Indicative significance of the magnetic susceptibility of substrate sludge to heavy metal pollution of urban lakes

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ABSTRACT: Soil magnetic susceptibility has been widely used as an alternative index of soil heavy metal pollution because of its simple process, fast measurement, and good correlation with heavy metal. However, whether soil magnetic susceptibility can be used as an indicator of heavy metal pollution in urban water has not been studied in depth. In this study, 34 samples of substrate sludge and 39 soil samples were collected from lakes/ponds and their surrounding areas in Xiangtan City, Hunan Province. The magnetic susceptibility of individual samples was measured by a Bartington MS2 dual-frequency susceptibility meter. The results showed that the magnetic susceptibility of lake sediment and soil samples fluctuated between $11.60–160.77\times10^{-8}$ m^3/kg and $5.33–107.17\times10^{-8}$ m^3/kg, respectively. The average magnetic susceptibility of lake sediment (48.50×10^{-8} m^3/kg) was slightly higher than that of the surrounding soil (41.75×10^{-8} m^3/kg). The magnetic susceptibility values of substrate sludge from small to large were Jiuhua Park, Juhuatang Park, and Yuhu Park. Many factors could affect lake sediment's magnetic susceptibility; and the main influencing factors could be: the shape of the lake, the strength of the current, the movement of the lake water, the aquatic ecosystem, the physical and chemical properties of the lake water, the intensity of human activities, the construction of buildings, and the types of factories and enterprises. More detailed studies and experiments are urgently needed to reveal the variation of laws and response mechanisms of sediment's magnetic susceptibility in urban lakes.

KEYWORDS: urban water, substrate sludge, magnetic susceptibility, heavy metal pollution

INTRODUCTION

In recent years, as a new technical approach, the medium's magnetic properties have been widely used to monitor and study the heavy metal pollution in soil and sediment [1–3]. The magnetic method has many advantages, such as rapidity, simplicity, low cost, no damages to samples, accessibility to fieldwork, and multi-parameter measurement [4, 5].

Many researches on heavy metal pollution, including tracing the source of pollutants, heavy metal pollution, land pollution classification, street dust, soil, automobile exhaust, showed that the magnetic parameters of media were intimately related to the degree of heavy metal pollution and could be used as an alternative indicator of heavy metal pollution [6–9]. Magnetic susceptibility is an essential magnetic parameter, which is the ratio of the magnetic intensity induced by the soil in the external magnetic field to the magnetic intensity [10–13].

The magnetic susceptibility can reflect the soil's magnetic strength and the content of ferromagnetic minerals in the soil, and it is closely related to the content of some heavy metals in the soil [14–17].

With the rapid development of China's economy, urbanization has been speeding up, and the number of urban populations has increased dramatically, leading to a series of urban pollution problems, such as the decline of urban air quality and water pollution. Urban waters play an essential role in the urban ecosystem. It can conserve water sources, regulate the local climate, and reduce pollutants' concentration in the atmosphere and soil, thus purifying the urban environment and playing an irreplaceable role in stabilizing and maintaining the urban ecological environment. Therefore, local governments and scientific researchers gradually began to pay attention to the maintenance, management, and rational use of urban waters [5]. Research on heavy metal pollution in urban waters has been imminent. The magnetic susceptibility had been

applied to the study of heavy metal pollution in soil, but whether it can be used to study heavy metal pollution in urban lakes remains to be discussed.

Substrate sludge plays a vital role in the environment and ecology in aquatic ecosystems and is an essential pollution source (/sink) [18–20]. Once heavy metals pollute the water, most of them will be converted into a solid phase and deposited in the sediment. However, the substrate sludge's heavy metals are unstable, being rereleased and polluting the water body due to the changes of water environment, causing harm to the aquatic ecosystem. The substrate sludge is also the habitat and food source of benthic organisms in lakes. Benthic organisms can use these accumulated heavy metals both directly and indirectly [21–23]. However, heavy metals have distinct characteristics of bioconcentration and refractory degradation and will not migrate or be degraded by natural processes. Therefore, they will be preserved in sediment as an endogenous source of water pollution for a long time [24, 25]. These heavy metals can return to the water body under specific physical and chemical conditions, causing secondary pollution and even endangering human health through environmental media or the food chain [18, 26, 27].

