



Using magnetic susceptibility to evaluate pollution status of the sediment for a typical reservoir in northwestern China

Huiyun Pan^{1,2} · Xinwei Lu¹ · Kai Lei³ · Dongqi Shi¹ · Chunhui Ren¹ · Linna Yang¹ · Lijun Wang¹

Received: 8 August 2018 / Accepted: 23 November 2018 / Published online: 30 November 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Intensive anthropogenic activities may add to pollution risks to lakes and rivers, which can be revealed by the magnetic characteristics of sediments. The present study aims to assess the pollution status of the sediment of a typical reservoir in northwestern China by application of magnetic susceptibility. The values of magnetic susceptibility exhibited significant positive correlations with trace metals (Co, Cu, Mn, Ni, and V) and natural radionuclides (²³²Th and ⁴⁰K). Multivariate statistical analysis indicated common sources and similar deposition characteristics of magnetic particles and trace metals. It was conformed that magnetic susceptibility could be used as an indicator to identify industrial sources of trace metals, but was not suitable to indicate the traffic or natural sources. Linear regression equations between the low-frequency magnetic susceptibility and the integrated pollution index as well as annual effective dose rate indicated a potential for using magnetic susceptibility in semi-quantitative assessment of trace metal pollution and radiological hazard in sediments. A three-step procedure is proposed for the use of magnetic susceptibility in pollution monitoring, which provides a fast and effective method for estimating the pollution extent and tracing the major sources of trace metals in the sediment of lakes and rivers.

Keywords Trace metal · Natural radionuclide · Pollution indicator · Source discrimination · Environmental magnetism method

Introduction

Sediment is an important environmental medium in aquatic ecosystem, which is considered as the environmental host of the waste discharged by natural and artificial processes (El-Taher and Madkour 2011). Numerous harmful contaminants such as metals and radionuclides are detected in sediments, which constitutes a very useful tool for the water environment quality assessment (Szarlowicz et al. 2013; Erenturk et al. 2014). Trace metals including heavy metals and metalloids,

such as nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As), are the most frequently detected contaminants in sediments, which have adverse effects on aquatic organisms and account for potential health risks for human being (Suresh et al. 2012; Acosta et al. 2015; Trujillo-González et al. 2016). These elements are precipitated or adsorbed on particulate material and accumulate in sediments and may influence the aquatic environment during the next few decades or even centuries because they are non-biodegradable (Doichinova et al. 2014, Peng et al. 2017).

Human activities cause obvious enrichment of trace metals in the sediment, such as vehicle traffic, industrial and agricultural activities, and mining activities (Jordanova et al. 2013). Therefore, much concern has been attracted to the monitoring and assessment of pollution status of the sediment (Erenturk et al. 2014, Jordanova et al. 2004, Prajith et al. 2015). Geochemical methods are generally applied to monitor the occurrences of metals in sediments (Jordanova et al. 2013). Considering the sampling procedures before analysis, the whole process is usually expensive and time consuming. Therefore, geophysical technologies which are generally time- and cost-efficient have been proposed to identify the occurrences and sources, and evaluate the risks of trace metals

Responsible editor: Philippe Garrigues

✉ Xinwei Lu
luxinwei@snnu.edu.cn

¹ Department of Environmental Science, School of Geography and Tourism, Shaanxi Normal University, Xi'an 710119, People's Republic of China

² Institute of Resources and Environment, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China

³ School of Environment, Beijing Normal University, Beijing 100875, People's Republic of China

in soils and sediments (Hay et al. 1997; Strzyszcz and Magiera 1998; Lu et al. 2007; Wang et al. 2017).

Previous studies have acknowledged correlations between trace metal content and magnetic properties, and proposed that some magnetic properties might be used as a proxy for metal contents (Chen et al. 2013; Liu et al. 2013; Dong et al. 2014; Chaparro et al. 2017). In these methods, magnetic susceptibility has been widely applied as approximation of trace metal contamination because it is an easily measurable and concentration-dependent geophysical parameter (Bityukova et al. 1999; Canbay et al. 2010; D’Emilio et al. 2012; Zhang et al. 2013). Furthermore, this method is especially useful in characterizing and screening of technogenic magnetic particles released by industrial and urban dust deposition derived from high-temperature technological processes (Magiera et al. 2011; Basavaiah et al. 2012; Rachwał et al. 2017). Enrichment in trace metals identified by high magnetic susceptibility values of soils and sediments was observed in the surroundings of various industrial plants like coke plants, power plants, iron and steel works, and nonferrous metallurgical works (Lu et al. 2007; Zhang et al. 2011; Liu et al. 2013; Rachwał et al. 2015). Therefore, magnetic measurements combined with geochemical analysis proved to be very helpful in identifying the trace metal pollution and tracing the sources of pollutants in soils and sediments (Wang et al. 2013; Szuskiewicz et al. 2016).

Meanwhile, natural radionuclides such as ^{40}K , ^{238}U , and ^{232}Th are typically presented in sediments, which might lead to extra human exposure to radiation when the sediments are used as building material (Baeza et al. 2009; Yii et al. 2009; El-Taher and Madkour 2011). Significant correlations between magnetic susceptibility and the concentrations of ^{232}Th , ^{238}U , and ^{40}K have been reported (Ramasamy et al. 2014; Chaparro et al. 2017). Therefore, magnetism methods may also be used as additional tools in the assessment of radioactivity levels of sediment (Erenturk et al. 2014).

Wangjiaya reservoir is an important part of the Baoji Gorge Weibei Irrigation Project, which pumps water to supplement the water shortage of Baoji Gorge Irrigation Area and supplies artesian water to the original irrigation area. With long-term and large-scale industrial activities as well as rapid urbanization in Baoji city, the environmental quality of the reservoir has been potentially affected. In 2003, the establishment of Changqing industrial park upstream greatly increased the environmental risk to the reservoir. Since the intensity of agricultural practices and industrialization are considered to be the main sources of radioactivity and heavy metals in rivers (Saç et al. 2012; Faweya et al. 2013), considerable increase in radioactivity and trace metal levels of the sediment in this reservoir is expected (Krmár et al. 2009; Chaparro et al. 2017). Therefore, Wangjiaya reservoir represents an interesting case study for environmental contamination and ecological deterioration disturbed by intense anthropogenic activities.

The contamination levels of trace metals and natural radionuclides in sediments of this reservoir have already been reported in our previous studies (Lu et al. 2016; Zhu et al. 2016). The results indicated potential ecological risks of anthropogenic pollutants in the reservoir (Shi et al. 2018). In this study, the magnetic susceptibility of the sediment in Wangjiaya reservoir was investigated. We focus on the study of the relationship between the magnetic susceptibility and the levels of trace metals and natural radionuclides. The main aim is to evaluate the applicability of using the magnetic susceptibility characteristics as environmental pollution proxies concerning the influence of pollution sources. In particular, this method will be available for rapid discriminating of hotspots with high pollution risks and for tracing the anthropogenic pollution sources in the sediment of lakes and rivers.

Materials and methods

Background of study area

The investigated area, Wangjiaya reservoir, is an artificial lake located in about 20 km northwest of Baoji city, NW China (Fig. 1). The Qian River enters the reservoir from the north. The western and eastern parts of the reservoir are surrounded by farmlands, uncultivated lands, villages, and the main trunk of the traffic. The Changqing industrial park with zinc smelting, ironworks, coking, and coal-fired power generation is situated on the northeast side (Fig. 1). Detailed information about the study area can be found in our previous studies (Lu et al. 2016; Zhu et al. 2016; Shi et al. 2018).

