Geochemical conditions of natural wetland and paddy fields in the Poyang Lake area, China

Evgeniya Soldatova¹ · Yihui Dong² · Jiale Li² · Irina Ivanova³ · Andrey Toropov⁴ · Irina Gromyak¹ · Denis Dogadkin¹ · Zhanxue Sun²

Received: 6 August 2020 / Accepted: 22 December 2020 / Published online: 13 January 2021
© The Author(s) 2021 **OPEN**

Abstract

During the last several decades, wetlands are losing their ecological functions due to increasing anthropogenic loads. One of these functions is the ability to bind elements forming geochemical barriers. The research aimed to study the geochemical conditions of natural wetlands and flooded paddy fields (artificial wetlands) in the Ganjiang River basin to trace geochemical barriers. The research approach was based on a comprehensive analysis of water and aqueous extracts from bottom sediments and paddy soils, including chemical and mineral composition. The samples were collected in November 2019, during the dry season at the end of harvesting. Chemical analysis was performed using standard methods for natural substances: titrimetry, photometry, ionic chromatography, high-temperature oxidation, ICP-MS, and ICP-AES. The mineral composition of the soils and sediments was determined by XRD. It was found that the main physicochemical characteristics (TDS, pH, main component concentrations) of the natural wetland water correspond to the surface water of the study area, whereas the irrigation water is similar to shallow groundwater. The content of trace elements in the irrigation water is higher than in the natural wetland water. Generally, the trace element composition of the natural wetland water corresponds to the geochemical background of the study area. Analysis of the mineral and chemical composition of the paddy soils and sediments indicates the geochemical barriers that accumulate a wide range of elements. In the natural wetland, the geochemical barrier is likely associated with a decrease in oxygen content and advective transport rate in the sediments, whereas in the paddy fields, the precipitation of clay minerals in the soil profile forms the geochemical barrier related to a decrease in filtration properties and advection–diffusion transport.

Supplementary Information The online version of this article (<https://doi.org/10.1007/s42452-020-04060-8>) contains supplementary material, which is available to authorized users.

✉ Evgeniya Soldatova, sea@geokhi.ru | ¹Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, 19 Kosygina Street, Moscow, Russia 119991. ²East China University of Technology, 418 Guanglan Avenue, Nanchang 330013, China. ³Tomsk Branch of the Trofimuk Institute of Petroleum Geology and Geophysics SB RAS, 4 Akademicheskoy Avenue, Tomsk, Russia 634021. ⁴Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, Russia 119991.

SN Applied Sciences (2021) 3:134 | <https://doi.org/10.1007/s42452-020-04060-8>

Graphic abstract

Natural wetland

Artificial wetland (paddy field)

Keywords Chemical composition · Toxic elements · Geochemical barriers · Aqueous migration · Agricultural landscapes · Jiangxi Province

1 Introduction

The buffering function of wetlands and their ability to regulate climate, at least at a regional level, explains the growth of scientific interest in wetland geochemistry and the factors controlling their evolution. During the last several decades, as a result of the dramatic increase of anthropogenic load, wetlands are losing their most important ecological functions, such as the role of a buffer zone for regulating natural disasters and the ability to self-purification [1]. This provokes further hydrological regime changes, sediment transport, nutrients dynamics, water quality, and disturbance of aquatic biota migration routes and habitat [2]. It determines the importance of a comprehensive study of geochemistry to prevent wetland degradation and save their services, which support local communities. Most research on wetland geochemistry has focused on nutrient dynamics and greenhouse gas emissions [3–5]. Separate studies are devoted to the geochemistry of water [6–8] and sediments [9–11]. However, wetland ecosystems' functioning includes complex water–rock interaction processes, making it necessary to study water and sediment geochemistry simultaneously, as Shomar

et al. [12] and Aguilera and Merino [13] have done in their research. In the current article, we consider the chemical composition of water and aqueous extracts from natural wetland sediments and paddy soils combined with their mineral composition. Such a comprehensive approach allows studying the geochemical conditions, migration, and accumulation of chemical elements in the water–rock system. Moreover, it helps to identify geochemical barriers that can impede the spread of pollution or retain nutrients. Combination of water and sediment research has already helped to analyze the wetland capability to limit pollution by municipal wastewater within the eutrophic Obskoye bog [14]. In the current research, this approach is implemented for the study of subtropical Poyang Lake wetland.

The Poyang Lake wetland ecosystem provides services for the community in a relatively densely populated area [15], such as water and food supply, floodwater storage, biodiversity maintenance, and supports habitat for rare and endangered species [16–18]. Since 1992, it is included in the Ramsar list due to the important ecological and social status [19]. This ecosystem is subjected to a high degree of spatial–temporal variation under natural and anthropogenic factors. The ecosystem demonstrates a

steady trend of degradation of its functions during the last several decades due to rapid urbanization, industrialization, and widespread agriculture [20, 21]. Thus, it is evident that geochemical monitoring is an essential component for the sustainable development of the Poyang Lake wetland ecosystem and the preservation of its ecological status as the wetland of international importance and the local community's well-being.

