Postprint: Effect of Pore Confined Groundwater Depth on Water Quality in the Yancheng Coastal Alluvial Plain

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Abstract

The spatial structure of aquifer(s) not only determines the spatial distribution pattern of groundwater, but also exerts a certain influence on groundwater quality conditions. Based on hydrogeological borehole data within the hydrogeological zoning of the Yancheng coastal plain and water quality factor monitoring data from 2005-2014, and comprehensively employing GIS and ANOVA methods, this study investigated the response characteristics of pore groundwater quality in the confined aquifer III of the experimental sample area to variations in aquifer roof burial depth across spatio-temporal dimensions, analyzed the dynamic evolution patterns of groundwater quality, and proposed recommendations for groundwater management and protection in the study area. The research results indicate that the burial depth of confined aquifer III in this area is predominantly located between -118.9 and -85.45 m; due to differences in hydrogeological conditions and exploitation/utilization status of groundwater at various burial depths, a certain correlation exists between typical groundwater quality factor concentrations and aquifer burial depth: mineralization, total alkalinity, and total bacterial count exhibited the highest correlation strength with burial depth (correlation degrees of 69.67%, 75.76%, and 58.09%, respectively), the correlation strength of the total hardness factor was at a moderate level (49.18%); potassium permanganate index was less affected by burial depth (35.27%); additionally, it was found that the correlation strength between each factor and burial depth varied significantly across different burial depth classification intervals, displaying distinct dynamic evolution characteristics.

Full Text

Preamble

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Influence of Pore Confined Groundwater Depth on the Groundwater Quality of the Alluvial Coastal Plain of Yancheng

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Abstract

Pore confined groundwater is an important freshwater resource for human beings, stored in systems of loose sedimentary aquifers. The spatial structure of an aquifer (or aquifer group) determines not only the spatial distribution pattern of groundwater but also influences groundwater quality. Based on hydrogeological data and groundwater quality monitoring data collected between 2005 and 2014 in the Yancheng coastal plain of China, methods including GIS and ANOVA were used to study the relationship between groundwater quality and the buried depth of the third confined aquifer. The dynamic evolution characteristics of groundwater quality were also analyzed, and recommendations were proposed to the local water resources management department.

Firstly, based on hydrogeological data in the study area, a Digital Elevation Model (DEM) of the aquifer roof burial depth was constructed and divided into 10 grades. The correlation between water quality factors and aquifer burial depth was analyzed using variance analysis. The least significant difference method was used to determine the influence of different grading intervals on water quality factors. The average value of monitored data for each year and each burial depth interval was calculated, and time-varying process curves of water quality factor levels were plotted to show the spatial and temporal variation of water quality factors with aquifer depth.

The results showed that: (1) In the study area, the III confined aquifer burial depth is mostly located between -118.9 m and -85.45 m. Owing to the variety of hydrogeological conditions and different buried depths, some correlation between typical groundwater quality and aquifer burial depth is presented. Mineralization degree, total alkalinity, and total bacterial count show the highest correlation with groundwater burial depth (69.67%, 75.76%, and 58.09% respectively). The correlation between total hardness factor and depth is moderate (49.18%). The potassium permanganate index is less influenced by burial depth

(35.2%). (2) It was found that the correlation between each factor and groundwater burial depth in each buried depth grading interval showed significantly different dynamic evolution characteristics. In the area where the aquifer was deeply buried (-160.8 m to -99.12 m), total hardness, mineralization degree, and total bacterial count were significantly affected by burial depth. The potassium permanganate index content only showed a significant difference with depth in specific intervals (between -99.12 m and -92.91 m and between -85.45 m and -75.09 m). (3) In addition, water quality factors showed different spatial distribution characteristics: the area with higher potassium permanganate index and total bacteria is mainly located between Sheyang County and Huangsha Port. The highest mineralization factor content values were found in the middle and western regions, while total alkalinity and total hardness varied little; total alkalinity was slightly lower in the shallow buried area, and total hardness showed some upward trend.

Keywords: confined aquifer; groundwater quality; aquifer burial depth; correlation; dynamic evolution characteristics

Introduction

Pore confined groundwater is widely distributed in the central parts of plains or basins. Generally deeply buried with closed geological structures and minimal climate influence, it represents an important water supply source for human populations. With rapid socioeconomic development, demand for groundwater resources has increased annually, leading to intensified exploitation. While this groundwater typically exhibits good quality and is less susceptible to pollution, excessive extraction has caused serious environmental problems and significant changes to the groundwater environment.