Sampling and preparation

Sediment samples were collected in 34 sites of Wangjiaya reservoir (Fig. 1). At every sampling site, a surface sediment sample (0–20 cm) was collected by using a grab sampler and the longitudes and latitudes of each sampling site were recorded by a hand-held global positioning system (GPS) instrument. An uncontaminated sediment sample was collected from the upstream of Qian River as the reference in the study area for background study.

All samples were dried, crushed, and sieved through a 1.0-mm nylon sieve to remove stones, coarse debris, dead organisms, etc. Approximate 50 g sediment sample was separated and ground with vibration mill, and then sieved through a 0.075-mm nylon mesh for measuring metal concentration. Additionally, one half of the preliminarily sieved sediment samples were dried at 110 °C for 36–48 h in an oven and ground and then sieved through a 0.16-mm mesh. The homogenized samples were weighted and then packed in a gas-tight, radon impermeable, cylindrical polyethylene plastic container (7.0-cm height and 6.5-cm diameter). These containers are

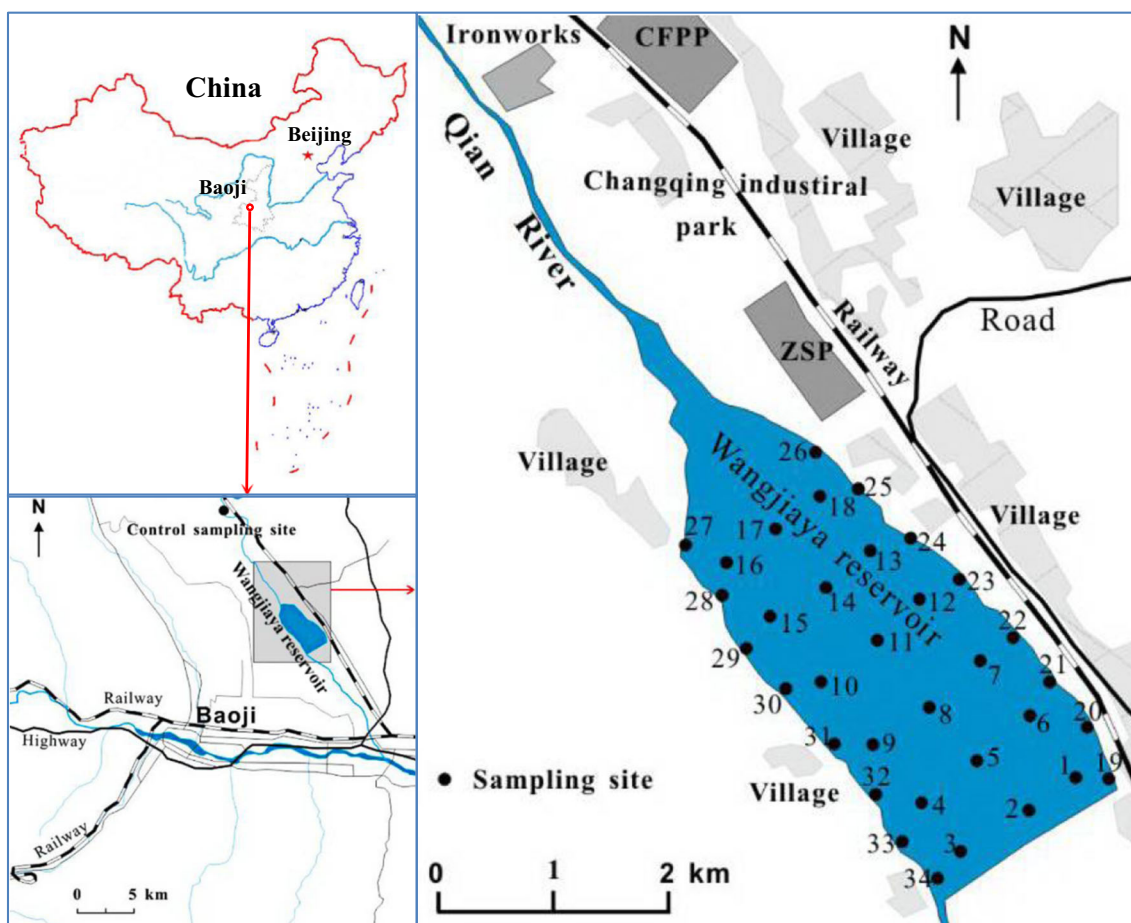


Fig. 1 Study area and the location of sampling sites in Wangjiaya reservoir. CFPP coal-fired power plant, ZSP zinc smelting plant

hermetically shielded and also shielded externally to ensure that all of the daughter products of uranium and thorium, radon isotope (^{222}Rn and ^{220}Rn) formed in particular, do not escape (Krishnamoorthy et al. 2014). The sealed samples were stored for about 30 days to allow ^{226}Ra and ^{224}Ra to reach the secular equilibrium with their short-lived decay products (Alencar and Freitas 2005; Lu et al. 2014a). After that period, the sediment samples were analyzed for natural radionuclide concentration using gamma ray spectrometry.

Experimental methods

For measuring metal concentration, 4.0 g of milled sediment sample and 2.0 g of boric acid were put into the pressure-instrument (YYJ-260) mold and crushed into a 32 mm diameter pellet under 30 t pressures. The contents of Co, Cr, Cu, Mn, Ni, Pb, V, and Zn in sediment samples were determined by wavelength dispersive X-ray fluorescence spectrometry (XRF, PANalytical PW-2403 apparatus) (Lu et al. 2010, 2014b, 2014c; Zhang et al. 2015). Duplicate samples and standard materials (GSS-1 and GSD-12) were used for quality control in the experiment, and the relative errors were less than 5% (Lu et al. 2014b, 2014c).

The concentrations of natural radionuclides ^{226}Ra , ^{232}Th , and ^{40}K in the sediment samples were determined by using a 3×3 -in. NaI (TI) gamma ray spectrometric system with excel 8% energy resolution (^{137}Cs 661.6 keV). The detector, housed in a lead cylindrical shield with a thickness of 10.5 cm and a height of 38 cm, was coupled to a 1024 microcomputer multi-channel pulse height analyzer and the system was calibrated for the γ -energy range 50 keV to 3.2 MeV (Lu et al. 2012). The activity of ^{232}Th was determined by 238.6 keV and 2614 keV gamma rays emitted from ^{212}Pb and ^{208}Tl , respectively. The activity of ^{226}Ra was measured by 609.3 keV and 1764.5 keV gamma rays emitted from ^{214}Bi , and ^{40}K activity was measured directly through its gamma ray energy peak of 1460.8 keV (El-Taher et al. 2010). All samples were counted for 18,000 s (Yang et al. 2013).

The low- and high-frequency magnetic susceptibility (low-frequency magnetic susceptibility χ_{LF} and high-frequency magnetic susceptibility χ_{HF}) was measured on 10 g samples by using a Bartington MS2 Magnetic Susceptibility Meter at frequencies of 0.47 and 4.7 kHz (Wang et al. 2015). The frequency-dependent magnetic susceptibility ($\chi_{\text{FD}}\%$) was defined as

$$\chi_{\text{FD}}(\%) = \frac{\chi_{\text{LF}} - \chi_{\text{HF}}}{\chi_{\text{LF}}} \times 100\%.$$

Assessment of trace metal contamination and radiological hazard

To explore the indicative function of magnetic susceptibility to trace metal contamination and radiological hazard, the pollution indexes of trace metals (single pollution index (PI) and integrated pollution index (IPI)) and the hazard index of radionuclides (annual effective dose rate (AED)) were calculated to assess the extents of trace metal contamination and radiological hazard. The PI was defined as the ratio of element concentration to the background content of the corresponding element (the control sample in this study). The PI of each element was classified as either low ($PI \leq 1$), middle ($1 < PI \leq 3$), or high ($PI > 3$). The IPI of all measured elements for each sample was defined as the average value of the element's P and was then classified as low ($IPI \leq 1$), middle ($1 < IPI \leq 2$), or high ($IPI > 2$) (Chen et al. 2005; Lu et al. 2009). The AED of each sediment sample was calculated to evaluate the radiological hazard due to gamma ray emission from ^{232}Th , ^{226}Ra , and ^{40}K (Gonzalez-Fernandez et al. 2012; Saç et al. 2012; Faweya et al. 2013; Lu et al. 2014a).