2 Materials and methods

2.1 Study area, sampling procedure, and sample preparation

The study area is located in the lower reaches of the Ganjiang River, the main tributary of Poyang Lake. Quaternary sediments in the Poyang Lake area form a wide, periodically flooded lacustrine–alluvial plain with low elevation values. The wetland has features of both terrestrial and aquatic ecosystems. It is characterized by a constant change in a land–water border [22] because of seasonal and annual fluctuations of water level in Poyang Lake and due to the abundant accumulation of sediments in the deltas of the rivers feeding Poyang Lake. The widespread rice and aquaculture cultivation and domestic waterfowl breeding within the study area explain many artificial

wetlands along with natural ones. Agricultural activity is also seasonal; paddy fields (artificial wetlands) are flooded from the beginning of March and drained to the end of October.

The values of annual precipitation vary from 1400 to 2400 mm [23]. The study area has two distinct seasons according to precipitation distribution during a year. The wet season usually lasts from March to June and brings abundant rains and surface runoff to Poyang Lake. From July to September, precipitation drastically decreases, and the dry season lasts until February. Features of precipitation distribution by months are given in [24].

Sampling was conducted in the dry season (October–November) of 2019 at the end of the agricultural season. Surface water samples within the natural wetland (P92, P94) were collected in the Nanjishan Wetland Nature Reserve, located at the Ganjiang River mouth (Fig. 1). The irrigation water (P103, P105) was taken from the paddy fields in the Ganjiang River to compare natural and artificial wetland geochemistry and their potential influence on the aquatic environment. In addition to the water samples, at the points P92 and P94, the bottom sediments were collected from the surface. The samples of paddy soil (one sample every 0.25 m down to a depth of 1 m) were taken at the sampling points P103 and P105 (uniformity of the soil profile determined the depth of sampling). During

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

sampling the sediments at the point P92, we noted a weak but persistent hydrogen sulfide odor.

In this research, we also use some geochemical data obtained earlier in 2013–2017 during the dry season. The data include the research results on the shallow groundwater, the water of the Ganjiang and Xiushui Rivers, the water of Poyang Lake collected from its deep-water zone, and atmospheric precipitates. Besides, near the sampling point P92, the groundwater sample was collected from a public well (P93) in 2019 to compare its chemical composition with natural wetland water.

Water samples for the chemical analysis of main ions were collected in 0.5 L plastic bottles pre-rinsed several times with sampling water. Water samples for ICP-AES and ICP-MS analyses were filtered through a polyethersulfone (PES) membrane with a pore size of 0.45 μm to 15-mL sterile polypropylene tubes and acidified with 0.45 mL of high-purity HNO_3 in situ. Temperature, pH, Eh, and the content of dissolved oxygen (DO) were measured in situ with a portable PH200 and ORP200 meters (HM Digital, South Korea), and AZ8401 Handheld DO meter (AZ Instrument, China). The samples were cooled and stored at a temperature of about 4 $^{\circ}\text{C}$ until delivery to the laboratory. The samples of sediments and paddy soils for mineralogical analysis and chemical analysis of aqueous extracts were collected in sterile labeled ziplocked plastic bags. The sampling of sediments and paddy soils for moisture determination was carried out in pre-dried and weighed aluminum containers. These samples were delivered to the East China University of Technology (Nanchang, China) within 2 h after sampling.

The soil and sediment sample preparation included air-drying, removing residues of plant roots from the sample, and grinding in a jasper mortar. Dried samples were sieved to No 18 mesh (denominated 1 mm). After grinding and sieving, the samples were homogenized by a five-spot pattern. Aqueous extracts of sediments and paddy soils were prepared by the volume–weight method with ratio 1:5 [25] using ultrapure water supplied from a Millipore Milli-Q system.

2.2 Analytical techniques

Physicochemical characteristics of the water samples and aqueous extracts were analyzed at the Chemical Department (Lomonosov Moscow State University, Russia) and at the Laboratory of Research Methods and Analysis of Substances and Materials (Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, Russia). The concentrations of CO_2 , HCO_3^- , and permanganate index (PI) in the water samples and aqueous extracts were determined by titrimetry, as well as Ca^{2+} and Mg^{2+} in the water samples. The contents of Cl^- , SO_4^{2-} , NO_3^- , and NO_2^- in

the water samples were measured by ionic chromatography (ICS 2000, Dionex). The content of NH_4^+ in the water samples and dissolved organic carbon (DOC) in the aqueous extracts were measured by photometry (PE-5300, Ecoskim). The DOC content in the water samples was analyzed by high-temperature oxidation (Vario TOC cube, Elementar).

The content of Al, Fe, K, Na, Si in the water samples and aqueous extracts, as well as the content of Ca, Mg, P, S in the aqueous extracts, were analyzed by ICP-AES considering their concentrations in a blank sample (iCAP 6500 Duo, Thermo Scientific). The content of other trace elements was determined by ICP-MS, also considering their concentrations in the blank sample (X Series II, Thermo Scientific equipped with a concentric nebulizer and Peltier cooled quartz cyclonic spray chamber).

