Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

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Citation:
Yu C, Wu LJ, Zhang YL, *et al*. 2022. Effect of groundwater on the ecological water environment of typical inland lakes in the Inner Mongolian Plateau. Journal of Groundwater Science and Engineering, 10(4): 353-366.

View online: https://doi.org/10.19637/j.cnki.2305-7068.2022.04.004

Journal homepage: http://gwse.iheg.org.cn

Effect of groundwater on the ecological water environment of typical inland lakes in the Inner Mongolian Plateau

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Abstract: To explore the causes of the ecological environment deterioration of lakes in the Inner Mongolia Plateau, this study took a typical inland lake Daihai as an example, and investigated the groundwater recharge in the process of lake shrinkage and eutrophication. Using the radon isotope (^{222}Rn) as the main means of investigation, the ^{222}Rn mass balance equation was established to evaluate the groundwater recharge in Daihai. The spatial variability of ^{222}Rn activity in lake water and groundwater, the contribution of groundwater recharge to lake water balance and its effect on nitrogen and phosphorus pollution in lake water were discussed. The analysis showed that, mainly controlled by the fault structure, the activity of ^{222}Rn in groundwater north and south of Daihai is higher than that in the east and west, and the difference in lithology and hydraulic gradient may also be the influencing factors of this phenomenon. The ^{222}Rn activity of the middle and southeast of the underlying lake is greater, indicating that the ^{222}Rn flux of groundwater inflow is higher, and the runoff intensity is greater, which is the main groundwater recharge area for the lake. The estimated groundwater recharge in 2021 was 3 017×10^4 m^3, which was 57% of the total recharge to the lake, or 1.6 times and 8.1 times that of precipitation and surface runoff. The TN and TP contents in Daihai have been rising continuously, and the average TN and TP concentrations in the lake water in 2021 were 4.21 mg·L^{-1} and 0.12 mg·L^{-1}, respectively. The TN and TP contents entering the lake with groundwater recharge were 6.8 times and 8.7 times above those of runoff, accounting for 87% and 90% of the total input, respectively. The calculation results showed that groundwater is not only the main source of recharge for Daihai, but also the main source of exogenous nutrients. In recent years, the pressurized exploitation of groundwater in the basin is beneficial in increasing the groundwater recharge to the lake, reducing the water balance difference of the lake, and slowing down the shrinking degree of the lake surface. However, under the action of high evaporation, nitrogen and phosphorus brought by groundwater recharge would become more concentrated in the lake, leading to a continuous increase in the content of nutrients and degree of eutrophication. Therefore, the impact of changes in regional groundwater quantity and quality on Daihai is an important issue that needs further assessment.

Keywords: Groundwater recharge; Radon isotopes; Nitrogen and phosphorus pollution; Ecological environment; Daihai

Received: 15 Jul 2022/ Accepted: 25 Oct 2022

Introduction

Lake has important ecological functions. It is a habitat for aquatic organisms, a regulator of regional climate change, and also serves as a storage of sediment and nutrients, transformation and hydrological regulation (Yang et al. 2022; Liu et al. 2022). It is a very valuable aquatic ecosystem (Schallenberg et al. 2013). In recent years, with the rapid development of the social economy, human activities such as aquaculture, irrigation water intake and industrial water consumption have caused great pressure on the lake ecosystem. Groundwater is an important part of the lake water balance (Jeppesen, 2013; Rosenberry and Winter, 2009; Stets et al. 2010; Zhou et al. 2013). Rech-

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DOI: 10.19637/j.cnki.2305-7068.2022.04.004

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arge of groundwater by lake or lake recharge by groundwater can significantly affect the biogeochemical process and ecological process of the lake (Jeppesen, 2013). Some studies have shown that phosphorus transported by groundwater is the main factor leading to long-term eutrophication of lakes (Kazmierczak et al. 2020; 2021; Nisbeth et al. 2019), and groundwater is very important for the nitrogen and phosphorus balance in lakes (Förster et al. 2021; Sadat-Noori et al. 2021). Therefore, understanding the interaction between groundwater and lakes and the related transport process of nitrogen, phosphorus and other nutrients is critical for protecting the lake ecological environment.

The stable isotope and radio isotope radon are widely used in the study of the interaction between groundwater and lake water (Arnoux et al. 2017; Zhang et al. 2021; Song et al. 2017; Kluge et al. 2012; Luo et al. 2016). Radon (^{222}Rn) is a natural environmental tracer. Due to the advances intesting methods, it has been widely used in the quantitative assessment of groundwater flow (Rodellas et al. 2018; Su et al. 2014) worldwide in recent years. It is a radioactive inert gas produced during the decay of radium (^{226}Ra) with a half-life of 3.8 days. Radon in surface water is mostly lost through self-decay and atmospheric escape, so the radon content in surface water is generally 2–3 orders of magnitude lower than in groundwater. It can be used to assess short-term groundwater recharge, with a maximum of 20 days, or about 5 half-lives (Petermann et al. 2018).

Lakes in the Inner Mongolia Plateau have been rapidly declining in recent decades, with the number of lakes larger than 10 km^2 reduced by 30% (Tao et al. 2018) since the late 1990s. The Daihai Basin, located in the south of the Inner Mongolia Plateau, is a typical closed inland lake basin, which constitutes the northern sand prevention belt in the strategic ecological security pattern of "two screens and three belts" in China. It is an important part of the ecological scheme in the Beijing-Tianjin-Hebei region (Wang et al. 2019). Daihai's surface has been steadily shrinking and the water quality has gradually deteriorated over the past 60 years (Sun et al. 2005; Sun et al. 2006; Liang et al. 2017). The cause of the lake's shrinkage has been a concern to some researchers over the past 20 years. Earlier water balance analysis suggested that the precipitation on the lake surface is less than half of the evaporation, therefore is not the main source of water supply for Daihai. The decrease of runoff into the lake is the main reason for the decrease of the lake water level, and human activity is the main controlling factor for the decrease of the lake water level, and the influence of climate change is small (Huang and Jiang, 1999). By analyzing the results of water balance calculation and partial correlation coefficient, Cao et al. (2002) indicated that the main controlling factor of the lake water level change is precipitation, and the increasing groundwater exploitation by agricultural irrigation is an important reinforcing factor. Sun et al. (2006) argued that additional irrigation water consumption has exacerbated evaporative water loss in the basin, resulting in a decrease in the amount of water entering the lake. Liang et al. (2017) concluded that the increase in industrial water consumption caused by the rapid social and economic development of the river basin was the main reason for the shrinkage of the lake. Wang et al. (2021) quantitatively calculated the influence of driving factors on the runoff variation in Daihai using the cumulative enhanced slope change rate. That study demonstrated the dominance of human activities in the runoff variation after 1975, and the influencing factors include the increase of water consumption by residents, industry, irrigation and agriculture. Nonetheless, all these studies did not properly distinguish between surface runoff and underground runoff.