Using the substrate sludge and topsoil of representative lakes and ponds in Xiangtan City as studied samples, this study aimed to find out: (i) the spatial variation of magnetic susceptibility of substrate sludge in urban lakes; and (ii) factors affecting magnetic susceptibility distribution of sediment in urban lakes. The findings were expected to provide a theoretical basis for urban water management and sustainable development.

MATERIALS AND METHODS

Research area

Xiangtan City (27°21′–28°05′N, 111°58′–113°05′E) mainly composes of typical low-mountain-hilly landforms with Xiangjiang River, Lianshui River, and Juanshui River lying in the valley plain of Xiangjiang River. The City belongs to the subtropical humid monsoon climate with distinct seasons, abundant precipitation, high temperature in the summer, and cold winter. The annual average rainfall is over 1425 mm. The precipitation concentrates from April to July, and the annual average temperature is 17.5 °C.

Because of its superior non-ferrous metal resources, mainly heavy industry has been developed in the studied area for a long time, leading to severe heavy metal pollution and ecological environment problems [28, 29]. However, since 2015, Xiangtan City has gradually closed down its polluting factories and enterprises, vigorously rectified and improved the urban ecological environment, and eventually been nominated the fifth "National Civilized City" in 2017.

Sampling, preparation, and analysis of soil samples

In March 2018, samples were collected from Yuhu Park, Juhuatang Park, Jiuhua De Culture Park, Yaai Village Farmland, and Xiannvshan Farmland (Fig. S1). Firstly, the Google Map was used to determine the sampling range and the location of sampling points. When sampling in the field was performed, the sampling point's original position was adjusted according to the actual circumstances; and the coordinates of the actual sampling point were recorded by GPS. Finally, Google Map and Golden Software Surfer 11 were used to generate the schematic diagram of sampling points.

Surface soil samples around the lake were collected using a soil ring knife (50.46 × 50 mm), and 39 samples were collected. By using a grab dredger, 34 samples of substrate sludge were also collected. All samples were sealed in polyethylene self-sealing bags and brought back to the laboratory for further testing.

Samples brought back to the laboratory were air-dried for a week. Then, litter, bricks, tiles, and garbage in individual samples were picked up, crushed, milled through 20 mesh sieves, uniformly mixed, and finally packed into polyethylene self-sealing bags. When testing, each sample was weighed, packed into 10 ml special plastic boxes with plastic covers. The low-frequency magnetic susceptibilities of soil and sediment were measured by Bartington MS2 dual-frequency susceptibility meter in a low-frequency (0.47 kHz) magnetic field at 25 °C, and the measured values were recorded. Each sample was tested in triplicates, and the average value was taken as the sample's low-frequency susceptibility value.

RESULTS AND DISCUSSION

Overall characteristics of magnetic susceptibility

There are two sources of magnetic minerals in materials. One is exogenous, i.e. from the outside in flowing water or atmosphere; including rock weathering products, industrial "three wastes", domestic refuse, and cosmic dust; and the other is endogenous, i.e.

Table 1 The magnetic susceptibility of the substrate sludge in different regions.

Sampling area	X_{lf} (10^{-8} m^3/kg)	
	Average	Range
Jiuhua Park	21.52	15.57–42.28
Xiannvshan Farmland	58.19	36.76–71.33
Yaai Village Farmland	66.54	43.00–83.00
Juhuatang Park	103.99	68.18–214.74
Yuhu Park	118.64	86.44–249.23
Total	63.92	15.57–249.23

Table 2 The magnetic susceptibility of the surface soil in different regions.

Sampling area	X_{lf} (10^{-8} m^3/kg)	
	Average	Range
Jiuhua Park	25.08	12.11–52.63
Yaai Village Farmland	30.06	8.06–51.86
Xiannvshan Farmland	46.14	20.46–83.10
Juhuatang Park	58.20	24.69–97.00
Yuhu Park	68.34	25.15–132.21
Total	48.73	8.06–132.21

secondary magnetic minerals formed by "primary" iron through chemical or biochemical processes [3]. Heavy metals in the sediment of urban lakes/ponds originate from both of the aforementioned sources; but more importantly, heavy metals often accumulate due to urban runoff and various wastewater discharges. The surface soil changes rapidly because of the interference of various external factors, but the substrate sludge is more likely to accumulate various heavy metals for a long time. Consequently, the sludge's accumulated heavy metals pollute the water body and endanger its ecological system and people's health [30, 31].