X-ray diffraction (XRD) with a Dron-3 m X-ray diffractometer (Burevestnik, Russia) was used to determine the mineral composition. The analysis was carried out in the Geological Department (Lomonosov Moscow State University, Russia). The number of mineral phases was determined using the equalizing coefficient, depending on the mass absorption of X-rays of each mineral phase. The unity of the absorption coefficient was equal to the value of the mass absorption coefficient of quartz. The clay fraction was analyzed separately. Specimens were enriched with clay minerals to obtain high-quality diffraction patterns in the analysis of clay minerals. The precipitation of clay particles from an aqueous suspension onto a glass plate was used to prepare oriented specimens of a clay fraction.

2.3 Geochemical data processing

The error of the water chemical analysis was determined based on the principle of water electroneutrality as follows:

$$x = \left| \frac{\sum A - \sum C}{\sum A + \sum C} \right| * 100\%, \quad (1)$$

where A is anion concentration (mEq/L), C , cation concentration (mEq/L). The name of the chemical type of water contains cations and anions, the content of which exceeds 25 mEq-%, in ascending order.

The background values of the physicochemical characteristics were calculated, taking into account a distribution law. The arithmetic mean value was taken as the mathematical expectation (background value) for normally distributed samples. For lognormally distributed samples, the geometric mean value was taken as the mathematical expectation. For samples components that obeyed other distribution laws, the mathematical expectation was estimated using the median value [26].

Table 1 Physicochemical characteristics of the waters in the Poyang Lake area (mg/L)

Parameter	Samples collected in 2019					Background values for		Atmospheric precipitation <i>n</i> = 1
	P92	P94	P103	P105	P93	Surface water*	Groundwater**	
	Natural wetland		Paddy fields		Groundwater	<i>n</i> = 7	<i>n</i> = 20	
pH	5.26	6.12	6.21	5.54	6.40	7.08	6.33	6.18
Eh, mV	144	188	147	85	166	125	46.7	n.d.
O ₂	5.66	5.52	6.84	6.09	1.95	n.d.	n.d.	n.d.
HCO ₃ ⁻	4.90	56.0	113.5	12.3	114.6	39.1	85.0	7.32
SO ₄ ²⁻	20.4	2.30	32.6	54.5	21.9	13.0	8.54	2.71
Cl ⁻	6.80	4.20	51.0	38.0	27.0	10.8	21.7	2.72
Ca ²⁺	8.52	12.5	32.5	27.4	23.0	13.8	21.4	0.60
Mg ²⁺	1.15	2.34	3.79	3.83	7.64	2.44	5.84	0.61
Na ⁺	3.54	3.83	27.2	11.9	15.5	7.91	16.5	2.08
K ⁺	2.14	1.83	9.60	16.1	21.6	2.08	2.96	2.00
TDS	51.5	83.7	270.2	164.0	247.7	92.1	173.5	20.4
NH ₄ ⁺	0.34	0.04	<0.05	<0.05	1.65	0.28	0.22	0.96
NO ₂ ⁻	0.04	0.008	<0.01	<0.01	3.80	0.03	0.02	0.03
NO ₃ ⁻	4.01	0.65	0.025	0.01	16.5	2.92	3.45	1.38
DOC	2.05	4.2	6.3	10.2	1.23	2.38	0.93	1.60
CO ₂	15.9	15.9	21.0	32.1	70.4	5.28	33.7	8.80
PI, mgO ₂ /L	5.2	4.0	1.9	2.5	4.5	n.d.	n.d.	3.10

n.d., no data

n, number of samples

*Ganjiang River, Xiushui River, Poyang Lake (the deep-water zone near the Xiushui River mouth)

**Shallow groundwater collected in the Ganjiang and Xiushui basins

3 Results and discussion

3.1 Water chemical composition

According to the value of total dissolved solids (TDS), the water of natural wetland is ultrafresh (TDS value is up to 100 mg/L), which corresponds to the values of TDS determined for the water of Ganjiang and Xiushui Rivers and Poyang Lake (Table 1, [27]). The values of Eh are also consistent with those in the water samples taken from Ganjiang and Xiushui Rivers in the littoral zone. Simultaneously, the pH values of the natural wetland water are lower than those measured in rivers and lake. According to the pH values, the natural wetland water is acidic and slightly acidic, similar to atmospheric precipitation (Table 1).

Among the cations, Ca²⁺ dominates (Table 1). The data on cations and the inorganic N-compounds content are in good correspondence with research on the surface water of the Ganjiang River basin performed by Shu et al. [28]. The anionic composition is heterogeneous: the carbonate system components (HCO₃⁻, CO₂) have an essential role; however, at the sampling point P92, SO₄²⁻ prevails (Table 1). The SO₄²⁻ prevalence among the anions in the

natural wetland water is a debatable issue. On the one hand, it may result from organic matter biodegradation in the sediments. Sulfur-containing organic matter enters with litterfall and other organic debris to the sediments, and then, it is mineralized to hydrogen sulfide. Forming hydrogen sulfide is oxidized in aerobic conditions to sulfate. The persistent hydrogen sulfide odor observed during the collection of sediments proves this suggestion. Another way is the anthropogenic load. The prevalence of SO₄²⁻ in the Xiushui and Ganjiang Rivers and Poyang Lake waters relates to industrial and mining activities [28] or fertilization in agricultural areas [29, 30]. As reported by Lamers et al. [31], sulfide accumulation in sediments is a response of freshwater wetlands to surface water and groundwater S pollution. Although the low pH values of the natural wetland water corresponding to the pH of atmospheric precipitation (Table 1) indicate a significant role of natural processes in its chemical composition formation, it is also confirmed by the low content of trace elements in comparison with the river, lake, and irrigation waters. Research on toxic elements in the sediments reported in [32] also demonstrates that the Poyang Lake at

the Xiushui and Ganjiang River confluences is less exposed to pollution.