Radium equivalent activity (Ra_{eq}) is defined according to the estimation that 1 Bq kg^{-1} of ^{226}Ra , 0.7 Bq kg^{-1} of ^{232}Th , and 13 Bq kg^{-1} of ^{40}K produce the same gamma radiation dose rate and it is calculated through the following relation:

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.07C_K$$

In this equation, the C_{Ra} , C_{Th} , and C_K are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in Bq kg^{-1} , respectively. To avoid radiation hazards, materials whose Ra_{eq} is greater than 370 Bq kg^{-1} should not be used for residential building constructions (Faweya et al. 2013).

Health effects of exposure to radiation are not determined by just the specific activity of the radiation source but also by the radiation energy and the dose absorbed by individuals (Faweya et al. 2013). Indoor air absorbed dose rate (D_{in}) due to the gamma radiation from activity concentrations of natural radionuclides was calculated by the following equation:

$$D_{in} = 0.908C_{Ra} + 1.06C_{Th} + 0.0767C_K$$

where C_{Ra} , C_{Th} , and C_K are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in Bq kg^{-1} , respectively.

The annual effective dose rate (AED) was calculated from the following equation:

$$E = T \times Q \times D_{in} \times 10^{-6}$$

where T is the time for 1 year and Q is the conversion factor of 0.7 Sv Gy^{-1} , which converts the absorbed dose rate in air into human-effective dose received, while indoor occupancy factor was given as 0.8 (because most people spend a high percentage of their time indoors) (Faweya et al. 2013).

Multivariate statistical methods

Multivariate techniques were widely used to study the association between trace metals and magnetic variables (Lu et al. 2010; Chaparro et al. 2011; Chaparro et al. 2012). Pearson correlation analysis, cluster analysis (CA), principal component analysis (PCA), and K-means cluster analysis were conducted in this study. Pearson correlation analysis was performed to detect the relationships between magnetic susceptibility, trace metals, and radionuclides. The methods of CA and PCA were applied to discriminate the potential sources of the pollutants in the sediments by defining geochemical groups with approximately the same geochemical pattern (Gallego et al. 2002; Wang et al. 2015). K-means cluster analysis was used to recognize the difference of sampling sites affected by different sources. All statistical analyses were performed by using SPSS 20.0 and SAS JMP Statistical 13.0.

Results and discussion

Distribution characteristics of magnetic susceptibility

The statistic values of mass-specific magnetic susceptibility in sediments from Wangjiaya reservoir are presented in Table 1. The low-frequency magnetic susceptibility (χ_{LF}) varies from 49.9 to 102.0 $\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ with a median of 91.2 $\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and high-frequency magnetic susceptibility (χ_{HF}) varies from 47.0 to 92.7 $\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ with a median of 82.4 $\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, respectively. Although the median values of χ_{LF} and χ_{HF} are very close to those in the control sample (91.7 and 83.8 $\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$), the 50% for χ_{LF} and 44% for χ_{HF} of the sampling sites are higher than those of the control sample. The relatively high χ_{LF} values are frequently distributed in both sides of the reservoir middle and upper

Table 1 Descriptive statistics of magnetic susceptibility ($\times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) in the sediments of Wangjiaya reservoir

	χ_{LF}	χ_{HF}	$\chi_{FD\%}$
Min	49.9	47.0	3.3
Max	102.0	92.7	11.1
Mean	87.1	79.3	8.8
Median	91.2	82.4	9.1
SD	13.4	11.5	1.4
CV(%)	15.4	14.5	16.0
Kurtosis	1.88	1.80	6.33
Skewness	-1.56	-1.53	-2.02
Control sample	91.7	83.8	8.6

Notes: *Min*, minimum; *Max*, maximum; *Mean*, arithmetic mean; *SD*, standard deviation; *CV(%)*, coefficient of variance; χ_{LF} , low-frequency magnetic susceptibility; χ_{HF} , high-frequency magnetic susceptibility; $\chi_{FD\%}$, frequency-dependent magnetic susceptibility

reaches, such as S23, S24, S25, S26, S27, S28, S29, S30, S31, and S32 (Fig. 2a). The previous study suggested that the magnetic susceptibility of the sediment was controlled by anthropogenic sources like emission from industrial and fossil fuel combustion, particles from vehicles, fertilizers, pesticides, etc. (Yang et al. 2007). Additionally, the magnetic susceptibility enhancement in these sediment samples might greatly indicate the anthropogenic input from long-distant sources, including industrial sources in Changqing industrial park and traffic sources (Chlupáčová et al. 2010; Rachwał et al. 2017).

The calculated frequency-dependence magnetic susceptibility ($\chi_{FD}\%$) ranges from 3.3 to 11.0% with a median of 9.1%. About 65% of sampling sites show higher $\chi_{FD}\%$ than that of the control sample (8.6%), which are generally distributed in the middle to downstream of the reservoir (Fig. 2b). Frequency-dependence magnetic susceptibility is considered to reflect the presence of ultra-fine super paramagnetic ferri-magnetic grains particularly those grains between 0.010 and 0.025 μm (Shilton et al. 2005). Thus, the relatively higher $\chi_{FD}\%$ values indicate the obvious contribution of fine magnetic particles and the existence of super paramagnetic (SP) grains in the sediment (Wang et al. 2015), which is probably due to anthropogenic activities (Ng et al. 2003; Chlupáčová et al. 2010). Through field investigation, in addition to the industrial emission from the Changqing industrial park upstream, vehicular traffic, agriculture sewage discharge, and domestic sewage discharge from surrounding villages are potential origins of target pollutants in the reservoir.

Distribution patterns and pollution assessment of trace metals

Trace metal concentrations in the sediments of Wangjiaya reservoir have been reported in the previous study (Shi et al. 2018). According to the classification reported by Wilding

(1985), the seven elements (Co, Cr, Cu, Mn, Ni, Pb, and V) show low variability ($CV \leq 15\%$), and Zn shows a high variability ($CV > 36\%$) in spatial distribution in this study. The high CV of Zn might be due to the extremely high values of Zn in the northeast bank, which indicates potential pollution sources around the area. To illustrate the spatial distribution of these metals, the concentrations of individual metal and the reference levels of these trace metals in each sampling site are illustrated in Fig. 3.

Generally, metal concentrations in the middle of the reservoir (S1–S18) record relatively higher values compared to other sampling sites, especially Co, Cr, Cu, Ni, and V. High values of Mn are mostly concentrated in the west bank of the reservoir (S27–S34). While high concentrations of Pb and Zn are more likely to be observed in the east bank of the reservoir (S19–S26), which might be due to traffic sources originating from vehicular emissions and the wear and tear of vehicle parts (tires, brakes, etc.) (Van der Gon and Appelman 2009, Dong et al. 2017). The higher concentrations of Zn in the northeast bank might also be related to the zinc smelting plant in the north (Shilton et al. 2005). Such spatial variation of these metals might be due to the distinct distances between the sampling sites and the emission sources, the variation in the water flow rate, the nature of the sediment particles, and potential emissions, as well as metal characteristics (Bastami et al. 2014; Pan et al. 2017a). It is noteworthy that most of the upper outliers are located near the bank of the reservoir, which might indicate the presence of potentially polluted sediments generated by punctual and diffuse pollution source (D’Emilio et al. 2012).