Be it between regions or between different sampling points in the same region, the variation range of the substrate sludge's magnetic susceptibility was enormous, ranging from 8.06×10^{-8} m^3/kg to 249.23×10^{-8} m^3/kg, with an average value of 55.81×10^{-8} m^3/kg (Table 1). The magnetic susceptibility of each region from small to large was as follows: Jiuhua Park < Xiannvshan Farmland < Yaai Village Farmland < Juhuatang Park < Yuhu Park.

Jiuhua Park, with a lake located within, is a newly-built urban park. The sediments at the bottom of the lake are mostly primitive soil layers, which are not affected by human factors. The low-frequency magnetic susceptibility of the bottom sludge in the lake was lower than that in the other

areas. On the contrary, Yuhu Park lies in the center of the city, surrounded by numerous residential areas, with a massive flow of people and close to the city's main road; so it is severely polluted by living and traffic pollution, which could be the main reason for the high magnetic susceptibility of the substrate sludge in the Park's lake. Juhuatang Park is close to the old industrial zone of Xiangtan City, and the industrial pollution is severe. Therefore, the magnetic susceptibility of the underwater sludge in Juhuatang Park was relatively high. However, in recent years, due to the optimization or halt of the old heavily polluting enterprises in Xiangtan City and the effective treatment of its environmental pollution by Juhuatang Park itself, the pollution was relatively reduced.

Compared with the substrate sludge's magnetic susceptibility, the variation range of the surface soil's magnetic susceptibility was relatively small, but there were still significant changes. The average value of soil magnetic susceptibility was 8.72×10^{-8} m^3/kg, which fluctuated from 8.06×10^{-8} m^3/kg to 132.21×10^{-8} m^3/kg. The magnetic susceptibility of each region from small to large was as follows: Jiuhua Park, Yaai Village Farmland, Xiannvshan Farmland, Juhuatang Park, and Yuhu Park (Table 2).
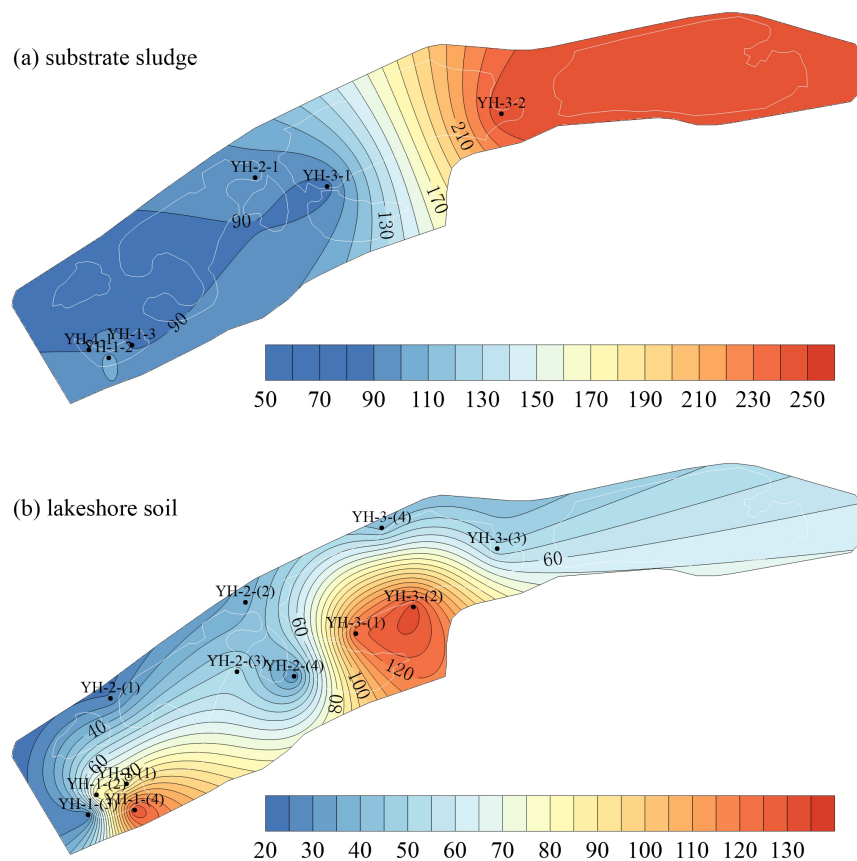
Characteristics of magnetic susceptibility of substrate sludge and soil in different urban areas

Sampled lakes lie in different parts of the City, including Urban Area (Yuhu Park and Juhuatang Park), Urban-rural Junction (Jiuhua De Culture Park and Yaai Village Farmland), and Rural Area (Xiannvshan Farmland). Fig. 1 and Fig. 2 are drawn by Golden Software Surfer 11 to clearly compare the variation of soil and sediment's magnetic susceptibility.