The content of CO_2 is relatively high, considering the low value of TDS. According to the PI and DO values, the natural wetland water corresponds to the II–III class of surface water quality [33].

The chemical composition of the irrigation water is similar to the polluted shallow groundwater in the Poyang Lake basin previously reported in [34]. The TDS value corresponds to freshwater; however, it is higher than that in natural water bodies (Table 1). The values of pH are similar to natural wetlands and correspond to a slightly acidic environment. Chloride ion and SO_4^{2-} play a significant role among anions along with HCO_3^- . Among the cations, Ca^{2+} prevails. However, the concentrations of Na^+ and K^+ are also significant. The content of Cl^- , SO_4^{2-} , Na^+ , and K^+ in the irrigation water is likely controlled by fertilization. Chloride, Na^+ , and K^+ are common pollutants under fertilization by manure and sewage spread in the study area. As for SO_4^{2-} , the irrigation water may be an essential source of sulfur for rice cultivation [35, 36]. Research on stable sulfur isotopes has shown that in standing irrigation water

on poorly drained soils, the dissolved sulfur content stays significant after fertilizer application [37]. Additionally, the evaporation influence cannot be ignored as the sampling was carried out during the dry season at the end of the harvesting when the water recharge is not maintained within the paddy fields.

The concentrations of the inorganic N-compounds (NO_3^- , NO_2^- , NH_4^+) are low, although those particular compounds are the primary pollutants of the shallow groundwater in the Poyang Lake area [38, 39]. The concentrations of DOC, CO_2 , and DO are slightly higher than those in the natural wetland water. The low content of the inorganic N-compounds in the irrigation water may be explained by the fertilizer applied. As previous studies have shown, the main source of the inorganic N-compounds within the study area is organic fertilizers and domestic sewage [38]. The application of organic substances explains the relatively high content of DOC in the irrigation water.

The shallow groundwater collected near the natural wetland (P93) is of $\text{HCO}_3\text{--Ca}$ type. Its chemical composition mostly corresponds to the data derived from previous research within the Poyang Lake area, including the high

Fig. 2 Content of the trace elements in the surface water of the Poyang Lake area (Lg C is the logarithm of chemical element concentration (in $\mu\text{g/L}$) based on 10)

concentrations of CO_2 , N-compounds, Cl^- , SO_4^{2-} , and K^+ , which patchy spread throughout the study area due to anthropogenic load [34, 40, 41]. However, pH and TDS values correspond to the groundwater of natural landscapes [34].

The content of most studied trace elements (Li, B, Ti, Ni, Cu, Rb, Sr, Cd, Cs, Ba, Re, Tl, and rare-earth elements (REE)) in the irrigation water is higher than in the natural wetland water (Fig. 2). Compared with previous research on the surface water of the Ganjiang and Xiushui Rivers and Poyang Lake [27], the trace element content in the natural wetland water is usually lower than that in the river and lake waters. The exception is Fe, Si, B, Mn, Rb, Sr, Ba, and Re, which concentrations are similar to those in the surface water (Fig. 2). Generally, the trace element composition of the natural wetland water is closer to the shallow groundwater and corresponds to the geochemical background of the study area. In the irrigation water, Si, Fe, Li, B, Mn, Co, Ni, Cu, Zn, Rb, Sr, Mo, Cd, Ba, Re, and Tl correspond to their content in the rivers and lake. Relatively high concentrations of Mn, Co, Ni, and Cd are traced in the sampling point P105. The most probable scenario of enrichment with these elements is the fertilization of paddy fields with manure and

sewage. The concentrations of the rest studied trace elements (Al, Ti, As, Y, Sb, Cs, REE, W, Pb, and U) are usually lower compared to the rivers and lake.

Thus, the natural and artificial wetland waters have features of both surface and groundwater. It indirectly reflects their hydraulic interconnection. The possibility of agricultural effluent percolation to the shallow aquifer has been shown on the example of the nearby Yougxiu area in the Xiushui River basin [30].