The single pollution index (PI) and the integrated pollution index (IPI) are calculated to estimate the pollution levels of trace metals in sediments (Table 2). The IPIs and the most PIs of individual elements are in the range of 1 to 2, indicating a moderate level contamination of trace metals in sediments.

Fig. 2 The low-frequency magnetic susceptibility (χ_{LF}) (a) and the frequency-dependence magnetic susceptibility ($\chi_{FD}\%$) (b) of the sediments in Wangjiaya reservoir

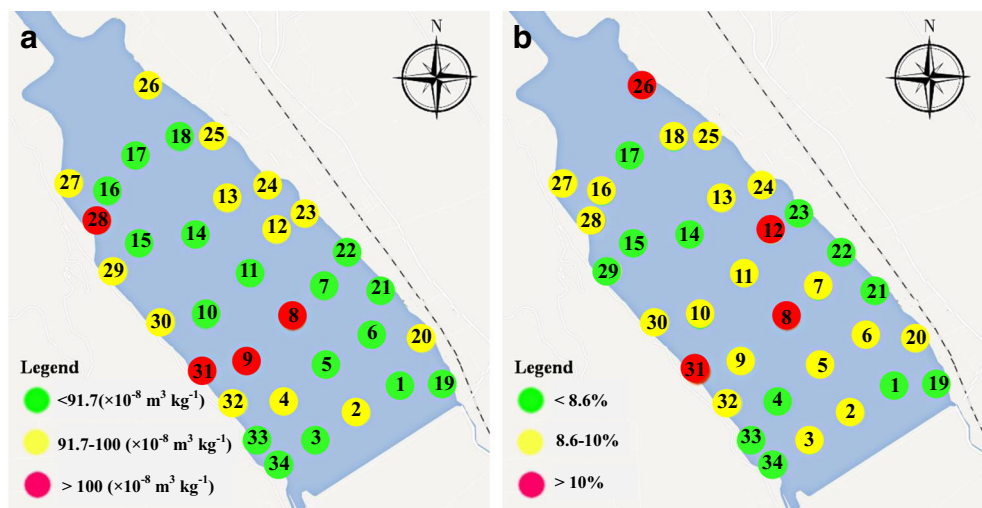


Fig. 3 Concentrations of Co, Cr, Cu, Mn, Ni, Pb, V, and Zn in the sediment of Wangjiaya reservoir

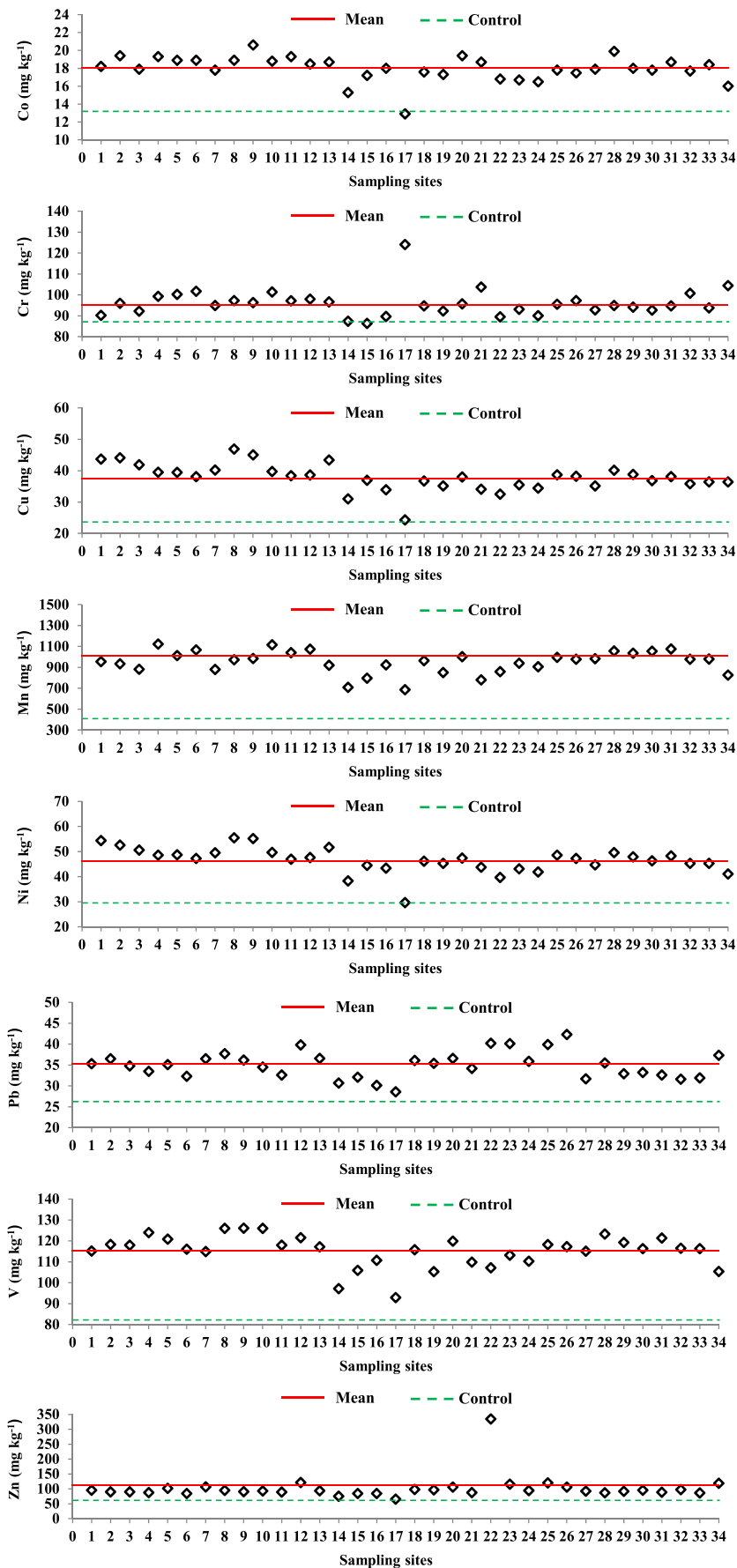


Table 2 Summary of the single pollution index (PI) and the integrated pollution index (IPI) in the sediments

	PI-Co	PI-Cr	PI-Cu	PI-Mn	PI-Ni	PI-Pb	PI-V	PI-Zn	IPI
Min	0.95	0.99	1.06	1.74	1.01	1.09	1.15	1.06	1.19
Max	1.51	1.42	2.05	2.85	1.89	1.61	1.56	5.45	1.94
Mean	1.32	1.10	1.65	2.41	1.59	1.33	1.43	1.66	1.56
Median	1.32	1.09	1.66	2.48	1.61	1.34	1.44	1.52	1.57

Radiation levels and radiological hazard in sediments

Activity concentration of natural radionuclide and associated radiation hazard indices in the sediments were shown in our previous study (Lu et al. 2016). The relatively high concentrations of ^{232}Th , ^{226}Ra , and ^{40}K are mostly observed in the downstream of the middle of the reservoir (e.g., S2–S6) with a few higher values scattered along the bank (e.g., S21, S26, and S33). This phenomenon might suggest that the variation in activity concentrations of ^{232}Th , ^{226}Ra , and ^{40}K might be due to agriculture activities surrounding these sites (Gonzalez-Fernandez et al. 2010; Saç et al. 2012). The previous studies have reported that the higher concentrations of ^{226}Ra and ^{40}K may be associated with the extensive exploitation of phosphate and potassium fertilizers in soils surrounding agricultural areas (Akhtar et al. 2005; Bikit et al. 2005; Krishnamoorthy et al. 2014). Although the specific levels of radionuclide activity in sediments are mostly related to the types of rocks or soils from which the sediments originate, the transport and mobility of natural radionuclide in the aqueous system is another important factor influencing the content of radionuclide in sediments at a given place (Tzortzis et al. 2004; Krmar et al. 2009; Strakhovenko et al. 2010). Thus, physicochemical conditions and water input from river runoff should be taken into consideration (Zorer et al. 2008; Suresh et al. 2011).

