
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