Urban area

The variation of magnetic susceptibility of sediment and surrounding soil in Yuhu Park was the most considerable. The magnetic susceptibility of lake sediment and surface soil in Yuhu Park varied from 86.44 to 249.23×10^{-8} m^3/kg and 25.15 to 132.21×10^{-8} m^3/kg, with average values of 118.64×10^{-8} m^3/kg and 68.34×10^{-8} m^3/kg, respectively.

The magnetic susceptibility of the substrate sludge of Yuhu Lake, situated in close proximity to the residential area's center, increased from the southwest to the northeast. Besides, the Middle Lake and the Lower Lake have a larger area and

Fig. 1 Distribution of magnetic susceptibility of sediment and soil in Yuhu Park.
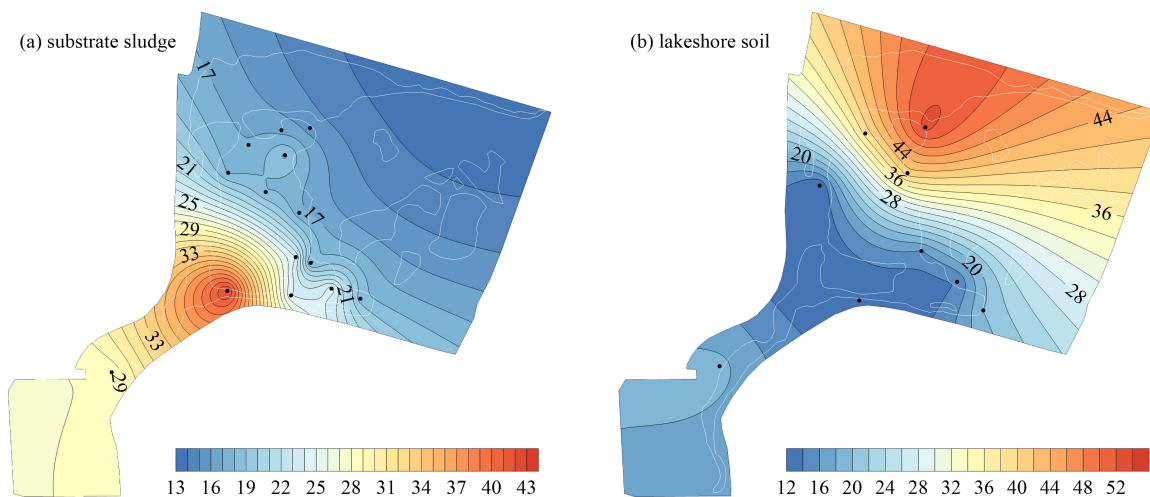
Fig. 2 Distribution of magnetic susceptibility of sediment and soil in Jiuhua De Culture Park.

more massive passenger flow. Therefore, the human impact is severe. At the junction of different lake areas, a large amount of sediment might accumulate due to the slow flow rate; hence high soil magnetic susceptibility was found at these sampling points, such as YH-3-2 (247.37×10^{-8} m^3/kg) (Fig. 1(a)).

The magnetic susceptibilities of YH-1-(4) (131.47×10^{-8} m^3/kg), YH-3-(1) (123.23×10^{-8}

m^3/kg), and YH-3-(2) (132.21×10^{-8} m^3/kg) were significantly higher than those of the other sampling points. The main reason was that the aforementioned sampling points were close to the Park's main roads and residential areas, so human activities contributed a significant impact on them and led to the high magnetic susceptibility. However, the magnetic susceptibilities of the other sampling points were significantly lower, such as YH-1-(3) (25.15×10^{-8} m^3/kg), YH-2-(1) (25.88×10^{-8} m^3/kg), and YH-2-(4) (30.34×10^{-8} m^3/kg), mainly because the soils at these points lay in the vicinity of shrubs [7] (Fig. 1(b)).