Relationships between magnetic susceptibility and trace metals and natural radionuclides

Correlation analysis

The Pearson correlation coefficients (R) between pairs of the variables are listed in Table 3. Significant correlations are observed between magnetic susceptibility indexes (χ_{LF} , χ_{HF} , and $\chi_{\text{FD}}\%$) and the levels of most of detected metals and natural radionuclides. χ_{LF} is used to discuss the correlation between magnetic susceptibility and trace metals and radionuclides owing to significant positive correlations among the pairs of χ_{LF} , χ_{HF} , and $\chi_{\text{FD}}\%$.

As showed in Table 3, significant positive correlations are observed between χ_{LF} and Co (0.622, $p < 0.01$), Cu (0.442, $p < 0.01$), Mn (0.483, $p < 0.01$), Ni (0.485, $p < 0.01$), and V (0.593, $p < 0.01$). The previous studies reported that the significant correlations between the magnetic susceptibility and

trace metals can indicate common sources (industrial pollution, parent rocks or pedogenic processes, vehicle-derived emissions, etc.), mutual dependence, and identical behavior of the magnetic particles and trace metals during the transport (Chaparro et al. 2010; Chlupáčová et al. 2010; Suresh et al. 2011; Castañeda Miranda et al. 2016). Trace metal pollution is in many cases accompanied by emission of ferrimagnetic particles and Co, Ni, Cu, and Mn are more likely to be concentrated in the magnetic fraction (Kukier et al. 2003; Rachwał et al. 2017), which well explains the strong relationship between χ_{LF} and these elements. On the contrary, no correlations are observed between χ_{LF} and Cr, Pb, and Zn in this study (Table 3). The absence of correlation between χ_{LF} and the three elements might suggest variations in the sources and specific circumstances (Lu et al. 2007; Zorer et al. 2008; Canbay et al. 2010). This result also indicates that magnetic susceptibility has not been affected significantly by anthropogenic activities which enhanced Pb and Zn concentrations in the sediment (Karimi et al. 2017). In addition, it should be noticed that the IPIs show significant correlations with χ_{LF} ($R > 0.500$, $p < 0.01$), which confirms that variations of ferrimagnetic mineral concentrations are consistent with the degree of trace metal pollution (Jordanova et al. 2004; Wang et al. 2015).

The obvious difference was found in correlation analysis results of magnetic susceptibility and natural radionuclides (Table 3). The positive correlation are observed between χ_{LF} and ^{232}Th (0.478, $p < 0.01$) and ^{40}K (0.378, $p < 0.05$), which are consistent with previous studies (Krishnamoorthy et al. 2014; Ramasamy et al. 2014) and might be the result of the absorption of magnetic minerals by lower grain sized fractions. In addition, significant positive correlations are observed between radioactive elements (^{232}Th and ^{40}K) and the five metals (Co, Cu, Mn, Ni, and V), which might be due to the common sources (e.g., the local agricultural activities and coal-fired power plant) and similar geochemical behavior of the radionuclides and these metals (Lu et al. 2014a; Özmen et al. 2004).

Overall, the correlation analysis can suggest a potential for indicating anthropogenic pollution by the intensity of magnetic susceptibility, which are easy, prompt, and cost-effective to perform (Chaparro et al. 2017). To determine the quantitative relationship between magnetic susceptibility indexes and the pollution levels of trace metals and radionuclides, linear

Table 3 Pearson correlation coefficients between magnetic susceptibility and the levels of heavy metals and natural radionuclides ($n = 34$). Italic values in the table represent the significant positive correlation between the variables

	χ_{LF}	χ_{HF}	χ_{FD}	Co	Cr	Cu	Mn	Ni	Pb	V	Zn	IPI	^{232}Th	^{226}Ra	^{40}K
χ_{LF}	1.000														
χ_{HF}	<i>0.998**</i>	1.000													
χ_{FD}	<i>0.754**</i>	<i>0.724**</i>	1.000												
Co	<i>0.622**</i>	<i>0.618**</i>	<i>0.502**</i>	1.000											
Cr	-0.308	-0.308	-0.302	-0.090	1.000										
Cu	<i>0.442**</i>	<i>0.428*</i>	<i>0.383*</i>	<i>0.815**</i>	-0.131	1.000									
Mn	<i>0.483**</i>	<i>0.476**</i>	<i>0.430**</i>	<i>0.760**</i>	0.079	<i>0.682**</i>	1.000								
Ni	<i>0.485**</i>	<i>0.470**</i>	<i>0.464**</i>	<i>0.868**</i>	-0.136	<i>0.984**</i>	<i>0.723**</i>	1.000							
Pb	0.281	0.264	0.150	<i>0.364*</i>	-0.041	<i>0.522**</i>	<i>0.416*</i>	<i>0.495**</i>	1.000						
V	<i>0.593**</i>	<i>0.583**</i>	<i>0.485**</i>	<i>0.891**</i>	0.035	<i>0.858**</i>	<i>0.919**</i>	<i>0.891**</i>	<i>0.505**</i>	1.000					
Zn	0.022	0.025	-0.083	0.005	-0.153	-0.039	0.058	-0.041	<i>0.503**</i>	0.025	1.000				
IPI	<i>0.576**</i>	<i>0.570**</i>	<i>0.403*</i>	<i>0.620**</i>	-0.261	<i>0.580**</i>	<i>0.591**</i>	<i>0.597**</i>	<i>0.670**</i>	<i>0.672**</i>	<i>0.647**</i>	1.000			
^{232}Th	<i>0.478**</i>	<i>0.472**</i>	<i>0.482**</i>	<i>0.655**</i>	-0.017	<i>0.594**</i>	<i>0.705**</i>	<i>0.633**</i>	<i>0.339*</i>	<i>0.728**</i>	-0.038	0.228	1.000		
^{226}Ra	-0.219	-0.219	-0.156	0.087	0.148	0.081	0.310	0.055	0.239	0.133	0.202	0.161	0.084	1.000	
^{40}K	<i>0.378*</i>	<i>0.384*</i>	0.304	<i>0.758**</i>	0.101	<i>0.610**</i>	<i>0.828**</i>	<i>0.663**</i>	<i>0.314</i>	<i>0.825**</i>	-0.063	0.322	<i>0.772**</i>	0.212	1.000

IPI integrated pollution index

*Correlation is significant at the 0.05 level (two-tailed)

**Correlation is significant at the 0.01 level (two-tailed)

regression analysis was performed between magnetic susceptibility parameters and the IPI and AED. Figure 4 illustrates that a good linear relationship between the magnetic properties and the IPI and AED, which reflects the indication role of magnetic susceptibility in identifying the pollution of trace metals and natural radionuclides in the sediments (Chaparro et al. 2011; Yang et al. 2007; Jaffar et al. 2017). Furthermore, the linear regression equations between MS and IPI, AED were established to semi-quantitatively assess trace metal pollution and radiological hazard.