Using hydrogen and oxygen stable isotopes and hydrochemical analysis, Chen et al. (2013) and Wang et al. (2017) found that atmospheric precipitation in the area around Daihai cannot be recharged into phreatic water. They speculated that deep circulating groundwater could be an important source of recharge for the lakes of the Inner Mongolia Plateau. Zhang et al. (2021) analyzed the variation characteristics and influencing factors of surface runoff in the basin during 1986–2019, and estimated the groundwater recharge in 34 years using water balance, accounting for 46% of the total recharge of Daihai. Being an important source of lake recharge, groundwater recharge is 1.47 times the recharge of surface runoff and 2.11 times the recharge of precipitation. However, there are limited studies on the impact of groundwater on water quantity and even on the water ecology of Daihai. Taking Daihai as the study area, this paper evaluates the groundwater recharge in the lakes by ^{222}Rn; analyzes the changing characteristics of the water balance and water quality of the lakes in recent years; and further investigates the effects of groundwater recharge on the water balance and water quality of the lake. The study outcomes could provide a scientific basis for the eco-environmental protection of the inland lakes of Daihai and the Inner Mongolia Plateau.

1 Study Area

Daihai (112.63°–112.75°E, 40.55°–40.61°N) is located in the middle of the Daihai Basin in Liangcheng County, Wulanchabu City, in the Inner Mongolia Autonomous Region (Fig. 1), with a watershed area of 2 312.75 km^2. The average annual temperature of the basin is 5.1°C (Liang et al. 2017), the average annual surface evaporation is 977.20 mm, and the average annual precipitation is 407.55 mm. Rainfall mainly occurs in summer, and rainfall from June to September accounts for 66%–80% of the total annual rainfall (Xiao et al. 2004; Xu et al. 2017). The typical windy season is from March to June, and the average wind speed is 2.04 m·s^{-1}. The Daihai basin was formed during the Miocene to Neogene and belongs to a symmetric graben-type faulted basin. Its formation was mainly influenced by the differential movement of NE and NW trending faults caused by the Yanshan movement. The basin is surrounded by mountains, hills and plateaus, the middle part of which is mainly composed of alluvial-proluvial deposits, alluvial-lacustrine deposits and a lacustrine plain. Daihai is the lowest part of the basin (Fig. 2).

Daihai was an outflow freshwater lake in the early stage of its formation, with an area of about 760 km^2. Influenced by the tectonic movement the late Pleistocene, it evolved into a closed internal lake. Since the Holocene, the lake surface has experienced many obvious expansions and contractions under the influence of climate changes (Zhou and Jiang, 2009). Since the early 1970s, the Daihai Lake has been shrinking continuously, with the lake area shrinking from 174.20 km^2 in 1970 to 57.14 km^2 in 2016, with a shrinking rate of 2.55 km^2·a^{-1} (Ma, 2021), during which there were only three slight expansions of short duration. Since 2016, in order to alleviate the continuous shrinking of the lake surface and the deterioration of the water ecology, comprehensive treatment measures such as "returning irrigation water to groundwater" and " technical transformation of power plants" have been implemented in the basin, which greatly reduced the exploitation of groundwater by industry and agriculture. From 2017 to 2020, the shrinking rate of the lake surface declined to 1.73 km^2·a^{-1}. The main supply sources of the lake water are atmospheric precipitation, surface runoff and groundwater, and the main outflow is lake evaporation. Dahai is fed by the flows from seasonal rivers like Gongba River, Tiancheng River, Wuhao River and Buliang River. During the sampling period (May 2021), only Gongba River was observed to pour into Daihai.