The Yancheng coastal plain is located in the central part of China’ s eastern coast. Pore confined groundwater buried deep beneath the surface has gradually become the main water supply source for many towns and cities in this region. In recent years, with population growth and rapid industrial and agricultural development, the area has experienced a series of groundwater environmental problems, including water level decline, saline water intrusion, and land subsidence due to concentrated exploitation in local areas. The region contains loose sedimentary strata of Tertiary and Quaternary systems, forming a huge loose pore water-bearing system. Among these, the water stored in phreatic and first confined aquifers has relatively high salinity, while water in the second and third confined aquifers offers better quality and serves as the primary water source.

Current research on groundwater quality distribution and evolution patterns in coastal plain areas is of practical significance for groundwater resource protection and production guidance. Existing studies in this region have mostly focused on groundwater quality surveys and analysis. For example, Chen Hongwei extracted monitoring data from 50 representative water quality wells in Yancheng City to analyze spatial and temporal distribution trends of mineralization and ammonia nitrogen. Bian Jinyu analyzed control factors of Yancheng’ s groundwater quality using principal component analysis based on water quality monitoring data. While these studies achieved quantitative description and analysis of spatiotemporal dynamic changes in groundwater quality, research on influencing factors of groundwater quality changes remains limited.

Numerous studies on groundwater quality influencing factors exist domestically and internationally. Liao Zisheng et al. analyzed factors affecting water quality changes in the Songnen Basin groundwater system. Han Yinli et al. constructed a mathematical model between groundwater mineralization and aquifer resistivity based on electrical sounding data for deep groundwater exploration in the Yinchuan Plain. Tang Changyuan et al. studied the impact of upstream wetlands on groundwater quality in Chiba City, Japan, noting that wetlands have a certain inhibitory effect on nitrate content in groundwater. Serhal et al. investigated the influence of fertilizers and pollutants on groundwater quality in the Cambrai region of France. These studies, employing different methods, revealed the influence mechanisms of various factors on the spatiotemporal distribution characteristics of groundwater quality, providing valuable references for dynamic change studies of groundwater quality in Yancheng’ s coastal hydrogeological zones. However, research on influencing factors of groundwater quality within Yancheng’ s coastal plain hydrogeological zones remains insufficient.

Given that aquifer burial depth is a typical characteristic of aquifer spatial distribution that influences the spatiotemporal evolution of certain groundwater quality factors to some extent, this study examines the correlation between groundwater quality factor concentrations and aquifer burial depth from the perspective of aquifer spatial distribution patterns. Based on hydrogeological borehole data and dynamic water quality monitoring data in the study area, we extracted stratification information of the target confined aquifer from boreholes and used ANOVA statistical analysis methods to reveal the influence degree of the third confined aquifer depth on pore groundwater quality in Yancheng’ s coastal plain hydrogeological zone, providing references for scientific management and protection of pore groundwater resources.

1. Study Area Overview

The study area is located in the northern part of the Yancheng coastal plain hydrogeological zone, between 33°15 –34°12 N and 119°34 –120°41 E, bounded by the Northern Jiangsu Irrigation Main Canal to the north and the Doulong Port to the south. The plain was formed by continuous alluviation from seawater and rivers over nearly 3,000 years and continues to extend seaward today. The total area is approximately 6,177.11 km^2. The terrain slopes gently from southeast to northwest, with higher elevations of 3-5 m in Dafeng territory gradually decreasing to about 1-1.5 m at the Sheyang River. The area features flat terrain with dense river networks, forming a coastal water network plain geomorphology.