Multivariate statistical analysis

In our previous study (Zhu et al. 2016), three clusters of the trace metals have been identified by using the methods of cluster analysis (CA) and principal components analysis (PCA). Copper, Ni, Mn, V, and Co are identified a cluster and well correlated with each other. These five elements generally present high correlation with magnetic susceptibility. According to previous studies and the discussion above, this cluster is identified to be a mixed source, including natural sources, industrial sources, and local consumption residues (Wang et al. 2014; Zhu et al. 2016; Pan et al. 2017a). However, the elements of Pb, Zn, and Cr show weak or no correlation with the magnetic susceptibility. The significant positive correlation between Pb and Zn (0.503, $p < 0.01$) indicates similar sources, which might be mainly related to traffic sources (Van der Gon and Appelman 2009; Pan et al. 2017b), while Cr mainly originates from natural sources (Banerjee 2003; Zhu et al. 2016). Therefore, the trace metals originated

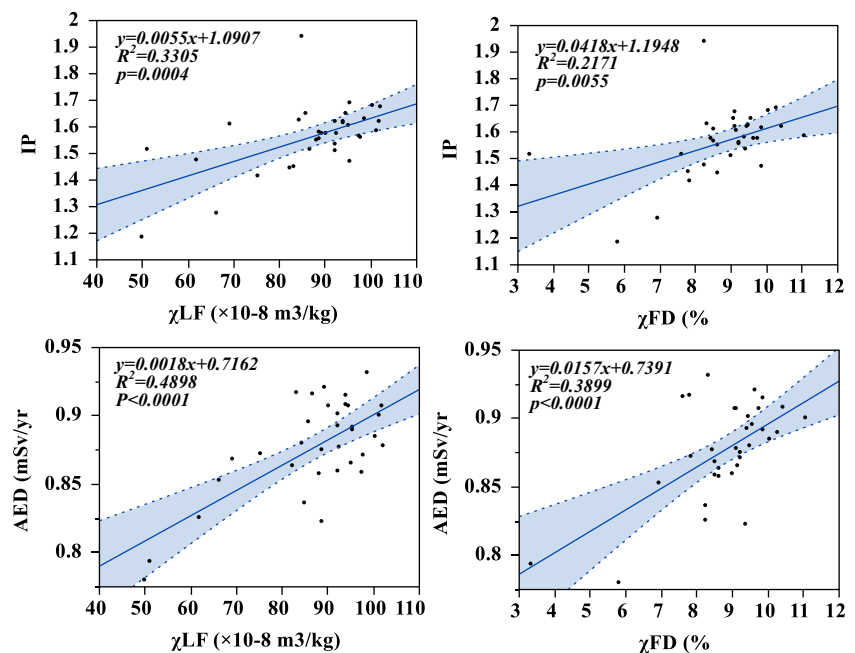
from industrial sources are more likely to present high correlation with magnetic susceptibility.

To explore the influence of different sources to contamination levels of sampling sites, K-means cluster analysis is carried out based on the variables of magnetic susceptibility, trace metals, and natural radionuclides. Three groups are well defined as illustrated by Fig. 5. Most of the sample sites are included in group 1 (18 of 34) and group 3 (14 of 34), while S14 and S17 compose the group 2. The cluster results of the sample sites are clearly shown in Fig. 6. Group 1 mainly consists of the sampling sites near the bank of the reservoir, which usually present higher values of certain variables determined in this study. This might be due to the point sources and untreated wastewater discharge along the bank (Chaparro et al. 2008; Yang et al. 2017). Group 2 only includes S14 and S17, which present lower values of the variables. Group 3 consists most of the sampling sites in the middle of the reservoir and the relatively low inter-site variability throughout the sites suggests that the sediment are mostly locally derived, well-mixed, and consistent in provenance (Zhang et al. 2011). The enhanced concentrations of the target pollutants in this group are taken to be a combination of industries and agricultures from upstream (Jiang et al. 2017).

Influence of different sources on magnetic susceptibility as an indicator

Previous studies have indicated that magnetic parameters offer potential as a proxy for trace metal levels in the sediments. However, the association of them might be complex, which is depended on the number and variety of emission sources, their

Fig. 4 Linear correlation analysis between magnetic susceptibility parameters and the integrated pollution index (IPI) and the annual effective dose rate (AED) in sediments ($n = 34$). Shaded area shows the confidence limits for the expected value, while outside dotted lines display the confidence limits for an individual predicted value



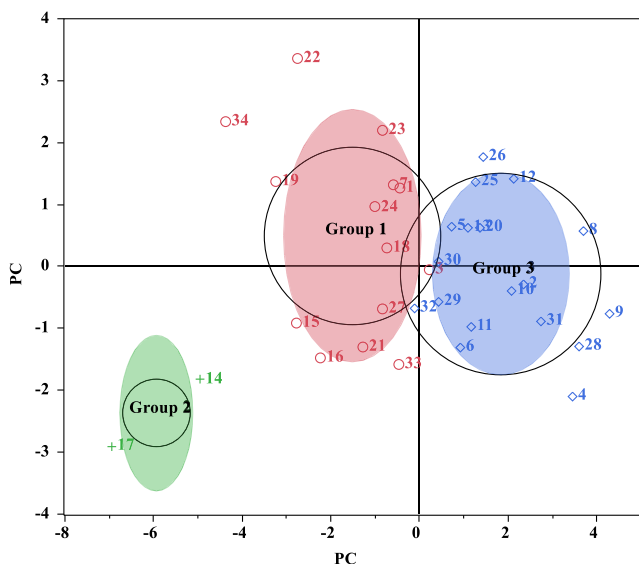


Fig. 5 K-means cluster analysis of all sampling sites ($n = 34$) based on the variables of magnetic susceptibility, heavy metals, and natural radionuclides. The sites were classified into three groups, showing group 1 (\circ), group 2 (+), and group 3 (\diamond)

distance from the study area (Strzyszczyk and Magiera 1998; Suresh et al. 2011). Except for human activities, natural processes including weathering of parent material or biologically mediated pedogenic processes can also influence the magnetic susceptibility of soils (Szuszkiewicz et al. 2016).

To evaluate the influence of different sources on the relationship between magnetic susceptibility and levels of trace metals and radionuclides, we analyzed the correlations of the three magnetic susceptibility parameters and levels of metals

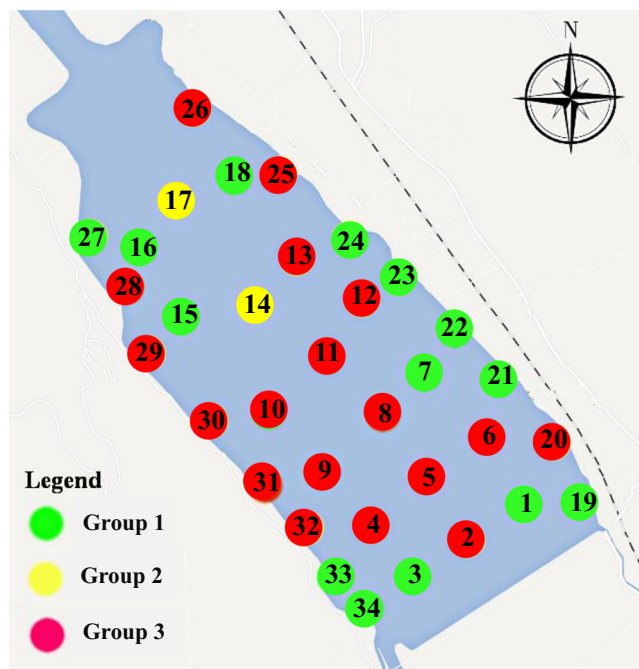


Fig. 6 Groups of all sampling sites ($n = 34$) according to the K-means cluster analysis

and radionuclides of the sediments in the middle, southwest, and northeast of the reservoir, respectively (Table 4). A significant improvement in correlation coefficients between magnetic susceptibility and the levels of trace metals and radionuclides are observed in the middle of the reservoir. In particular, the correlation coefficients between χ_{LF} and IPI is 0.856 ($p < 0.01$) for samples from the middle of the reservoir, which is obviously higher than the value for samples from the overall reservoir (0.576, $p < 0.01$, Table 3). Such difference can confirm that magnetic proxies provide a rapid means for detecting trace metal contamination caused by multi-anthropogenic pollution sources in a large-scale area and the sensitivity was controlled by pollution sources (Wang et al. 2015). Thus, magnetic susceptibility could be used as a first screening of the industrial pollution in the investigated areas.