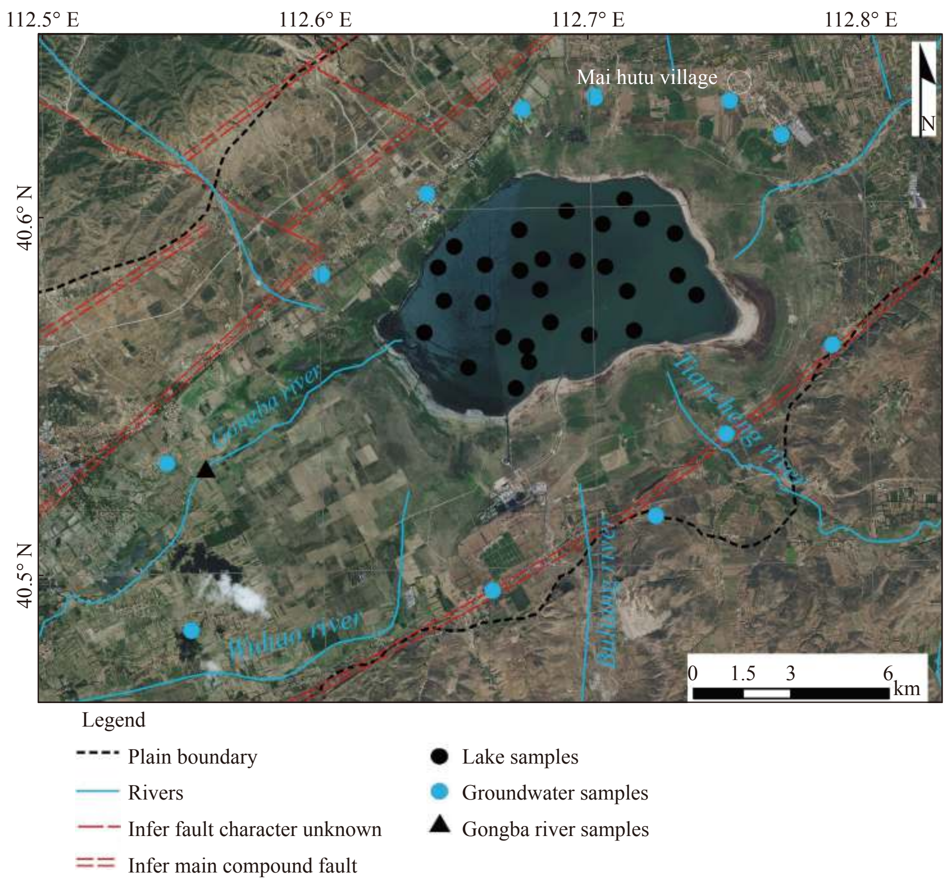

Fig. 1 Location and distribution of sampling points in the study area

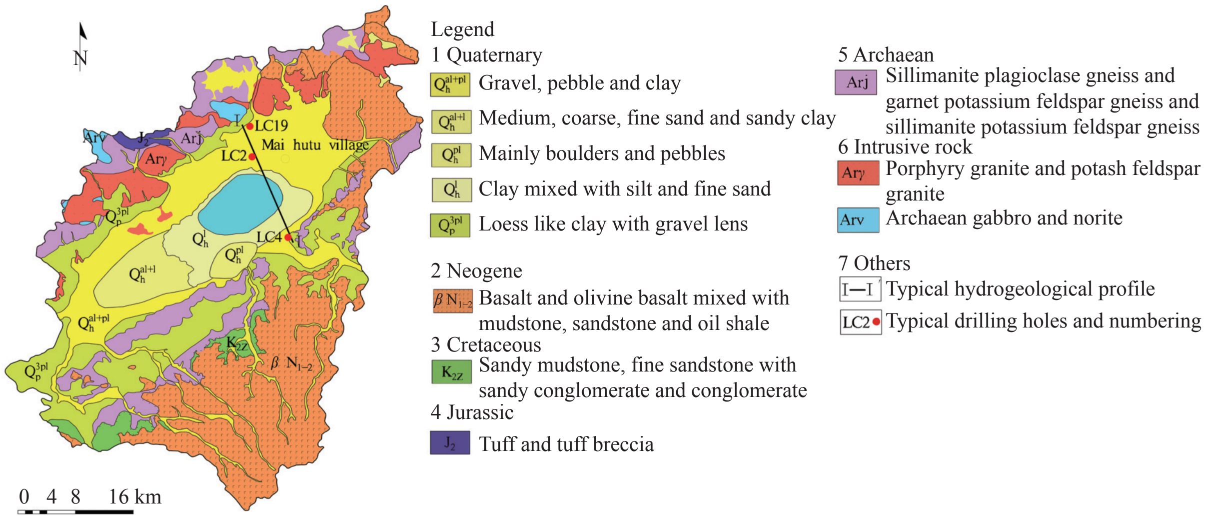

Fig. 2 Geomorphic map of Daihai Basin

The basin contains four aquifer systems. The fractured aquifer system is distributed in the northern mountainous area, and its lithology is mostly Archean gneiss and granite. It is mainly replenished by infiltration of atmospheric precipitation, and the pore aquifer is replenished by lateral runoff. The fissure aquifer system is mainly distributed in the southern basalt platform. Groundwater occurs in the Neogene basalt pores and fissures, which is formed by the infiltration of atmospheric precipitation. It recharges the pore aquifer from south to north. The fractured aquifer system mainly includes a Cretaceous aquifer and a Neogene aquifer. The Cretaceous aquifer is exposed and scattered in the central region, and consists of fine sandstone. The Neogene aquifer is distributed in the local area north of Daihai, which is composed of conglomerate and glutenite, and water in the bedrock fissure is the main supply. The pore aquifer system presents in the Daihai Basin with Quaternary sediment as the major material. From piedmont to Daihai, the lithology of the aquifer gradually changes from sandy gravels and medium fine sands to silty fine sands, and the groundwater table changes from deep to shallow (Fig. 3 and Fig. 4). Groundwater flows from all around to Daihai, and the

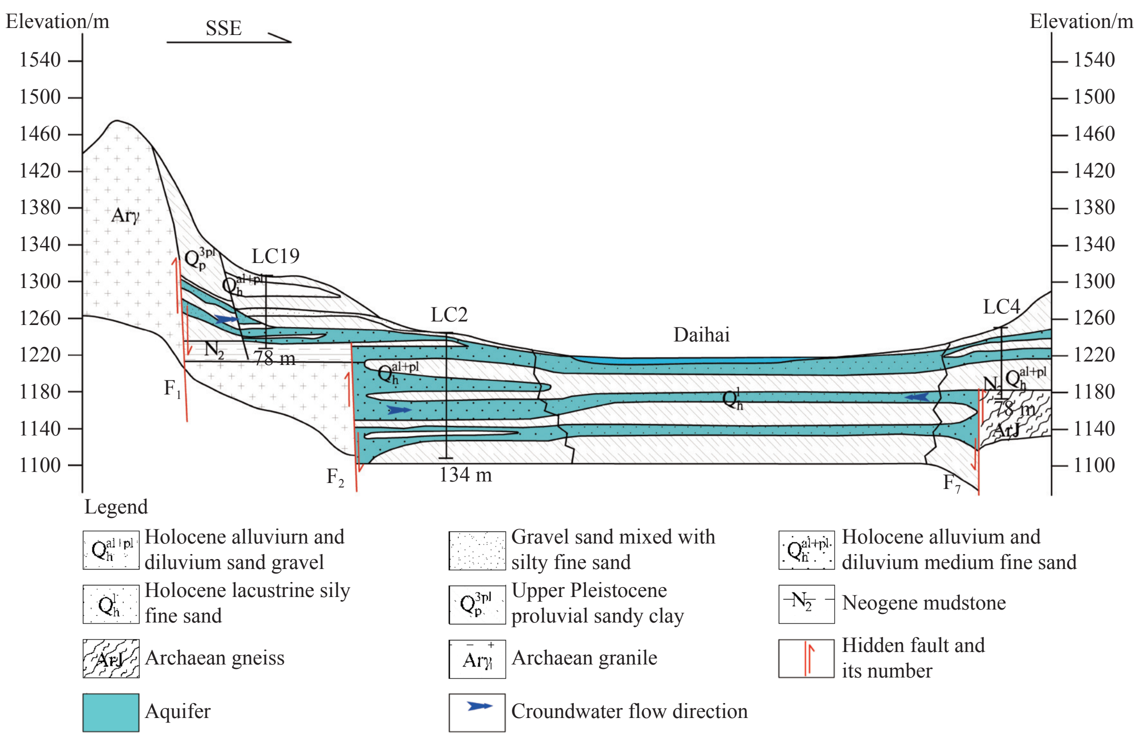

Fig. 3 Typical hydrogeological profile I - I’

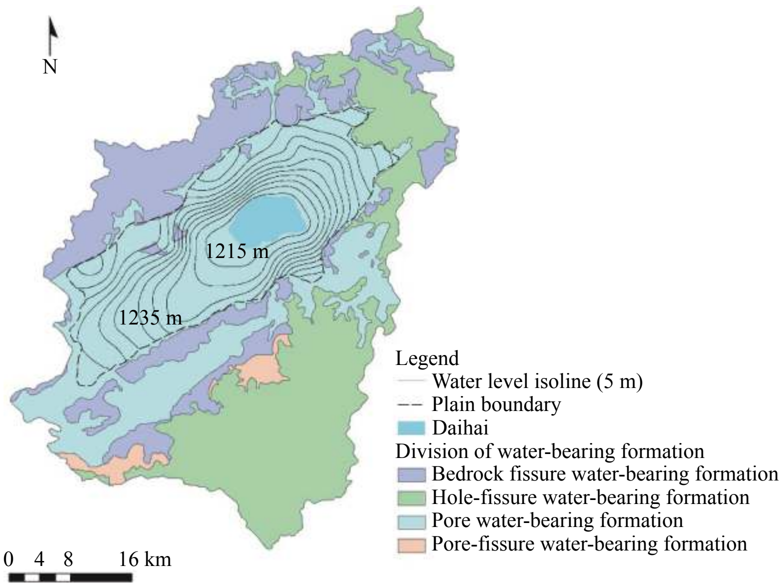

Fig. 4 Watershed aquifer groups partition and groundwater flow field in plain area