Location and extent of study area

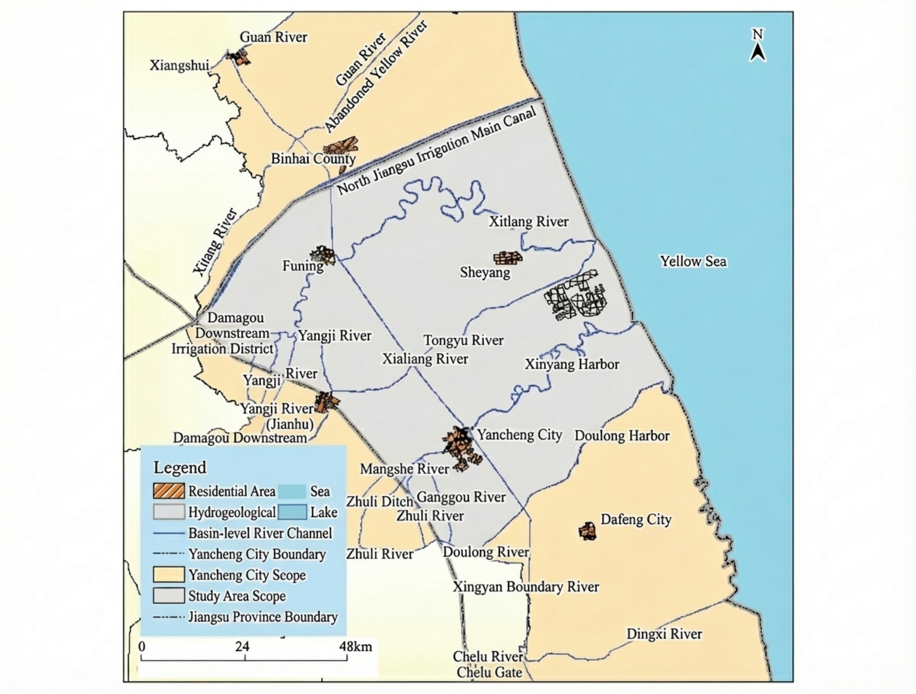

Figure 1: Figure 1

2. Hydrogeological Conditions of the Study Area

Confined groundwater in the study area mainly occurs in the pores of loose sedimentary rock layers. These layers, composed of sand, gravel, or limestone, form a loose sedimentary aquifer system with abundant water content. According to sediment age, stratigraphic structure, and hydrogeological characteristics, the Tertiary and Quaternary systems have developed three aquifer groups. Clay or silty clay layers form aquitards between different aquifers. Pore phreatic and micro-confined water mainly receive recharge from atmospheric precipitation and surface water infiltration from agricultural irrigation, with discharge through evaporation and exploitation. Confined water quality is slightly saline, with artificial exploitation as the main discharge method, receiving recharge from upward leakage and lateral inflow from mountains in the west-central region.

The confined aquifer is composed of medium-fine sand and medium-coarse sand from the Lower Pleistocene, with good water yield properties. As the main exploitation layer of regional groundwater and closely related to human activities, the third confined aquifer was selected as the research object, with burial depths ranging from 20.00-35.00 m.

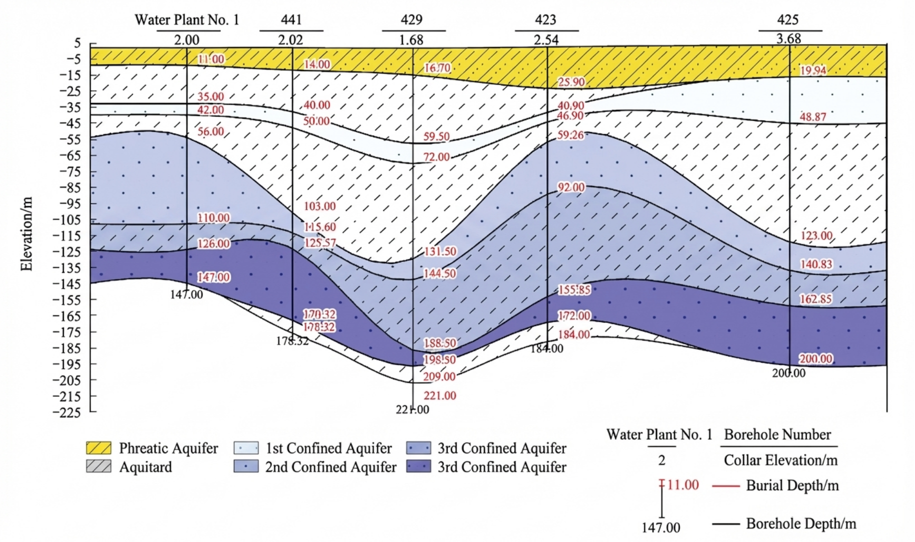

Figure 2: Figure 2

Confined groundwater burial conditions schematic

3. Methods

3.1 Data Sources

Research data included 35 hydrogeological borehole exploration data points within Yancheng City, from which the third confined aquifer roof burial depth information was extracted to produce aquifer distribution maps. Combined with groundwater dynamic change patterns and aquifer burial depth classification thematic maps, 9 dynamic monitoring wells were selected. The study used water quality monitoring data from 2005-2014. Location information for each borehole and monitoring well was obtained through Xi’ an 1980 Gauss-Krüger projection coordinates with 3-degree zones.