The magnetic susceptibility of sediment in Juhuatang Park rangeed from 68.18×10^{-8} m^3/kg to 214.73×10^{-8} m^3/kg, with an average of 103.99×10^{-8} m^3/kg. The magnetic susceptibility of soil ranges from 24.69×10^{-8} m^3/kg to 96.99×10^{-8} m^3/kg, with an average of 58.19×10^{-8} m^3/kg. Juhuatang Park is located on the west side of Dongsi Road in Xiangtan City. In the Park, there are various sports facilities, cruise boats, tea houses, and barbecue grounds. Moreover, there are many commercial shops and residential areas nearby the Park. In the southwest direction, there are also some processing plants of Xiangtan Iron & Steel Co. LTD. of Hunan Valin. These might be the reasons for its high magnetic susceptibility.

Urban-rural junction

The magnetic susceptibility of sediment in Jiuhua De Culture Park ranges from 15.57×10^{-8} m^3/kg to 42.28×10^{-8} m^3/kg, with an average of 21.52×10^{-8} m^3/kg. The magnetic susceptibility of soil ranges from 12.11×10^{-8} m^3/kg to 52.63×10^{-8} m^3/kg, with an average of 25.08×10^{-8} m^3/kg. The Park covers a large area with abundant waterscape resources. There are many commercial residences around the scenic spot. The spatial variation of magnetic susceptibility is complex (Fig. 2). Generally speaking, the overall magnetic susceptibility is low, which may be related to that the Park is located in the new development zone and is disturbed by human activities for a short time.

Yaai Village Farmland's sampling point is near the campus of Hunan University of Science and Technology and the Shanghai-Kunming Expressway, beside which there is farmland. The sediment's magnetic susceptibility in Yaai Village Farmland ranges from 43.00×10^{-8} m^3/kg to 83.00×10^{-8} m^3/kg, with an average of 66.54×10^{-8} m^3/kg. The sediment's magnetic susceptibility in Yaai Village Farmland ranges from 8.06×10^{-8} m^3/kg to 51.86×10^{-8} m^3/kg, with an average of 30.06×10^{-8} m^3/kg. This area's magnetic susceptibility value is lower than that of many other areas, which may be due to its distance from the urban area and its proximity to farmland.

Rural area

Because the Xiannvshan Farmland is far away from the urban area, its magnetic susceptibility value was low. The average magnetic susceptibility of sediment in Xiannvshan Farmland was 58.19×10^{-8} m^3/kg, and the average magnetic susceptibility of surrounding soil was 46.14×10^{-8} m^3/kg. However, the excessive agricultural activities and nearby highway transportation kept their magnetic susceptibility at a certain level, not the lowest in all of the studied areas.

Spatial configuration relations and discussion

Based on lake sediment and surrounding soil's magnetic susceptibility data, this study explored the spatial distribution of lake sediment magnetic susceptibility and its possible collocation with other factors by taking Xiangtan typical parks as examples.

Yuhu Park, founded in 1954, lies in the center of Xiangtan City and covers an area of 12 hectares, including Upper Lake, Middle Lake, and Lower Lake. Jiuhua Park, founded in 2011, lies in the central area of Jiuhua Binjiang New Town, with an area of about 66.67 hectares, including about 40 hectares of water area. It is adjacent to Shanghai-Kunming Expressway in the north and Xuefu Road in the south (Fig. S1). Both parks have large water storage areas, typical representatives of new and old parks, and urban and suburban parks. In this study, only these two parks were discussed and not the other sampling areas because of their small water bodies.