3.2 Mineral composition of the sediment and soil samples

The mineral composition of the upper horizon of sediments (0–0.25 m) of the natural wetland is similar to the paddy soils' upper horizon (Table 2). It was found that quartz and clay minerals prevail. Orthoclase, plagioclase, and goethite are in less quantity. Among the clay minerals, kaolinite and illite dominate, chlorite and mixed-layer mica/smectite are presented in less quantity. In the clay fraction of the paddy soils, smectite and mixed-layer chlorite/smectite are also presented. In the sample P92 collected within the natural wetland on the border of Poyang

Table 2 Mineral composition of the bottom sediments and paddy soils in the Poyang Lake area, %

Sample	Depth, m	Quartz	Potassic feldspar	Plagioclase	Amphibolite	Dolomite	Apatite	Goethite
P92	0–0.25	44	7	7	0	3	2	4
P94	0–0.25	41	11	4	0	0	0	7
P103	0–0.25	45	3	5	1	0	0	3
	0.25–0.50	52	2	0	0	0	0	5
	0.50–0.75	34	8	4	0	0	0	2
	0.75–1.00	48	3	2	0	0	0	5
P105	0–0.25	59	6	2	0	0	0	4
	0.25–0.50	59	6	4	2	0	0	6
	0.50–0.75	63	3	2	0	0	0	3
	0.75–1.00	71	6	2	0	0	0	8
Total content of clays in the bulk mineral composition			Speciation of clay minerals (percent from total clay content)					
			Kaolinite	Smectite	Illite	Mica/smectite	Chlorite/smectite	Chlorite
P92	0–0.25	31	33	0	33	14	0	16
P94	0–0.25	40	52	0	23	7	0	14
P103	0–0.25	44	23	5	32	17	1	19
	0.25–0.50	38	32	4	20	17	1	21
	0.50–0.75	50	26	4	25	15	0	28
	0.75–1.00	46	29	4	27	13	0	22
P105	0–0.25	31	36	2	35	7	1	15
	0.25–0.50	26	46	0	25	7	1	15
	0.50–0.75	30	38	0	34	11	1	13
	0.75–1.00	18	22	2	31	19	0	18

Fig. 3 Changes in the mineral content with depth in the paddy soils (quartz and clays (total) are given in % of bulk mineral composition; kaolinite* and illite* – % of clay content)

Lake, dolomite and apatite were found. The moisture of the paddy soils slightly decreases with depth (up to 5–7%).

The general trend in paddy soils changes with depth is an increase in the clay content with decreased quartz content. We also trace an increase in the content of illite when kaolinite content decreases (Fig. 3). The clay content increases in a bulk mineral composition at depths 0.25–0.5 m (P103) and 0.5–0.75 m (P105), with more pronounced growth in P103. Generally, for the sampling point P103, we observe more significant fluctuations of the mineral composition within 0.25–0.75 m than that for P105.

3.3 Chemical composition of the aqueous extracts from the bottom sediments and paddy soils

The distribution of the chemical elements in the water and sediments/soils of the upper horizon (0–0.25 m) allows identifying a group of elements that tend to accumulate in sediments and soils rather than in water regardless of the wetland type: Al, Be, Ti, V, Cr, Zn, Ga, Zr, Pb, Th, U, and REE (Supplementary material 1). It should be noted that within the natural wetland, most chemical elements, as well as DOC, accumulate in the sediments. Within the paddy fields, the chemical elements tend to stay in the irrigation water, especially at the sampling point P105. At this point, the concentrations of almost all elements and DOC in the irrigation water are higher than in the aqueous extracts from the upper soil horizon (Supplementary material 1).

As for the cross-sectional distribution of the chemical elements in the paddy soils, at the sampling point P103, the concentrations of most chemical elements increase in the interval 0.25–0.75 m (Fig. 4), basically at the depth 0.25–0.50 m. Only Mo and Sr concentrations do not obey this dependency. Simultaneously, the PI values and DOC

concentrations in the aqueous extracts decrease from 0.25–0.50 to 0.50–0.75 m (Fig. 5).

At the sampling point P105, the concentrations of most chemical elements increase deeper, in the interval 0.50–1.0 m or have a steady growth with depth (Fig. 4), except for Li, Mn, Zn, Rb, Sr, Mo, Cd, Tl, and U. Arsenic demonstrates the maximum concentration at the depth 0.25–0.5 m, as well as Al and Zr accumulated at the same depth. The DOC and PI values decrease from 0.5–0.75 to 0.75–1.0 m (Fig. 5). The decrease in the DOC and PI values is likely related to the formation of poorly soluble complexes of fulvic and humic acids with metals [42].

3.4 Geochemical barriers in the natural wetland and paddy fields under study

The functioning of the geochemical barrier can explain the occurrence of apatite in the sediments of the natural wetland. This barrier corresponds to the substantial decrease of oxygen content and the rate of advective flow of substances. The possibility of such barrier formation has been shown in the examples of the oligotrophic bog of Western Siberia [43]. The geochemical barrier in the sediments indicates the potential buffering capacity of the natural wetland ecosystem to retain the sustainable water chemical composition. Chemical element distribution between the wetland water and the sediments confirms this statement: The sediments accumulate chemical elements and bind pollutants.