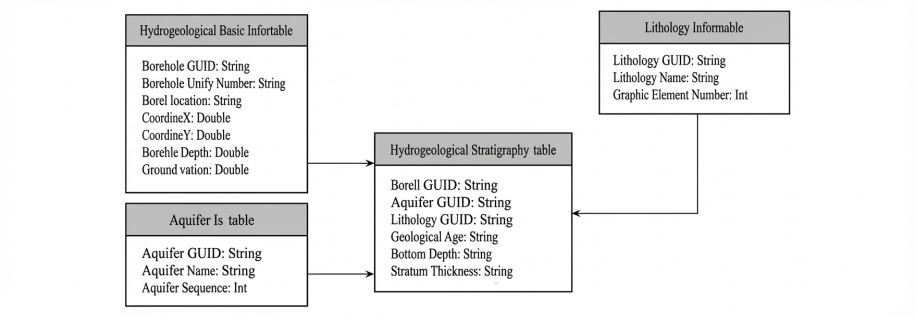

Figure 3: Figure 3

Spatial distribution map of hydrogeological bore and groundwater monitoring well

3.2 Water Quality Factor Classification

Yancheng coastal plain has numerous groundwater quality monitoring factors. Based on regional groundwater distribution characteristics, the Groundwater Environmental Quality Standard (GB/T 14848-93), and considering local water quality monitoring practices and the impact of different indicators on industrial, agricultural production and human life, five factors were selected for analysis: mineralization degree, total hardness, total alkalinity, potassium permanganate index, and total bacterial count.

3.3 Aquifer Burial Depth Processing

Original data from hydrogeological borehole exploration in the study area were interpreted to generate standardized hydrogeological borehole cards and establish a hydrogeological borehole database. The database structure is shown in

. Based on this structure, a stratigraphic burial depth data extraction algorithm was designed to read each borehole’ s location coordinates and stratigraphic

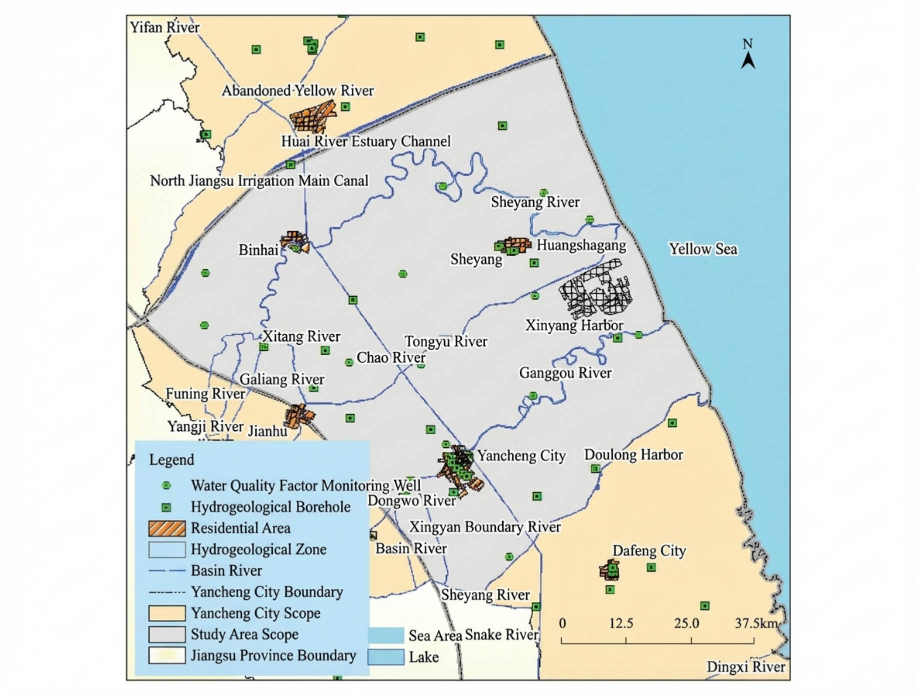

Figure 4: Figure 4

burial depth from the database, forming original stratigraphic interface sampling points. These sampling points were imported into ArcGIS to call spatial interpolation tools for establishing an irregular triangular network (TIN) model of the stratigraphic interface. After rasterizing this model and intersecting it with the study area boundary layer, the aquifer roof elevation Digital Elevation Model (DEM) was obtained.