The magnetic susceptibility of soil around Yuhu Park showed two high-value centers, and one low-value center was shown in the sediment. From the spatial distribution of high and low-value centers, the locations were relatively close, indicating that the change of magnetic susceptibility of lake sediment was affected by the lakeshore soil. The soil could be the dominant factor in the variation of magnetic susceptibility of the Yuhu Park's substrate sludge. However, the locations of high and low susceptibility centers of the lakeshore soil and the substrate sludge did not entirely coincide with each other, which might be related to lake water movement, lake ecosystem, and even artificial siltation removal.
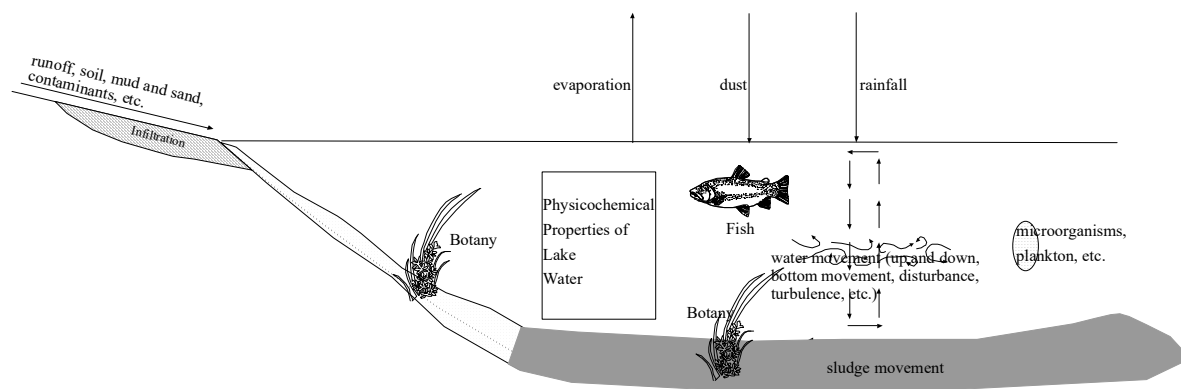
Fig. 3 Sources and influencing factors of heavy metals in lake sediment.

The variation of magnetic susceptibilities of lakeshore soil and lake sediment of the Jiuhua Park was rather complicated. The spatial locations of the high and low magnetic susceptibility centers of the sediment and the soil were quite different. The high-value area of magnetic susceptibility of substrate sludge lay in the low-value area of magnetic susceptibility of the surrounding soil, while the low-value area of magnetic susceptibility of substrate sludge lay in the high-value area of surrounding soil magnetic susceptibility. This configuration was quite different from the Yuhu Park's. The reason might be closely related to the Park's lake area and shape. Because the open area of Yuhu Park is small, and the shapes of the Park and the lake are long and narrow, the surrounding soil would enter the water body immediately under runoff. Moreover, the transport capacity of the lake water could be weaker due to its smaller area. Therefore, the high and low magnetic susceptibility values of sediment and soil were close in space.

However, Jiuhua Park's lake area is large, and the ability of lake water movement is strong, resulting in significant regional differences. Simultaneously, the high-value area of the substrate sludge's magnetic susceptibility in Jiuhua Park was located in the narrowest location of the lake. The long and narrow channel was beneficial to sediment accumulation but not to diffusion. Numerous magnetic materials accumulated at the channel, resulting in high magnetic susceptibility of sediment. Besides, the Park is located adjacent to a construction site, and magnetic materials produced in the construction process also enter the waterway under the runoff, which could be one reason for the sediment's high magnetic susceptibility value. From this point of view, the change of lake sediment's magnetic sus-

ceptibility could be affected by many factors, such as the shape of the lake, the strength of water flow, the intensity of human activities, the construction process, and the types of factories and enterprises [32, 33].

The magnetic susceptibility of lake sediment, which reflects the accumulation and transformation of heavy metals, is an indicator of heavy metal pollution in lakes. Although the application of environmental magnetic methods to the study of heavy metal pollution in river sediments is relatively rare [34], a large number of studies have shown that there is a significant correlation between the magnetic characteristics of soil and sediment and heavy metal pollution, which can reflect the degree of heavy metal pollution [35–38]. For urban rivers, due to their relatively closed environmental conditions, their self-purification capacity and water renewal speed are far less than those of large rivers, so they are more vulnerable to the impact of coastal pollutant emissions [39]. As far as this study is concerned, urban lakes/ponds' environmental conditions are more closed and more affected by coastal pollutants. Some pollutants, including heavy metals, are transferred into sediment and stored under specific conditions, which is very easy to cause secondary pollution to the water body [40]. The sources of heavy metals in lake sediment are very complex, and the physical and chemical processes of their accumulation and transformation are also very complex (Fig. 3). Influenced by lake water's movement, aquatic ecosystem, physical and chemical properties of lake water, the distribution of heavy metals in lakes is not uniform [41, 42]. This non-uniform distribution is not static and will change under certain conditions with very complicated factors [43–45]. The changes of heavy metal content in the

sediment affect the changes and safety of the whole water ecosystem.

CONCLUSION

The results showed that the low-frequency magnetic susceptibility of substrate sludge in Xiangtan City fluctuated widely. The soil's magnetic susceptibility was lower than the substrate sludge's. The magnetic susceptibility of substrate sludge increased gradually from the suburb to the urban areas, reflecting the significant influence of human activities.