In the paddy soils, the geochemical barrier is connected with the formation of clay minerals. The rise in the clay content and the substitution of kaolinite to illite in the paddy soil cross section relate to the increase of water–rock interaction time. Water percolating through a soil interacts with primary minerals and is saturated with

Fig. 4 Changes in the content of selected chemical elements with depth in the aqueous extracts from the paddy soils (lg C is the logarithm of chemical element concentration (in $\mu\text{g/L}$) based on 10; full data are presented in the Supplementary material 2)

secondary minerals. Kaolinite is formed at the initial stages of the water–rock interaction. With an increase of depth and residence time of water in the system, illite starts to form [44]. The distribution of the chemical elements between the upper soil horizon (0–0.25 m) and the irrigation water demonstrates a weak ability of the upper soil horizon to accumulate the chemical elements. The highest concentrations of the chemical elements are found in the irrigation water as opposed to the natural wetland,

Fig. 5 Changes in the DOC content and the value of permanganate index (PI) with depth in the aqueous extracts from the paddy soils

where the chemical elements tend to accumulate in the sediments. The sharp increase in element concentrations in the paddy soils occurs deeper: at a depth of 0.25–0.75 m for the sampling point P103, and at a depth of 0.50–1.0 m for the sampling point P105. It is followed by a decrease in DOC and PI values and coincides with an increase in the clay content and with general trends in mineral composition changes. At the mentioned depths, Si, B, Co, Ti, U, Al, Fe, Mn, Be, Ti, V, Cr, Ga, Y, REE, Zr, Nb, Cs, Pb, Bi, Th, and other elements accumulate (Supplementary material 3). Such a geochemical barrier is likely a complex of a sorption barrier related to clay mineral sorption capacity and a mechanical barrier connected with the deterioration of filtration properties and advection–diffusion transport of chemical elements.

The authors would like to point out that the limited number of samples collected in 2019 does not allow using advanced statistical techniques for data processing. The sampling depth also imposes limitations on the analysis of further chemical and mineral composition changes in the sampling point P105 and natural wetland sediments. However, our previous research with abundant representative data supports evaluates the geochemical conditions with a high degree of reliability. For a detailed assessment of the geochemical barrier functions, the numerical modeling of the element migration and precipitation should be conducted. Particular attention should be paid to sorption on clay minerals in the paddy soils.

4 Conclusions

The natural wetland water and irrigation water of paddy fields correspond to ultrafresh and fresh with similar pH values. In cationic composition, Ca^{2+} dominates. Among anions, the carbonate system components (HCO_3^- , CO_2)

prevail. However, rather high SO_4^{2-} call for attention. In the irrigation water, it could be explained by fertilizer application and evaporation. Sulfate in the natural wetland water is rather connected with natural factors, such as organic matter transformation, but further study of this issue is necessary. The main physicochemical characteristics of the natural wetland water correspond to the surface water of the study area (Ganjiang and Xiushui Rivers and Poyang Lake), whereas the irrigation water is similar to shallow groundwater (except for inorganic N-compound content). The concentration of most trace elements in the irrigation water is higher than in the natural wetland water. Generally, the trace element composition of the natural wetland water is closer to the shallow groundwater and corresponds to the geochemical background of the study area.

Analysis of the mineral and chemical composition of the paddy soils and sediments of the natural wetland indicates the geochemical barriers that accumulate a wide range of elements. In the natural wetland, the geochemical barrier is likely associated with a decrease in oxygen content as well as the velocity of the advective flux in the sediments, whereas in the paddy soils, the precipitation of the clay minerals provokes the formation of the geochemical barrier related to a decrease in filtration properties and advection–diffusion transport. Potentially, these barriers help maintain the sustainability of the surface water chemical composition and protect groundwater from pollution by toxic elements.

Acknowledgements The authors thank colleagues from East China University of Technology, National Institute of Technology Durgapur, and Tomsk Polytechnic University who helped with the fieldwork and water samples analysis. We are also grateful to colleagues Evgeniya Sidkina and Ilya Bugaev for their kind support and assistance with sample preparation and analysis.

Authors' contributions ES contributed to conceptualization, investigation, fieldwork, and writing of the original draft. YD and JL contributed to investigation, soil moisture analysis, fieldwork, and draft validation. IL contributed to investigation, fieldwork, and draft validation. AT contributed to water extract preparation and analysis, soil properties analysis, data, and draft validation. IG and DD contributed to chemical analysis of water samples. ZS contributed to sampling organization and draft validation.

Funding The current research on the wetland water, sediments, and soils was funded by the Russian Science Foundation (Project No 19-77-00014). Fieldworks within Poyang Lake wetland were supported by the BRICS STI Framework Programme (National Natural Science Foundation of China, project No 51861145308). Analysis of the soils' physical characteristics was funded by the Russian Foundation for Basic Research (Project No 19-33-60030).