Considering both modeling area and burial depth variation, a raster cell size of 500 m × 500 m was adopted. The maximum elevation of the third confined aquifer roof was -55.19 m, and the minimum was -160.87 m. To study the correlation between burial depth and water quality, continuous burial depth values were classified. Based on the water quality monitoring well spatial distribution map, classification trials were conducted to ensure water quality factor distribution patterns showed good differentiation. Ten equal intervals could comprehensively display the spatial distribution characteristics of the aquifer. The study area aquifer burial depth and classification results are shown in

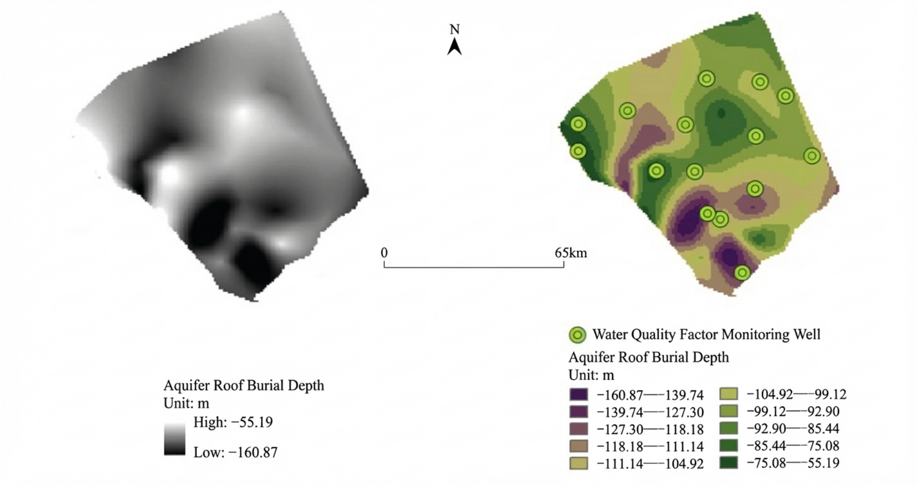

Figure 5: Figure 5

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Hydrogeological bore database structure

Aquifer III roof burial depth DEM and its classification

3.4 Data Processing

3.4.1 Time-Based Single Well Data Processing The confined aquifer is deeply buried with closed geological structure, stable groundwater environment, and smooth water quality changes. Local water management departments have conducted only one water quality sampling per year since 2005. For analysis