main recharge sources are the lateral recharge of bedrock fissure water, pore fissure water, atmospheric precipitation and flood infiltration recharge in mountainous areas. In the piedmont area of the northern basin, affected by concealed faults, the basement of the Quaternary system is buried shallowly, and the groundwater level is 50–70 m deep. The aquifer is thin and water scarce, so it has not been exploited. The lithology of alluvial-proluvial aquifer and alluvial-lacustrine plain aquifer in the central basin is mainly gravel and medium coarse sand, with a buried depth of 5–20 m. The aquifer is thick and rich in water, so it is the main exploitation area of groundwater. The lithology of lacustrine plain aquifer around Daihai is mainly silty fine sand. The aquifer is thin and the buried depth of water level is less than 5 m. The water abundance is poor, thus the groundwater is not exploited, and the drainage is mainly via evaporation.

2 Data and methods

2.1 Data

In May 2021, ^{222}Rn isotope sampling and testing work was conducted in Daihai and surrounding areas. To reduce gas loss, a total of 56 lake water samples were collected using a micro submersible pump, including 28 surface water samples (0.5 m below the lake' s surface) and 28 bottom water samples (0.5 m above the lake bottom), 12 groundwater samples and 4 river water samples. The river sampling point was located at the lower reaches of the Gongba River about 15 km west of Daihai (Fig. 1). The water temperature was simultaneously measured on the spot. While sampling the lake water, the depth of the water was determined with a sounding hammer. The river discharge was measured four times using the buoy method. The sampling container was a special sampling bottle of RAD7-H_2O produced by Durridge Company of the United States. The volume of surface water sampling bottle was 250 mL, and was 40 mL for groundwater sampling. In addition, 3 samples of 5L lake water were collected for the ^{226}Rn test.

Before collecting water samples, some control points were determined as evenly as possible along the shoreline of the lake by hand-held GPS, and the lake area in the investigation period was delineated with a combination of remote sensing images. During the sampling interval of the lake, the ^{222}Rn and wind speed of the lake atmosphere were measured at a fixed point in the northern part of the lake, with a total of 6 times, and the time interval was 1 hour. The average value was calculated and analyzed.

In September of the same year, 6 samples of lake water, 12 samples of groundwater and 7 samples of river water were collected for TN and TP analysis. The samples were refrigerated at 2–8°C and analyzed within 48 hours.

2.2 Measurement and analysis

^{222}Rn activity in the lake atmosphere and water samples were all tested by RAD7 portable alpha energy spectrum radon detector. Water samples were also tested using special accessories RAD7-H_2O. The measuring activity range was 0.4–750 000 $Bq{\cdot}m^{-3}$, and the measuring error was within 5%①. It has the advantages of short response and recovery time, high sensitivity and portability. By combining with optional parts, it can also realize on-site continuous monitoring, which is very suitable for field investigation and research and is thus widely used. The wind speed of the lake was measured using a hand-held digital anemometer, and the measurement error was 2.0%.

The test of water sample ^{226}Rn was completed at the Analysis and Testing Research Center of Beijing Institute of Geology. The test instrument was a PC-2100 radium radon analyzer. We adopted the test method from the national standard GB 11214-1989, and the measurement error was 4.76%. TN and TP contents were determined by the Key Laboratory of Rivers and Lakes Ecology in the Inner Mongolia Autonomous Region with a UV-visible spectrophotometer 0XCS-YQ005. We adopted the analytical methods from the national standards, namely alkaline potassium persulfate digestion UV spectrophotometry and ammonium molybdate spectrophotometry. The standard numbers are HJ636-2012 and GB 11893-89, and the detection limits are 0.05 mg·L^{-1} and 0.01 mg·L^{-1}, respectively. Multi-3620, a portable multi-parameter water quality analyzer of WTW, Germany, was used in the field test. The conductivity electrode equipped with the instrument has a wide measurement range of water temperature, and the measurement error was 0.2°C, which meets the test requirements.

2.3 ^{222}Rn mass balance equation

Daihai's ^{222}Rn mass balance equation can be expressed as (Burnett, 2012; Dimova et al. 2013; Dimova and Burnett, 2011):

$$Q_{gw}{}^{222}Rn_{gw} + F_{diff}A_{bot} + Q_{in}{}^{222}Rn_{in} + \lambda_{226}I_{226} - F_{atm}A_{sur} - \lambda_{222}I_{222} = 0 \quad (1)$$

In Equation (1), Q_{gw} is the recharge of groundwater, m^3·d^{-1}; $^{222}Rn_{gw}$ is the activity of ^{222}Rn of groundwater, Bq·m^{-3}; F_{diff} is the diffusion flux of lake sediment ^{222}Rn, Bq·m^{-2}·d^{-1}; F_{atm} is the flux of ^{222}Rn from lake water to the atmosphere, Bq·m^{-2}·d^{-1}; A_{bot} and A_{sur} are the area of lake sediments and lake area, m^2; Q_{in} is the surface runoff into the lake, m^3·d^{-1}; $^{222}Rn_{in}$ is the activity of ^{222}Rn of surface runoff, Bq·m^{-3}; λ_{226} and λ_{222} are the decay constants of ^{226}Ra and ^{222}Rn, which are 1.37×10^{-11} d^{-1} (Huang, 2019) and 0.181 d^{-1} (Wang et al. 2020), respectively; I_{222} and I_{226} are the stocks of ^{222}Rn and ^{226}Ra in lake water, Bq, respectively.

Following previous studies (Macintyre, 1995; Rodellas, 2018; Burnett and Dulaiova, 2003), the main source-sink terms of the mass equation can be calculated. The parameter values and calculation results are presented in Table 1. Given the shallow depth of the lake, the area of lake sediments is approximately equal to the lake area. Other parameters are described in section 3.2.

3 Results

3.1 The content of ^{222}Rn in water body

Our measurement suggests that, in May 2021, the activity of ^{222}Rn in the surface layer of Daihai was 39.35–306.94 Bq·m^{-3}, showing a double-peak frequency curve; while that in the bottom layer of the lake ranged 71.35–298.63 Bq·m^{-3}, showing a single peak frequency curve to the left. The average activity of ^{222}Rn in the surface layer was 137.44±76.03 Bq·m^{-3}, and the median was 114.67 Bq·m^{-3}, which were slightly smaller than those in the bottom layer. The ^{222}Rn activity of groundwater ranged 3 371–25 068 Bq·m^{-3}, with an average value of 11 524.26±5 741.17 Bq·m^{-3}, i.e. about two orders of magnitude higher than that of lake water (Fig. 5), showing a single-peak frequency curve to the left. The ^{222}Rn activity of Gongba River was 337.5±102.57 Bq·m^{-3}.