Availability of data and materials The data that support the findings of this study are available in the electronic supplementary material and upon request from the authors.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Reid WV, Mooney HA, Cropper A et al (2005) Ecosystems and human well-being—synthesis: a report of the millennium ecosystem assessment. Island Press, Washington, DC
2. Finlayson M, Cruz RD, Davidson NC et al (2005) Millennium Ecosystem Assessment: Ecosystems and human well-being: wetlands and water synthesis. Island Press, Washington, DC
3. Holloway JAM, Goldhaber MB, Mills CT (2011) Carbon and nitrogen biogeochemistry of a Prairie Pothole wetland, Stutsman County, North Dakota, USA. *Appl Geochemistry* 26:S44–S47. <https://doi.org/10.1016/j.apgeochem.2011.03.025>
4. Martin RM, Wigand C, Oczkowski A et al (2020) Greenhouse gas fluxes of mangrove soils and adjacent coastal waters in an urban, subtropical estuary. *Wetlands* 40:1469–1480. <https://doi.org/10.1007/s13157-020-01300-w>
5. Wang W, Wang C, Sardans J et al (2015) Agricultural land use decouples soil nutrient cycles in a subtropical riparian wetland in China. *CATENA* 133:171–178. <https://doi.org/10.1016/j.catena.2015.05.003>
6. Hong Z, Zhao Q, Chang J et al (2020) Evaluation of water quality and heavy metals in wetlands along the Yellow River in Henan Province. *Sustainability* 12:1300. <https://doi.org/10.3390/su12041300>
7. Skrzypek G, Dogramaci S, Grierson PF (2013) Geochemical and hydrological processes controlling groundwater salinity of a large inland wetland of northwest Australia. *Chem Geol* 357:164–177. <https://doi.org/10.1016/j.chemgeo.2013.08.035>
8. Zhang XY, Liu XY, Wang J et al (2010) Contamination characteristics of heavy metals in the water of Daqing Wetlands. *J Shanghai Univ* 14:262–265. <https://doi.org/10.1007/s11741-010-0641-2>
9. Adelana AO, Oluwatosi GA, Agunbiade C et al (2016) Distributions of cadmium and lead in peri-urban wetlands as influenced by soil organic matter, clay fraction, and moisture content. *Cogent Food Agric* 2:1159406. <https://doi.org/10.1080/23311932.2016.1159406>
10. Hu C, Deng ZM, Xie YH et al (2015) The risk assessment of sediment heavy metal pollution in the East Dongting lake wetland. *J Chem* 2015:835487. <https://doi.org/10.1155/2015/835487>
11. Xie Z, Zhang H, Zhao X et al (2016) Assessment of heavy metal contamination and wetland management in a newly created coastal natural reserve, China. *J Coast Res* 318:374–386. <https://doi.org/10.2112/JCOASTRES-D-14-00222.1>