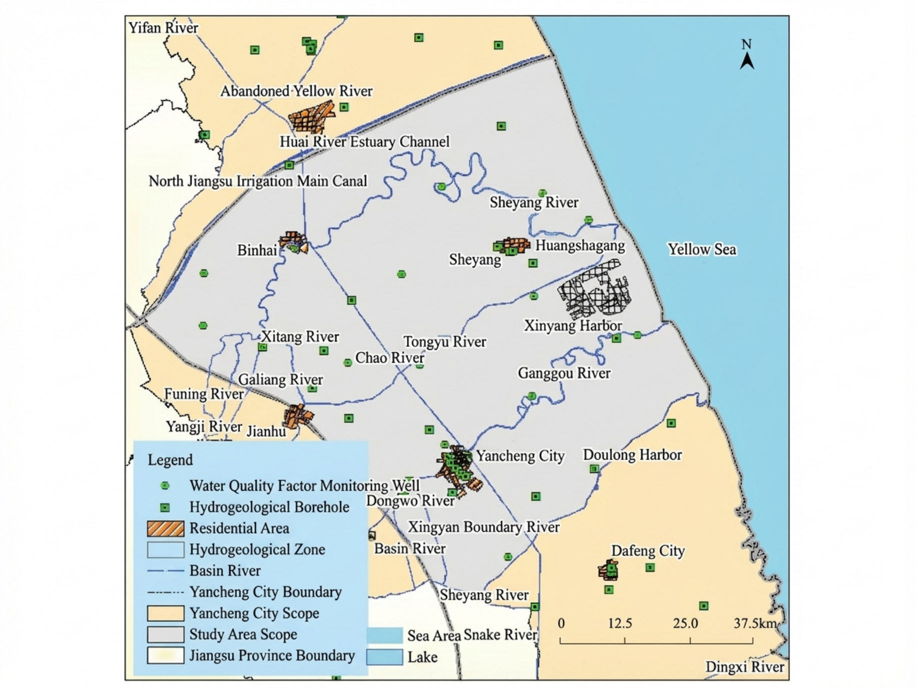

Figure 6: Figure 4

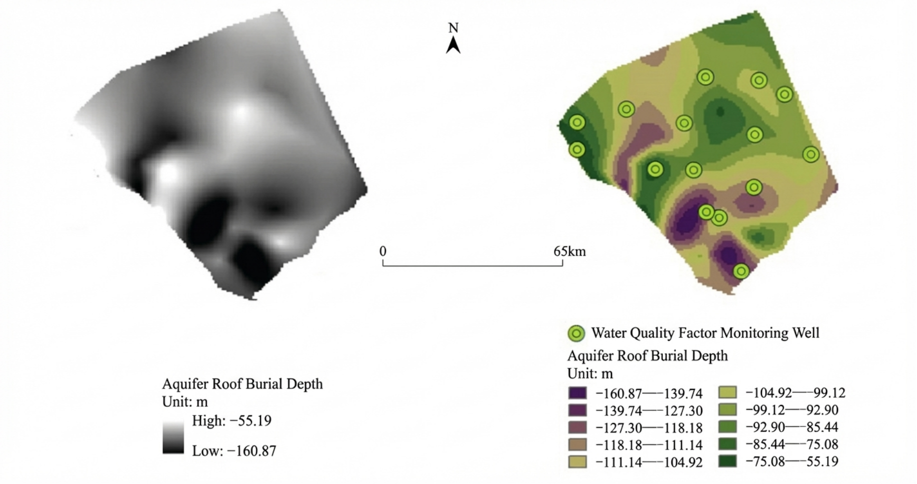

Figure 7: Figure 5

convenience, if a year contained multiple samplings, the average of the sampling values was taken as the annual sampling value, given the stability of water quality changes. The processed monitoring well water quality factor data structure is shown in .

Monitoring well 1# data structure

3.4.2 Spatial Monitoring Data Statistical Processing Different burial depth classification regions show significant area and distribution differences. To ensure continuity of burial depth classification elevation values, a few burial depth classification intervals without monitoring wells were merged into adjacent intervals. After processing, 9 effective classification intervals were obtained. Using overlay analysis tools, monitoring wells within each classification interval were obtained. Since each interval contained varying numbers of monitoring wells, all historical monitoring data from these wells were used as samples to form the water quality factor monitoring data structure shown in .

Valid burial depth classification interval and equivalent water quality sampling data structure

4. Analysis and Discussion

4.1 Basic Characteristics of Confined Aquifer Burial Depth Distribution

Analysis of hydrogeological borehole data and aquifer roof burial depth characteristics in the study area indicates that the third confined aquifer burial depth varies significantly across the study area. The deepest roof elevation is approximately -160.88 m, and the shallowest is about -55.19 m, showing obvious depth variation. In the open coastal areas of the eastern and northern parts of the study area, the aquifer is influenced by sedimentation with gentle trends and shallow burial. In the narrow western zone, the Xitang River develops to form a plain water network, where river cutting is significant and causes notable changes in aquifer burial depth. The aquifer gradually rises from southwest to northeast, showing a distribution pattern roughly opposite to ground surface elevation. The Dongwo River basin exhibits obvious groundwater burial depth changes with deep burial, while the area near the irrigation main canal' s estuary tends to be gentle with shallow aquifer burial.

The roof elevation is located between -118.9 m and -85.45 m in most regions, accounting for 54.26% of the total study area. Areas with roof elevation below -129.31 m and above -75.05 m occupy 21.45% and 7.14% of the study area respectively, mostly distributed in the mountainous regions of the central-western part of the study area.