3.2 Groundwater recharge of ^{222}Rn

The measured surface water temperature of Daihai Lake was 18.40°C, the activity of ^{222}Rn in the lake atmosphere was 9.61 Bq·m^{-3}, and the wind speed was 1.77 m·s^{-1}. The activity of ^{222}Rn in lake water was 78.96±5.28 Bq·m^{-3}, which was taken as the activity of lake water near the measuring point of atmosphere and wind speed. The water storage capacity of the lake can be estimated as the product of the average water depth of the lake by the lake area. According to the survey, the average water depth of Daihai in the sampling period was 3.88 m and the lake area was 46.20 km^2, so the water storage capacity was about 1.74×10^8 m^3. Considering the discharge conditions of groundwater and the possible gas loss in the sampling process, the activity of groundwater ^{222}Rn in the mass balance equation was taken as 15 102.7±1 744.47 Bq·m^{-3} in the north and south bank of Daihai, larger than the average activity of all sampling points. Due to the restriction of lake area control and investigation time, no sediment samples were collected for indoor experimental analysis, so it is assumed that the ^{222}Rn activity of sediment pore water is equal to

①http://www.durridge.com/products_rad7.shtml.

Table 1 Calculation of groundwater recharge flux based on ^{222}Rn activity

Source-sink terms	Parameter	Unit	Value	Description
Atmospheric loss	Radon concentration in surface lake (C_{ws})	$Bq·m^{-3}$	78.96±5.28	Measured in the field
	Radon concentration in air (C_{air})	$Bq·m^{-3}$	9.61	Measured in the field
	Partition coefficient (α)	Dimensionless	0.27	(Burnett and Dulaiova, 2003)
	Temperature in lake (T)	°C	18.4	Measured in the field
	Gas transfer coefficient (k)	$m·d^{-1}$	0.18	(Rodellas et al. 2018)
	Wind speed (u)	$m·s^{-1}$	1.77	Measured in the field
	Schmidt number (Sc)	Dimensionless	1 064.37	(Pilson, 1998)
	Atmospheric loss flux (F_{atm})	$Bq·m^{-2}·d^{-1}$	14.03±0.96	(Macintyre et al. 1995)
	Radon from atmospheric loss	$Bq·d^{-1}$	$(6.50±0.45)×10^{8}$	Equation (1)
Decay of radon	Decay constant of radon	d^{-1}	0.181	(Wang et al. 2020)
	Radon inventory (I_{222})	Bq	$1.37×10^{10}$	Product of storage and the concentration of radon in lake
	Decay from radon	$Bq·d^{-1}$	$(2.49±0.17)×10^{9}$	Equation (1)
Sediment diffusion	Radon concentration in pore water (C_{eq})	$Bq·m^{-3}$	15 102.7±1 744.47	Assumed to be equal to groundwater
	Radon concentration in bottom lake (C_{wb})	$Bq·m^{-3}$	163.88±12.59	Measured in the field
	Radon molecular diffusion coefficient (Ds)	$cm^{2}·s^{-1}$	$4.09×10^{-6}$	(Ullman and Aller, 1982)
	Porosity (θ)	Dimensionless	0.38	Empirical value according to lithology
	Sediment diffusive flux (F_{diff})	$Bq·m^{-2}·d^{-1}$	37.78±4.41	(Martens et al. 1980)
	Radon from sediment diffusion	$Bq·d^{-1}$	$(1.89±0.22)×10^{9}$	Equation (1)
Decay of radium	Decay of radium	d^{-1}	$1.37×10^{-11}$	(Huang, 2019)
	Radium inventory (I_{226})	Bq	$8.70×10^{9}$	Product of storage and the concentration of radium in lake
	Radon from radium decay	$Bq·d^{-1}$	$0.12±4.77×10^{-3}$	Equation (1)
River input	Radon concentration in river ($^{222}Rn_{in}$)	$Bq·m^{-3}$	337.50±102.57	Measured in the field
	River inflow flux (Q_{in})	$m^{3}·d^{-1}$	7 084.80±574.78	Measured in the field
	Radon from river input	$Bq·d^{-1}$	$(2.39±0.75)×10^{6}$	Equation (1)
Groundwater input	Radon concentration in groundwater ($^{222}Rn_{gw}$)	$Bq·m^{-3}$	15 102.7±1 744.47	Measured in the field
	Groundwater recharge (Q_{gw})	$m^{3}·d^{-1}$	$8.27×10^{4}$	Radon from groundwater input divided by its concentration
	Radon from groundwater input	$Bq·d^{-1}$	$(1.25±0.28)×10^{9}$	Equation (1)

that of groundwater. According to Sukanya et al. (2022), the ^{222}Rn content in rainwater is very low, and the rainfall in the study area is scarce during the sampling survey period, so it can be neglected. The porosity of sediment takes empirical value according to its lithology. The activity of ^{226}Ra in lake water was 50±2 $Bq·m^{-3}$. The discharge of Gongba River was 7 084.8±574.78 $m^{3}·d^{-1}$.

Table 1 shows the main inflows and outflows and calculation parameters of the ^{222}Rn mass balance equation of Daihai. The calculated results reflect that the loss of lake radon is mainly due to its own decay, and the atmospheric emission accounts for 21% of the total loss. The sum of ^{226}Ra decay in lake water and ^{222}Rn inflow from rivers was less than 0.1% of the lake radon source term, which can be neglected. ^{222}Rn from sediment and groundwater accounted for 60% and 40% of the total, respectively, which is the main source of lake radon supply. The inflow of ^{222}Rn of groundwater was $(1.25±0.28)×10^{9}$ $Bq·d^{-1}$, with a relative standard deviation of 22%, and the recharge of groundwater was $(8.27±2.09)×10^{4}$ $m^{3}·d^{-1}$, with a relative standard deviation of 25%. From the average value of groundwater recharge, the groundwater recharge in 2021 was 3 017×10^{4} m^{3}.