Magnetic detection of trace metal contamination in the sediment

Based on the correlation relationship between magnetic susceptibility and trace metals, a three-step procedure is proposed for using magnetic susceptibility in identification of areas and extents polluted by trace metals in this study.

The first step is a broad investigation of the distribution of magnetic susceptibility within a large area. Monitoring grids could be uniformly distributed in the study area, and 4 to 8 sampling sites per square kilometer are appropriate for long-term monitoring program according to our practice. Meanwhile, since the measurement of magnetic susceptibility is time- and cost-effective, more sampling sites could be included as required by special cases. High values of magnetic susceptibility would provide useful hints for preliminary screening of areas polluted by trace metals. Furthermore, the outliers and anomalies would provide information of potential sources. It has been suggested that this method might be more promising for areas where single source dominate the pollution pattern. Therefore, it is recommended that source identification should be fully explored for particular study areas (Wang et al. 2015). This step offers facilities in optimizing monitoring campaigns in a large area. As second step, the field survey of magnetic susceptibility in situ is conducted in areas highlighted with high values of magnetic susceptibility. A field magnetic susceptibility meter with sensor coils or probes could be used in this step and the calibration of in situ magnetic susceptibility measurements with laboratory data should be conducted (Kapička et al. 1997; Gattacceca et al. 2004; Porsch et al. 2010). The enhancement in magnetic susceptibility could indicate an increase of the concentration of heavy metals in contaminated sediments (Yoshida et al. 2003; Boyko et al. 2004). Therefore, a detailed picture of the spatial distribution of trace metals can be obtained based on the result of magnetic susceptibility determination. These areas are supposed to be with trace metal pollution. Chemical analysis is

Table 4 Pearson correlation coefficients between magnetic susceptibility and the levels of heavy metals and natural radionuclides in different locations of the Wangjiaya reservoir. Italic values in the table represent the significant positive correlation between the variables

	Middle (S1–S18)			Northeast (S19–S26)			Southwest (S27–S34)		
	X _{LF}	X _{HF}	X _{FD}	X _{LF}	X _{HF}	X _{FD}	X _{LF}	X _{HF}	X _{FD}
Co	<i>0.882**</i>	<i>0.877**</i>	<i>0.841**</i>	0.046	0.053	−0.222	<i>0.883**</i>	<i>0.881**</i>	<i>0.809*</i>
Cr	−0.285	−0.292	−0.279	0.042	0.064	−0.157	−0.754*	−0.761*	−0.684
Cu	<i>0.775**</i>	<i>0.766**</i>	<i>0.775**</i>	0.376	0.330	0.475	0.444	0.455	0.277
Mn	<i>0.713**</i>	<i>0.703**</i>	<i>0.747**</i>	0.612	0.560	0.667	<i>0.961**</i>	<i>0.957**</i>	<i>0.904**</i>
Ni	<i>0.775**</i>	<i>0.766**</i>	<i>0.792**</i>	0.111	0.071	0.266	<i>0.860**</i>	<i>0.866**</i>	<i>0.747*</i>
Pb	<i>0.698**</i>	<i>0.683**</i>	<i>0.745**</i>	0.559	0.528	0.416	−0.538	−0.535	−0.641
V	<i>0.877**</i>	<i>0.867**</i>	<i>0.850**</i>	0.690	0.660	0.552	<i>0.930**</i>	<i>0.932**</i>	<i>0.861**</i>
Zn	<i>0.580*</i>	<i>0.561*</i>	<i>0.749**</i>	−0.037	−0.016	−0.389	−0.889**	−0.894**	−0.851**
IPI	<i>0.856**</i>	<i>0.842**</i>	<i>0.896**</i>	0.174	0.176	−0.195	0.599	0.598	0.471
²³² Th	<i>0.641**</i>	<i>0.637**</i>	<i>0.607**</i>	<i>0.781*</i>	<i>0.780*</i>	0.579	<i>0.881**</i>	<i>0.885**</i>	<i>0.849**</i>
²²⁶ Ra	0.150	0.132	0.399	−0.308	−0.298	0.022	−0.885**	−0.897**	−0.829*
⁴⁰ K	<i>0.642**</i>	<i>0.649**</i>	0.461	0.094	0.087	0.174	<i>0.906**</i>	<i>0.913**</i>	<i>0.854**</i>

suggested in this step to identify the results and get accurate concentrations of trace metals. In the third step, a field survey based on chemical analysis in well-defined areas is performed and correlation between magnetic susceptibility and trace metals are to be analyzed. The correlation between magnetic susceptibility and environmental pollution should be further identified to establish a semi-quantitative method for long-term monitoring (Chaparro et al. 2015).

In conclusion, we propose a monitoring procedure to use magnetic susceptibility in long-term pollution monitoring in sediment in lakes and rivers. The magnetic susceptibility could be used in discriminating potentially contaminated areas and chemical analysis subsequently could give detailed information of trace metal concentrations. Furthermore, interrelationship obtained by multivariate analysis will provide approximate estimations of trace metal concentrations by determination of magnetic susceptibility. This methodology gives a relatively fast and cost-effective tool for monitoring the pollution level by trace metals of the sediment. It is especially useful in tracing toxic metal pollution and repeat measurements within shorter intervals.

Conclusions

This study revealed site-specific correlations between magnetic susceptibility and the levels of trace metal and natural radionuclides in the sediments. Significant enrichment of magnetic susceptibility is presented in those areas where concentrations of trace metals and natural radionuclides are higher. Because of the significant correlations between the variables, X_{LF} is a good indicator for assessing the contamination levels of the sediment. Magnetic susceptibility is helpful in the rapid

monitoring and discriminating different anthropogenic pollution. This provides a rapid and cost-effective methodology in assessment of trace metal pollution in sediment, especially those from industrial sources. A three-step procedure for the use of magnetic susceptibility in pollution monitoring is proposed. The environmental magnetism method is a helpful supplement to traditional geochemical methods in estimating the pollution levels and tracing the major sources of hazardous components in sediments. However, the nature of the relationship should be explored fully for particular environment and individual field settings before using magnetic susceptibility as a proxy for anthropogenic pollution.

Acknowledgements We thank Cancan Chen and Xiaoxue Li for their help with the sampling and the experiments.

Funding information The research was supported by the National Natural Science Foundation of China through Grant 41271510 and the Fundamental Research Funds for the Central University through Grants GK201601009 and 2017TS027.