Aquifer III burial depth height classification and percentage

4.2 Significance Analysis of Aquifer Burial Depth Impact on Water Quality Factors

4.2.1 Hypothesis Testing To test whether aquifer burial depth has significant impact on water quality factors, the following hypothesis was proposed in the form of H : = = ···= (i = 1, 2, ···, 9), where represents the overall mean of water quality factor monitoring samples in the i-th classification interval. The null hypothesis means that the overall means of water quality factor monitoring values in different burial depth classification intervals are equal, indicating no significant burial depth effect on water quality. The alternative hypothesis H indicates that not all are equal, suggesting a significant correlation between aquifer burial depth and water quality.

4.2.2 ANOVA Analysis ANOVA is a statistical method that uses sampling data to test whether multiple population means are equal. By calculating total error (SST), level term sum of squares (SSA), and error term sum of squares (SSE), it constructs test statistics to study the impact of categorical independent variables on numerical dependent variables. After processing water quality sampling data temporally and spatially, data were imported for significance testing of correlation hypotheses with significance level set at 0.05.

The ANOVA analysis results are shown in . The table presents the sum of squares due to depth (SSA) measuring the effect of burial depth on water quality factors, and SSE representing error sum of squares caused by other factors including sampling error, groundwater flow velocity, and aquifer lithology.

ANOVA result table of water quality monitoring data

4.2.3 Statistical Decision and Correlation Measurement According to ANOVA principles and results, the critical value F was found in the F-distribution table with numerator degrees of freedom 8 and denominator degrees of freedom 261 at = 0.05, yielding F = 2.01. The test statistic F = MSA/MSE was calculated and compared with the critical value. From the calculation results, the statistical values for mineralization degree, total alkalinity, and total bacterial count are 15.44, 22.054, and 8.34 respectively, far exceeding the test critical value, indicating that burial depth significantly affects these water quality factors. The statistical values for potassium permanganate index and total hardness are 5.34, showing they are less affected by burial depth but still have some influence.

The relationship strength between burial depth and water quality factor content can be measured using R^2 = SSA/(SSE+SSA). The R^2 values for mineralization degree, total alkalinity, and total bacterial count are 48.53%, 57.39%, and 33.74% respectively, indicating that burial depth explains these proportions of total variation in the three water quality factor contents. The R^2 value for total hardness is 24.58%, showing burial depth explains only 24.58% of total hardness variation. The R^2 value for potassium permanganate index is 12.44%, with its square root R = 35.27%, indicating weak correlation between the two variables.

4.3 Multiple Comparison Analysis

Since the relationships between the five water quality factor contents and burial depth all reached statistical significance, multiple comparison analysis was introduced to determine which specific elevation classification intervals show the most significant differences. The Least Significant Difference (LSD) method, which uses t-tests for pairwise comparison of grouped data to detect 微小差异 between different population levels, was applied.

Given that the study area was divided into 9 different elevation classifications with continuous distribution from low to high, the test hypothesis for the i-th group can be described as H : = (j = i+1). The LSD value was calculated using the formula LSD = t / × √[MSE×(1/n + 1/n)], where n represents the sample capacity of the i-th classification interval, and the t-distribution degrees of freedom is n-k.

From the t-distribution table, the critical value t / = t . = 1.980 was obtained. Using MSE and test statistics from , multiple analysis results for each water quality factor were calculated as shown in .

Multiple comparative analysis result

Decision and Analysis: By comparing test statistics with LSD values, if the statistical value exceeds LSD, the null hypothesis is rejected, indicating significant differences in water quality factor content between the two burial depth classifications; otherwise, the difference is not significant. Results show that mineralization degree factors in tests 1-4, 7, and 8; total alkalinity factors in tests 1, 2, 3, 4, and 7; and total bacterial count factors in tests 2, 3, 4, and 7 show significant differences.

From the elevation classification data, total hardness, mineralization degree, and total bacterial count are significantly affected by burial depth in deeply buried aquifer regions (-160.8 to -99.12 m), corresponding to 54.26% of the total study area. Total alkalinity factors show significant differences in both deeply and shallowly buried areas, accounting for 31.6% of the study area. Potassium permanganate index factors only show significant differences in specific intervals (-99.12 to -92.91 m and -85.45 to -75.09 m), occupying 47.26% of the study area, indicating that potassium permanganate index content has a certain correlation with aquifer burial depth at these locations.