3.3 Total nitrogen and phosphorus contents in water

TN and TP are the main influencing factors of eu-

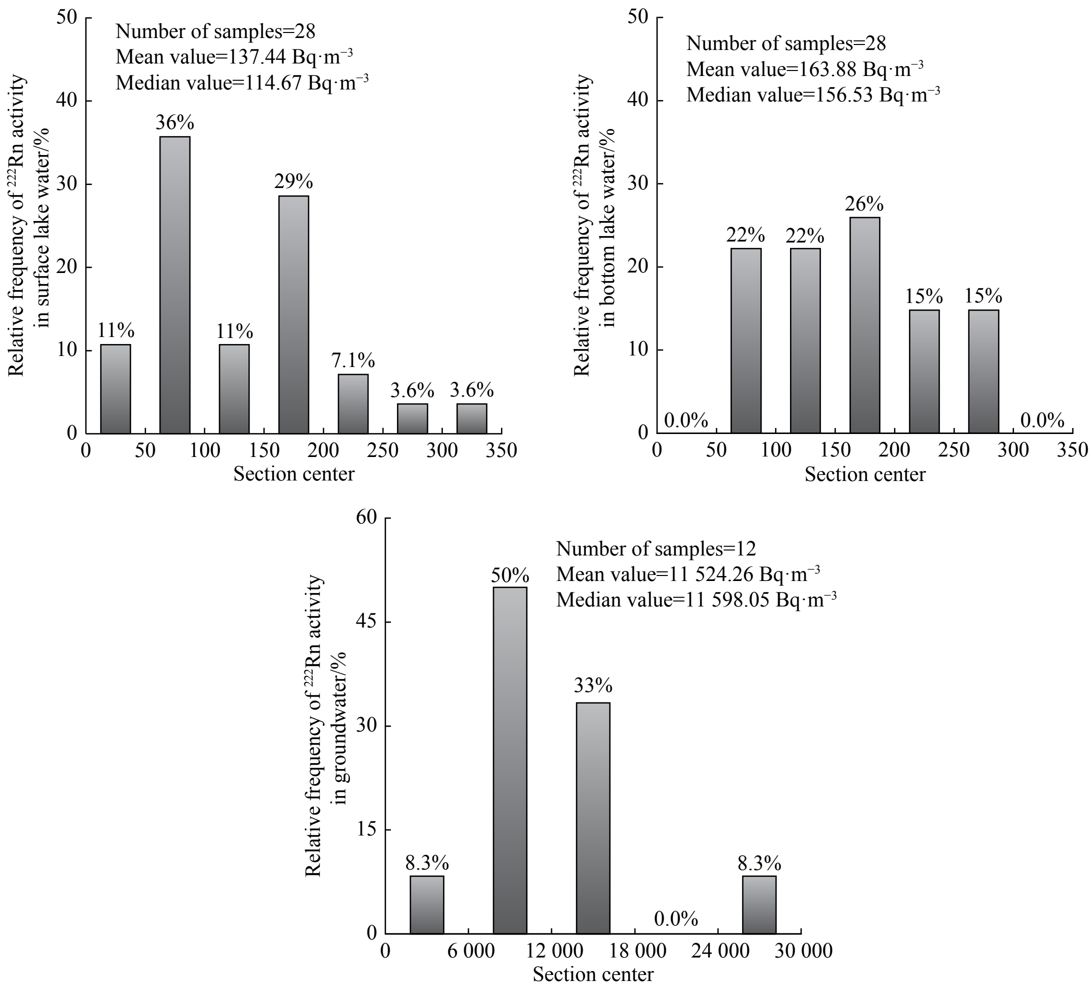

Fig. 5 Frequency distribution histograms of the ^{222}Rn activity measured in Daihai and groundwater

trophication in the Daihai Lake (Zhou, 2006). The increase of nitrogen and phosphorus contents can accelerate the eutrophication of water body, cause algae and other aquatic plants to multiply in large numbers, reduce dissolved oxygen, degrade water quality, and then cause serious damage to water ecosystem. TN and TP contents in Daihai have seasonal variation characteristics, with higher TN content in autumn and winter and higher TP content in summer. During 2000–2019, the TN and TP contents in the Daihai Lake showed an overall upward trend (Liang, 2021). In 2019, the average TN and TP contents inthelake water were 3.93 mg·L^{-1} and 0.11 mg·L^{-1}, respectively (Zhao et al. 2020), and the lake eutrophication was serious.

The survey results (Fig. 6) show that the TN content in Daihai was 3.71–4.52 mg·L^{-1}, with an average concentration of 4.21±0.29 mg·L^{-1}. According to the Environmental Quality Standard for Surface Water (GB 3838–2002), the TN contents of all samples exceeded the standard limit of Class V water (2.0 mg·L^{-1}), and 83% of the sampling points exceeded the standard by more than 2 times. TP content was 0.08–0.16 mg·L^{-1}, and the average concentration was 0.12±0.04 mg·L^{-1}. The TP content always exceeded the standard limit of Class III water (0.05 mg·L^{-1}), and the compliance

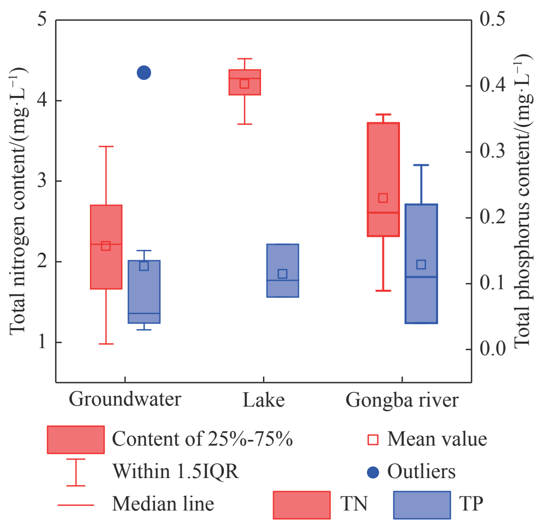

Fig. 6 Distribution characteristics of TN and TP contents in groundwater in and around Daihai

rates of Class IV and V water were 50% and 100%, respectively. Compared to 2019, the contents of TN and TP in lake water increased further.

The TN content of the Gongba River ranged 1.64–3.83 mg·L^{-1}, with an average concentration of 2.79±0.78 mg·L^{-1}. The TN content of all samples exceeded the class IV water standard, and 86% of the samples exceeded the class V water standard. The TP content was 0.04–0.28 mg·L^{-1}, and the average concentration was 0.13±0.09 mg·L^{-1}. The TP content of 71% of the samples surpassed Class III water standard, and those of 29% of the samples exceeded Class V water standard.

The TN content of groundwater was 0.98–3.43 mg·L^{-1}, with an average concentration of 2.19±0.77 mg·L^{-1}. TP content was 0.03–0.42 mg·L^{-1}, and the average concentration was 0.13±0.14 mg·L^{-1}. The TN content of 58% groundwater samples surpassed the standard limit of Class V surface water, which exceeded the standard by 1.1–1.9 times, and 83% samples exceeded the standard limit of Class IV water. The TP contents of 17% groundwater samples exceeded the limit of Class V water standard, and the rest samples were lower than the limit of Class III water standard.