12. Shomar BH, Müller G, Yahya A (2005) Seasonal variations of chemical composition of water and bottom sediments in the wetland of Wadi Gaza, Gaza Strip. *Wetl Ecol Manag* 13:419–431. <https://doi.org/10.1007/s11273-004-0412-3>
13. Aguilera H, Merino LM (2018) Data on chemical composition of soil and water in the semiarid wetland of Las Tablas de Damiel National Park (Spain) during a drought period. *Data Br* 19:2481–2486. <https://doi.org/10.1016/j.dib.2018.04.085>
14. Ivanova IS, Savichev OG, Soldatova EA et al (2020) Conditions of transformation of municipal wastewater in bog ecosystems (on the example of Obskoe bog, Western Siberia). *Bull Tomsk Polytech Univ Geo Assets Eng* 331:39–51. <https://doi.org/10.18799/24131830/2020/3/2530>
15. Brinkhoff T (2019) City Population. Jiangxi Province. http://www.citypopulation.de/en/china/admin/36_jiangxi/. Accessed 26 May 2020
16. Huang LL, Wu ZQ, Li JH (2013) Fish fauna, biogeography and conservation of freshwater fish in Poyang Lake Basin, China. *Environ Biol Fishes* 96:1229–1243. <https://doi.org/10.1007/s10641-011-9806-2>
17. Kanai Y, Ueta M, Germogenov N et al (2002) Migration routes and important resting areas of Siberian cranes (*Grus leucogeranus*) between northeastern Siberia and China as revealed by satellite tracking. *Biol Conserv* 106:339–346. [https://doi.org/10.1016/S0006-3207\(01\)00259-2](https://doi.org/10.1016/S0006-3207(01)00259-2)
18. Wang HF, Ren MX, López-Pujol J et al (2015) Plant species and communities in Poyang Lake, the largest freshwater lake in China. *Collect Bot* 34:e004. <https://doi.org/10.3989/collectbot.2015.v34.004>
19. The Ramsar List (2020) The List of Wetlands of International Importance. http://www.ramsar.org/sites/default/files/documents/library/strategic_framework_rsis_fr.pdf. Accessed 5 Dec 2020
20. Xiaolong W, Jingyi H, Ligang X et al (2014) Soil characteristics in relation to vegetation communities in the wetlands of Poyang Lake, China. *Wetlands* 34:829–839. <https://doi.org/10.1007/s13157-014-0546-x>
21. You H, Fan H, Xu L et al (2019) Poyang lake wetland ecosystem health assessment of using the wetland landscape classification characteristics. *Water* 11:825. <https://doi.org/10.3390/w11040825>
22. Lei S, Zhang XP, Li RF et al (2011) Analysis the changes of annual for Poyang Lake wetland vegetation based on MODIS monitoring. In: *Procedia environmental sciences*. Elsevier B.V. New York, pp 1841–1846
23. Wang Q, Riemann D, Vogt S, Glaser R (2014) Impacts of land cover changes on climate trends in Jiangxi province China. *Int J Biometeorol* 58:645–660. <https://doi.org/10.1007/s00484-013-0645-z>
24. Ye X, Zhang Q, Liu J et al (2013) Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, china. *J Hydrol* 494:83–95. <https://doi.org/10.1016/j.jhydrol.2013.04.036>
25. GOST 26423-85 (2011) Soils. Methods for determination of specific electric conductivity, pH and solid residue of water extract. Standartinform, Moscow
26. Soldatova E, Dong Y, Li J et al (2020) Nitrogen transformation and pathways in the shallow groundwater–soil system within agricultural landscapes. *Environ Geochem Health*. <https://doi.org/10.1007/s10653-020-00733-w>
27. Soldatova EA, Guseva NV, Sun Z, Mazurova IS (2015) Size fractionation of trace elements in the surface water and groundwater of the Ganjiang River and Xiushui River basins, China. *IOP Conf Ser Earth Environ Sci* 27:012037. <https://doi.org/10.1088/1755-1315/27/1/012037>
28. Shu W, Wang P, Zhao J et al (2020) Characteristics, sources and risk assessment of heavy metals in the Ganjiang river basin, China. *Polish J Environ Stud* 29:1849–1868. <https://doi.org/10.15244/pjoes/109846>
29. Mateo-Sagasta J, Zadeh SM, Turral H (2018) More people, more food, worse water? A global review of water pollution from agriculture. FAO, Water, Water, Land and Ecosystems (WLE) Program of the CGIAR, International Water Management Institute (IWMI), Colombo
30. Xu B, Wang G (2016) Surface water and groundwater contaminations and the resultant hydrochemical evolution in the Yongxiu area, west of Poyang Lake, China. *Environ Earth Sci* 75:1–16. <https://doi.org/10.1007/s12665-015-4778-8>
31. Lamers LPM, Ten Dolle GE, Van Den Berg STG et al (2001) Differential responses of freshwater wetland soils to sulphate pollution. *Biogeochemistry* 55:87–102. <https://doi.org/10.1023/A:1010629319168>
32. Niu Y, Niu Y, Yu H et al (2019) Concentration distribution and toxicity of heavy metals in surface sediment of Poyang Lake, China. *Wetlands* 39:55–62. <https://doi.org/10.1007/s13157-017-0904-6>
33. GB3838-2002 (2002) Environmental quality standards for surface water. Beijing: Ministry of Environmental Protection, PR China
34. Shvartsev S, Shen Z, Sun Z et al (2016) Evolution of the groundwater chemical composition in the Poyang Lake catchment, China. *Environ Earth Sci* 75:1239. <https://doi.org/10.1007/s12665-016-6065-8>
35. Yoshida S, Chaudhry MR (1979) Sulfur nutrition of rice. *Soil Sci Plant Nutr* 25:121–134. <https://doi.org/10.1080/00380768.1979.10433152>
36. Yoshida S (1981) Fundamental of rice crop science. International Rice Research Institute, Los Baños
37. Satrusajang A, Snitwongse P, Buresh RJ, Friesen DK (1991) Nitrogen-15 and sulfur-35 balances for fertilizers applied to transplanted rainfed lowland rice. *Fertil Res* 28:55–65. <https://doi.org/10.1007/BF01048856>
38. Soldatova E, Guseva N, Sun Z et al (2017) Sources and behaviour of nitrogen compounds in the shallow groundwater of agricultural areas (Poyang Lake basin, China). *J Contam Hydrol* 202:59–69. <https://doi.org/10.1016/j.jconhyd.2017.05.002>
39. Soldatova E, Sun Z, Maier S et al (2018) Shallow groundwater quality and associated non-cancer health risk in agricultural areas (Poyang Lake basin, China). *Environ Geochem Health* 40:2223–2242. <https://doi.org/10.1007/s10653-018-0094-z>
40. Soldatova E, Guseva N, Wang G (2014) Characteristic features of groundwater pollution in the Poyang Lake catchment. *IOP Conf Ser Earth Environ Sci* 21:012023. <https://doi.org/10.1088/1755-1315/21/1/012023>
41. Sun Z, Soldatova EA, Guseva NV, Shvartsev SL (2014) Impact of human activity on the groundwater chemical composition of the south part of the Poyang Lake Basin. *IERI Procedia* 8:113–118. <https://doi.org/10.1016/j.ieri.2014.09.019>
42. Ephraim JH, Allard B (1997) Metal Ion Binding by Humic Substances. In: Grenthe I, Puigdomenech I (eds) *Modelling in aquatic chemistry*. OECD, Nuclear Energy Agency, Paris, pp 207–244
43. Savichev O, Soldatova E, Rudmin M, Mazurov A (2020) Geochemical barriers in oligotrophic peat bog (Western Siberia). *Appl Geochem* 113:104519. <https://doi.org/10.1016/j.apgeochem.2019.104519>
44. Shvartsev SL (2008) Geochemistry of fresh groundwater in the main landscape zones of the Earth. *Geochemistry Int* 46:1285–1398. <https://doi.org/10.1134/S0016702908130016>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.