4.4 Distribution and Evolution Characteristics of Water Quality Factors with Burial Depth

To reflect spatial and temporal variation characteristics of water quality factors with burial depth, monitoring wells within each burial depth classification zone were first counted. The average value of all monitoring data from wells in the same burial depth classification interval for a given year was used to represent the water quality condition of that burial depth zone in that year. [FIGURE:6] shows statistical curves of mineralization degree, total hardness, total alkalinity, potassium permanganate index, and total bacterial count varying with burial depth classification in different years.

Overall, confined groundwater quality factors show relatively small changes in total alkalinity and total hardness, while potassium permanganate index, total bacterial count, and mineralization degree show greater variation, particularly in shallow aquifer burial areas. Total bacterial count peaked in 2014, indicating a worsening pollution trend. The interval (-92.91, -85.45) is the dominant distribution depth for potassium permanganate index, while (-85.45, -75.09) is the dominant interval for total bacterial count. Potassium permanganate index shows an increasing trend in most intervals. The significant increase in total bacterial count in groundwater with aquifer burial depth less than -104.92 m is due to intensified impact of human waste discharge on shallow groundwater.

Total hardness and total alkalinity dominant distribution depth intervals are (-118.9, -99.12). Compared with potassium permanganate index and total bacterial count, changes between 2005-2014 were not significant. However, for aquifers with burial elevation above -104.92 to -99.12 m, total hardness shows a slight increase, attributed to continuously increasing groundwater exploitation intensity in the shallow coastal areas of the eastern region. Groundwater salinity is typically higher in these areas, especially in the eastern reclamation and beach areas, showing an obvious growth trend in recent years due to coastal salt field development and seawater intrusion. Mineralization degree content is higher in the middle and western regions of the aquifer, which may adversely affect domestic water supply for residents. Total alkalinity factor shows higher content in shallow burial areas and intervals (-111.14, -104.92), indicating stronger buffering capacity of water bodies in these zones. However, due to water level decline and volume reduction caused by groundwater exploitation, total alkalinity shows a slight decreasing trend within the overall stable pattern, which should be given attention.

[FIGURE:6] Different water quality curve alone with aquifer burial depth variance

5. Conclusions and Discussion

This study combined water quality monitoring practices and groundwater utilization status in the sample area to analyze the response characteristics of typical water quality factor dynamic changes to aquifer burial depth factors, yielding the following conclusions:

1. The confined aquifer, as the main exploitation layer in the area, shows uneven spatial distribution of burial depth, presenting a trend of gradual uplift from west to east. The southwestern region shows significant depth variation, while the central and northeastern regions show relatively gentle

changes. Most regional aquifer burial depths are located between -118.9 m and -85.45 m, accounting for 54.26% of the total study area.

2. Confined groundwater quality in the study area shows significant correlation with aquifer burial depth factors. Mineralization degree, total alkalinity, and total bacterial count show the highest correlation strength with burial depth, with corresponding R values of 69.67%, 75.76%, and 58.09%. Total hardness correlation strength reaches a near-moderate level (R = 49.18%). Potassium permanganate index is limitedly affected by burial depth, with R = 35.27%.
3. In deeply buried aquifer regions (-160.8 to -99.12 m), total hardness, mineralization degree, and total bacterial count are significantly affected by burial depth factors, accounting for 54.26% of the total area. Potassium permanganate index only shows significant differences in specific burial depth intervals (-99.12 to -92.91 m and -85.45 to -75.09 m), accounting for 47.26% of the total area.
4. Potassium permanganate index and total bacterial count show higher content in groundwater with burial depth between -85.45 and -75.09 m, mainly distributed between Sheyang County and Huangsha Port, showing an increasing trend in recent years under human exploitation and waste discharge impacts. Mineralization degree shows higher content in the middle and western regions of the aquifer, which has increased in recent years due to coastal salt field development and seawater intrusion, potentially adversely affecting residents' domestic water supply. Total alkalinity and total hardness show little overall change, with dominant distribution depth intervals of -111.14 to -104.92 m. Total hardness shows a slight increase in shallow burial areas, indicating that the suitability of eastern groundwater for industrial and agricultural production may be affected.

Factors influencing groundwater quality include groundwater flow velocity, seawater intrusion, lithology, and hydraulic properties. Future research directions include extracting and quantifying other factors and conducting joint analysis under multiple factor influences.

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