4 Discussion

4.1 The spatial variability of ^{222}Rn activity in the lake water and groundwater

4.1.1 Lake water

The distribution of ^{222}Rn activity in the surface and bottom layers of lake Daihai exhibited an obvious spatial variability. The activity of ^{222}Rn of the surface layer was the highest in the north, ranging from 150 Bq·m^{-3} to 300 Bq·m^{-3}, followed by the northeast, the southeast and the west, with activity basically less than 100 Bq·m^{-3} (Fig. 7a). The diff-

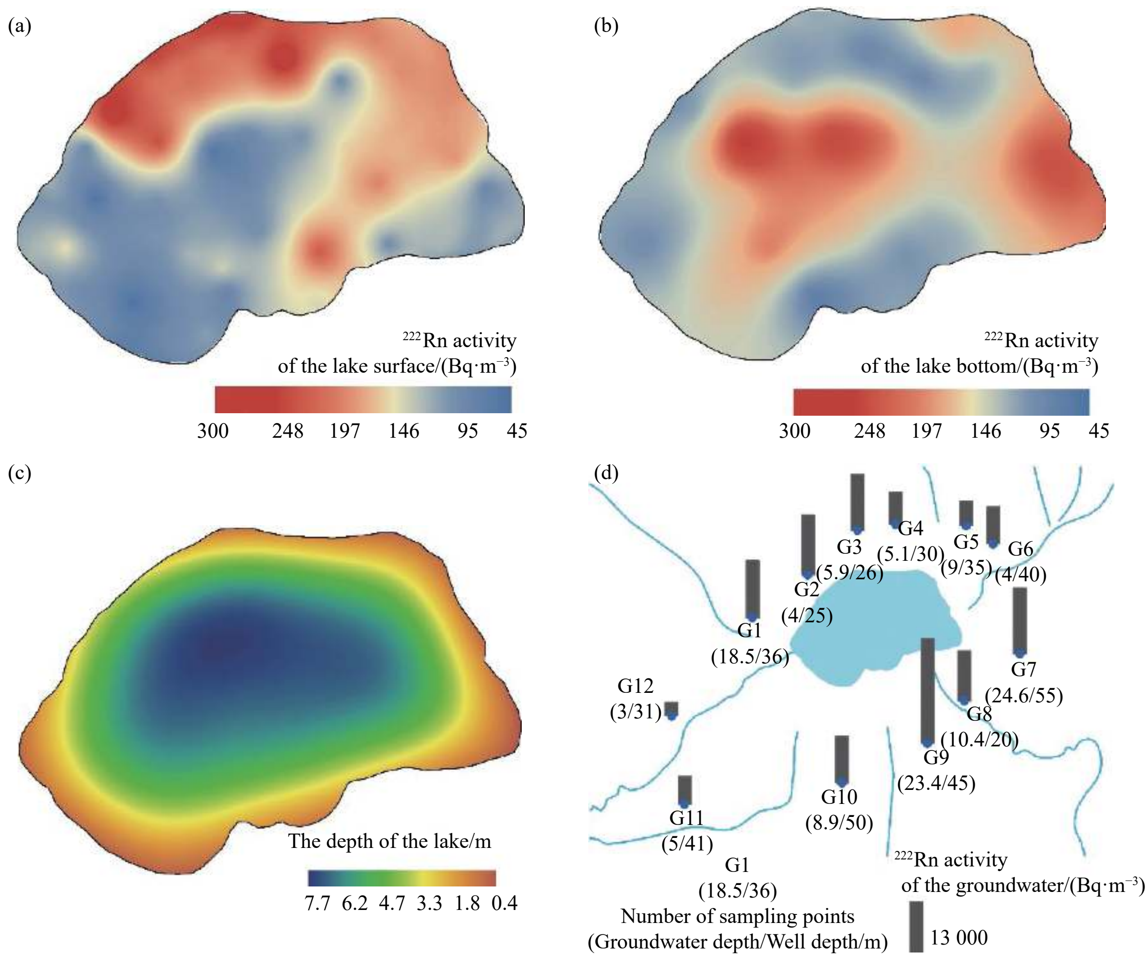

Fig. 7 Distribution of ^{222}Rn activity of Daihai Lake bottom, lake water and groundwater (a, b and d are ^{222}Rn activity of surface and bottom lake water and groundwater, respectively, and c is the depth of lake bottom②)

②Institute of water resources for pastoral area, MWR, 2018. Study on the influence of "returning irrigation water in the basin to groundwater" on the Daihai Lake.

erence is that the activity of ^{222}Rn of the bottom layer in the middle and southeast was the highest, generally more than 180 Bq·m^{-3}, while it was lower in the north, south and west, with activity of less than 100 Bq·m^{-3} (Fig. 7b). Fig. 7c shows that, influenced by the shape of the lake basin, the water in the middle of the lake area is deep, with the water depth ranged 5.6–7.6 m, and the deepest part was in the north of the middle area. In contrast, the depth of the near shore area was shallow, and the water depth was generally less than 1.5 m. The north shore was relatively deep, while the east, west and south shores were shallow.

The activity of ^{222}Rn in the bottom layer was unaffected by the shape. Assuming that the content of ^{238}U in lake sediments in the region is evenly distributed, and the decay product ^{226}Ra and its daughter ^{222}Rn keep a balance with the content of sediment pore water for a long time, the influence of the content change of ^{222}Rn in sediment pore water on the activity of lake water can be neglected. Then, the spatial variation of the activity of ^{222}Rn in lake water will mainly be caused by the different recharge of groundwater, which can indicate the recharge intensity of groundwater in different regions. The distribution characteristics of ^{222}Rn activity in the bottom of the lake indicate that the ^{222}Rn flux of groundwater in the middle and southeast of the lake area was high and the runoff intensity was high, which was the main recharge area of groundwater (Fig. 7b). The high activity of ^{222}Rn in the southeast of the lake area indicates that there might be lenses with high permeability in the lake sediments in this area, and the recharge of groundwater was relatively large.

The difference of spatial distribution of ^{222}Rn activity in the surface and bottom layers indicates the water supply source of lake water. Generally speaking, the ^{222}Rn activity of lake water increases with the depth of lake water (Corbett et al. 1997), and the ^{222}Rn activity of surface lake water in the middle layer of the Daihai Lake was lower than that of bottom layer. However, the activity of ^{222}Rn in the surface lake water in Hubei province was significantly higher than that in the bottom water, and it had a high activity value, indicating the existence of other water sources with high radon content that supply the lake water from the surface water. The slope of the sloping plain in front of the mountain in northern Daihai is large, and groundwater often overflows in the form of descending springs. During the sampling period, two streams collected by spring water were observed in the northern part of the Daihai Lake near the lake shore and injected into the lake. According to the test, the average activity of ^{222}Rn in the streams was 505 Bq·m^{-3}, which was about 1.7 times that of the northern lake. It is assumed that the supply of spring water is the direct cause of the high activity of ^{222}Rn in the northern surface lake.