Many factors, such as the shape of the lake, the strength of the current, the movement of the lake water, the aquatic ecosystem, the physical and chemical properties of the lake water, the intensity of human activities, the construction of buildings, and the types of factories and enterprises, could affect the changes of the magnetic susceptibility of lake sediment, revealing the changes of heavy metals in the lake. Therefore, more detailed studies are needed to reveal the law of change.

Appendix A. Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2021.048.

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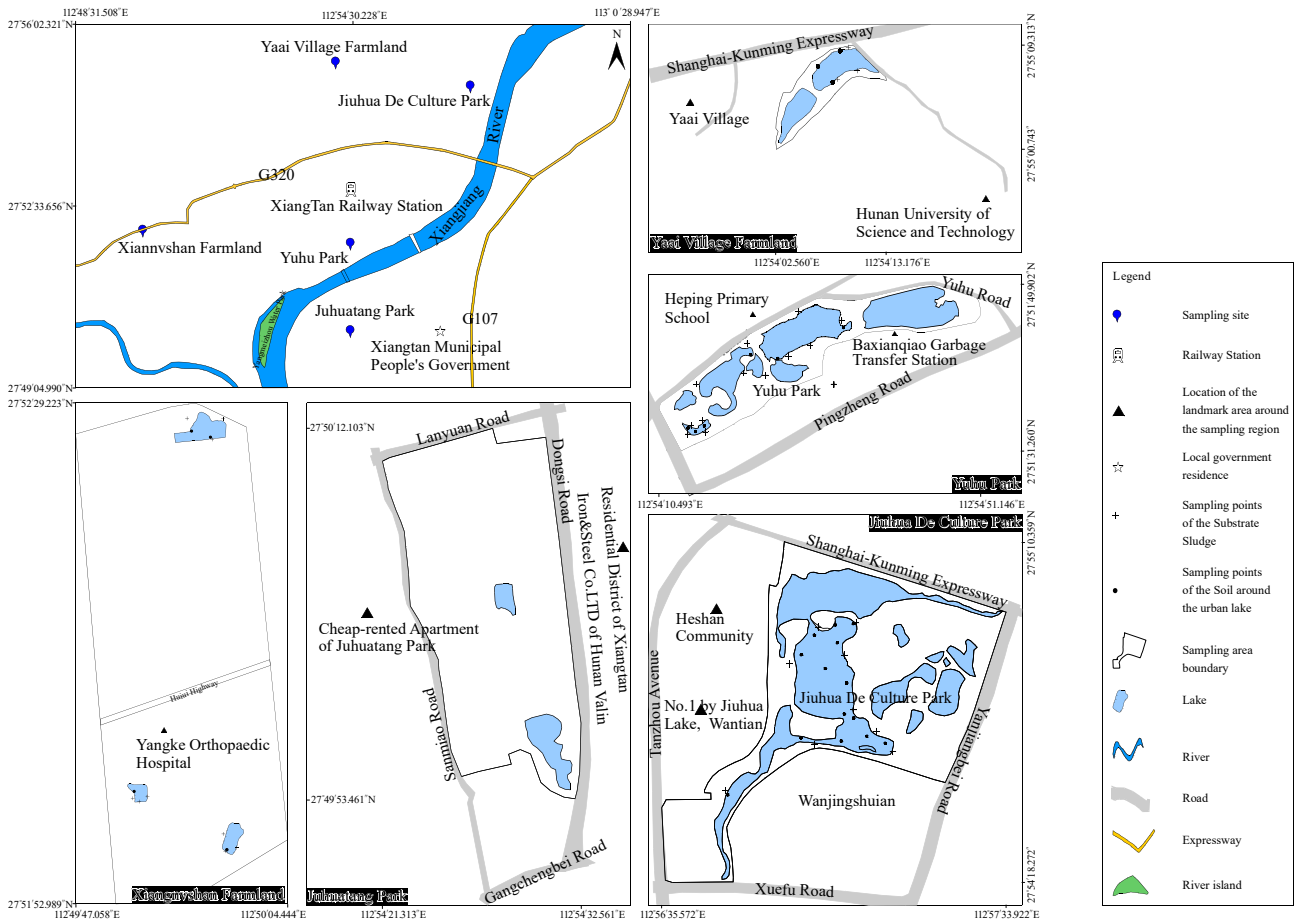
Appendix A. Supplementary data

Fig. S1 Distribution of sampling points.