4.1.2 Groundwater

The activity of ^{222}Rn in groundwater is mainly influenced by the geological structure, hydrodynamic conditions and the hydrogeochemical environment, and it is formed under the comprehensive action of many factors. The contents of radioactive elements such as uranium and radium in different types of rocks can vary a lot. The hydrodynamic conditions and hydrogeochemical environment that control the transfer of radioactive elements into groundwater are different, which can lead to the change of ^{222}Rn content in groundwater.

The ^{222}Rn activity distribution of groundwater around Daihai experienced obvious spatial variability, with the northern and southern parts significantly higher than the eastern and western parts, and the eastern part slightly higher than the western part (Fig. 7d). The Daihai basin belongs to a tectonic faulted basin. Under the action of tectonic movement from Archean to Mesozoic, the NE-SW buried fault was formed in the piedmont of the south and north of the basin. Under the action of in-situ stress in the north and south, the NW-trending secondary fault zone also occurred in the piedmont of the north, which became the water delivery channel for the bedrock fissure water in the northern mountainous area to supply the groundwater in the plain area. The basin between the south and north buried fault zones descends, and the Quaternary deposits are thick, which is the concentrated exploitation area of groundwater. The sampling point of this study was also located in this area (Fig. 1). The high degree of fracture and strong gas emission of rocks in the fault zone are beneficial to the enrichment of radon in groundwater, while the weak gas emission of rocks is unfavorable to the enrichment of radon in groundwater in areas with undeveloped structural fissures. This could be the main reason why the activity of ^{222}Rn in groundwater in the north and south of Daihai exceeded that in the east and west.

In addition, groundwater in the north of Daihai is mainly supplied by lateral runoff of the fissure water of the Archean granite and gneiss bedrock in the northern mountainous area, while groundwater in the east and south is mainly supplied by the lateral runoff of the fissure water of the Neogene basalt platform, and the groundwater in the west is mainly supplied by river water infiltration. The content of radioactive elements and emissivity of magmatic rocks are higher than those of basic rocks, and the average content of radium and uranium in granite is 2.3 times and 2.8 times that of basic rocks, respectively (Research Group of North China Geochemical Background Field, State Seismo logical Bureau, 1990). The higher radioactive element content of the rocks in the recharge area might also be one of the reasons for the higher activity of ^{222}Rn in the groundwater in the north and south.

Furthermore, according to Balanov' s theory of radon enrichment in groundwater, areas with a large flow or strong water alternation are beneficial to radon enrichment. According to the investigation of the convection field, the hydraulic gradient of groundwater is in the order of north > south > east > west (Fig. 4), indicating that the groundwater flow in the north and south is larger than that in the east and west, and it is easier to be enriched in radon. This might be another reason for the different distribution of ^{222}Rn content in groundwater.

4.2 Impact of groundwater replenishment on nitrogen and phosphorus in lake

Daihai has been shrinking seriously for many years despite no significant upward or downward trend in the rainfall in the basin over the last 70 years. However, due to change inland use and land cover types, the surface runoff in the basin has decreased greatly (Zhang et al. 2021). The average annual surface runoff into the lake during 2016–2019 was about 347.33×10^4 m^3 (Wang et al. 2019; Wang, 2021). Since no local meteorological data have been collected, by assuming that the rainfall in 2021 is equal to the multi-year average of 407.55 mm, the annual rainfall supply of the lake can be estimated as 1 882.65×10^4 m^3. The water supply of the Daihai Lake is composed of surface runoff, rainfall and groundwater. According to the above estimated groundwater supply, the total supply of the Daihai Lake in 2021 was 5 246.98×10^4 m^3, slightly smaller than the average annual evaporation in recent years of 5 280.06×10^4 m^3 (Wang, 2021). The water balance difference is negative, so the Daihai Lake is still shrinking. Surface runoff, rainfall and groundwater inflow into the lake account for 7%, 36% and 57% of the total amount, respectively, indicating that groundwater is an important source of water supply for the Daihai Lake, which is consistent with Zhang et al. (2021).

Based on the average contents of TN and TP in rivers, lakes and groundwater, in 2021, the TN content of groundwater supplied to the Daihai Lake was 66.07 t, accounting for 87% of the total TN entering the lake; and the TN content of surface runoff input was 9.69 t, accounting for 13% of the total. The TP content of groundwater recharge is 3.92 t, accounting for 90% of the total TP entering the lake; and the TP content of surface runoff input is 0.45 t, accounting for 10% of the total. By maintaining the groundwater recharge and the water storage capacity of the lake at the current level, assuming that the TN and TP entering the lake with groundwater will not be transformed, they will cause the concentrations of TN and TP in the lake water to increase at a rate of 0.38 mg·L^{-1} and 0.02 mg·L^{-1} , respectively every year, indicating that groundwater is the main source of TN and TP in the Daihai Lake. Whilst the contents of TN and TP in the water are not high, the amount of recharge water is large, and the recharge is continuous over the long-term. Under the influence of a high evaporation, N and P contents in the lake water would continue to rise, which would in turn worsen the eutrophication of the water body.

5 Conclusion

This study demonstrated that ^{222}Rn is an effective means to quantitatively investigate the interaction between groundwater and lake water. It contains the advantages of convenient data acquisition, are latively simple model mechanism and easy application. Daihai is the representative of the tectonic inland lake inthe Inner Mongolia Plateau. The surface water system of the basin is not well developed. Nitrogen and phosphorus in the soil of agricultural areas are transported by rainwater and irrigation water to groundwater through infiltration, and then enter the lake.

According to the ^{222}Rn mass balance equation and the water balance equation, the groundwater recharge to Daihai Lake has high contribution rate, accounting for approximately 57% of the total supply, more than eight times the recharge from surface runoff. It is the main source of water supply of the lake. In relation to water quantity, the influence of groundwater on the water quality of the lake is much greater than that of surface runoff. Together with the water supply, groundwater transported a large amount of nutrients to the lake. The transported TN contributed 87% of the total amount into the lake, while the transported TP contributed 90% of the total amount. Under the influence of high evaporation, when the local supply of groundwater and surface runoff becomes insufficient, the lake water tends to develop in a negative equilibrium. This leads to the decrease of the water storage capacity of the lake, the shrinkage of the lake, and the increase of the nutrient content in the lake, which causes lake eutrophication.

This study confirmed that groundwater is the main source of nutrients in Daihai Lake. Understanding the mechanism of lake eutrophication is critical for the decision-making of lake water ecological protection and management. The mechanism of the change of groundwater quantity and quality driving lake eutrophication is a key topic to be explored in a future study.

Acknowledgements

This study was supported by the national key research and development program "Spatio-temporal evolution and mechanism of ecological degradation of water resources in the 'one lake and two seas' basin" (2019YFC0409201).

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