References

Acosta JA, Gabarrón M, Faz A, Martínez-Martínez S, Zornoza R, Arocena JM (2015) Influence of population density on the concentration and speciation of metals in the soil and street dust from urban areas. *Chemosphere* 134:328–337

Akhtar N, Tufail M, Ashraf M, Iqbal MM (2005) Measurement of environmental radioactivity for estimation of radiation exposure from saline soil of Lahore, Pakistan. *Radiat Meas* 39:11–14

Alencar AS, Freitas AC (2005) Reference levels of natural radioactivity for the beach sands in a Brazilian southeastern coastal region. *Radiat Meas* 40:76–83

Baeza A, Guillén J, Ontalba Salamanca MÁ, Rodríguez A, Ager FJ (2009) Radiological and multi-element analysis of sediments from

- the Proserpina reservoir (Spain) dating from Roman times. *J Environ Radioact* 100:866–874
- Banerjee AD (2003) Heavy metal levels and solid phase speciation in street dusts of Delhi, India. *Environ Pollut* 123:95–105
- Basavaiah N, Blaha U, Das PK, Deenadayalan K, Sadashiv MB, Schulz H (2012) Evaluation of environmental magnetic pollution screening in soils of basaltic origin, results from Nashik Thermal Power Station, Maharashtra, India. *Environ Sci Pollut Res* 19:3028–3038
- Bastami KD, Bagheri H, Kheirabadi V, Zaferani GG, Teymori MB, Hamzehpoor A, Soltani F, Haghparast S, Harami SRM, Ghorghani NF, Ganji S (2014) Distribution and ecological risk assessment of heavy metals in surface sediments along southeast coast of the Caspian Sea. *Mar Pollut Bull* 81:262–267
- Bikit I, Slivka J, Conkic L, Krmar M, Veskovic M, Zikic-Todorovic N VE, Curcic S, Mrdja D (2005) Radioactivity of the soil in Vojvodina (northern province of Serbia and Montenegro). *J Environ Radioact* 78:11–19
- Bitjukova L, Scholger R, Birke M (1999) Magnetic susceptibility as indicator of environmental pollution of soils in Tallinn. *Phys Chem Earth A Solid Earth Geod* 24:829–835
- Boyko T, Scholger R, Stanjek H, Team M (2004) Topsoil magnetic susceptibility mapping as a tool for pollution monitoring: repeatability of in situ measurements. *J Appl Geophys* 55:249–259
- Canbay M, Aydin A, Kurtulus C (2010) Magnetic susceptibility and heavy-metal contamination in topsoils along the Izmit Gulf coastal area and IZAYTAS (Turkey). *J Appl Geophys* 70:46–57
- Castañeda Miranda AG, Chaparro MAE, Chaparro MAE, Böhnell HN (2016) Magnetic properties of *Tillandsiarecurvata* L. and its use for biomonitoring a Mexican metropolitan area. *Ecol Indic* 60:125–136
- Chaparro MAE, Sinito AM, Ramasamy V, Marinelli C, Chaparro MAE, Mullainathan S, Murugesan S (2008) Magnetic measurements and pollutants of sediments from Cauvery and Palaru River, India. *Environ Geol* 56:425–437
- Chaparro MAE, Marié DC, Gogorza CSG, Navas A, Sinito AM (2010) Magnetic studies and scanning electron microscopy – X-ray energy dispersive spectroscopy analyses of road sediments, soils and vehicle-derived emissions. *Stud Geophys Geod* 54:633–650
- Chaparro MAE, Chaparro MAE, Rajkumar P, Ramasamy V, Sinito AM (2011) Magnetic parameters, trace elements, and multivariate statistical studies of river sediments from southeastern India, a case study from the Vellar River. *Environ Earth Sci* 63:297–310
- Chaparro MAE, Chaparro MAE, Sinito AM (2012) An interval fuzzy model for magnetic monitoring: estimation of a pollution index. *Environ Earth Sci* 66:1477–1485
- Chaparro AEMAE, Chaparro MAE, Castañeda Miranda AG, Böhnell HN, Sinito AM (2015) An interval fuzzy model for magnetic biomonitoring using the specie *Tillandsiarecurvata* L. *Ecol Indic* 54:238–245
- Chaparro MAE, Suresh G, Chaparro MAE, Ramasamy V, Sundarajan M (2017) Magnetic assessment and pollution status of beach sediments from Kerala coast (southwestern India). *Mar Pollut Bull* 117:171–177
- Chen TB, Zheng YM, Lei M, Huang ZC, Wu HT, Chen H, Fan KK, Yu K, Wu X, Tian QZ (2005) Assessment of heavy metal pollution in surface soils of urban parks in Beijing, China. *Chemosphere* 60:542–551
- Chen X, Lu X, Yang G (2013) Correlativity study of the distribution of soil magnetic susceptibility and the heavy metal contents in Xi'an city. *Environ Sci* 34:1086–1093 (in Chinese)
- Chlupáčová M, Hanák J, Müller P (2010) Magnetic susceptibility of cambisol profiles in the vicinity of the Vir dam, Czech Republic. *Stud Geophys Geod* 54:153–184
- D'Emilio M, Macchiato M, Ragosta M, Simoniello T (2012) A method for the integration of satellite vegetation activities observations and magnetic susceptibility measurements for monitoring heavy metals in soil. *J Hazard Mater* 241–242:118–126
- Doichinova V, Zhiyanski M, Hursthouse A, Bech J (2014) Study on the mobility and bioavailability of PTEs in soils from Urban Forest Parks in Sofia, Bulgaria. *J Geochem Explor* 147:222–228
- Dong C, Zhang W, Ma H, Feng H, Lu H, Dong Y, Yu L (2014) A magnetic record of heavy metal pollution in the Yangtze River sub-aqueous delta. *Sci Total Environ* 476–477:368–377
- Dong S, Gonzalez RO, Harrison RM, Green D, North R, Fowler G, Weiss D (2017) Isotopic signatures suggest important contributions from recycled gasoline, road dust and non-exhaust traffic sources for copper, zinc and lead in PM10 in London, United Kingdom. *Atmos Environ* 165:88–98
- El-Taher A, Madkour HA (2011) Distribution and environmental impacts of metals and natural radionuclides in marine sediments in-front of different wadies mouth along the Egyptian Red Sea Coast. *Appl Radiat Isot* 69:550–558
- El-Taher A, Makhluf S, Nossair A, Abdel Halim AS (2010) Assessment of natural radioactivity levels and radiation hazards due to cement industry. *Appl Radiat Isot* 68:169–174
- Erenturk S, Yusan S, Turkozu DA, Camtakan Z, Olgen MK, Aslani MAA, Aytas S, Isik MA (2014) Spatial distribution and risk assessment of radioactivity and heavy metal levels of sediment, surface water and fish samples from Lake Van, Turkey. *J Radioanal Nucl Chem* 300:919–931
- Faweya EB, Oniya EO, Ojo FO (2013) Assessment of radiological parameters and heavy-metal contents of sediment samples from lower Niger River, Nigeria. *Arab J Sci Eng* 38:1903–1908
- Gallego JL, Ordóñez A, Loredó J (2002) Investigation of trace element sources from an industrialized area (Avilés, northern Spain) using multivariate statistical methods. *Environ Int* 27:589–596
- Gattacceca J, Eisenlohr P, Rochette P (2004) Calibration of in situ magnetic susceptibility measurements. *Geophys J Int* 158:42–49
- Gonzalez-Fernandez D, Garrido-Perez MC, Nebot-Sanz E, Sales-Marquez D (2010) Fecal pollution in coastal marine sediments from a semi-enclosed deep embayment subjected to anthropogenic activities: an issue to be considered in environmental quality management frameworks development. *Ecosyst Health* 7:473–484
- Gonzalez-Fernandez D, Garrido-Perez MC, Casas-Ruiz M, Barbero L, Nebot-Sanz E (2012) Radiological risk assessment of naturally occurring radioactive materials in marine sediments and its application in industrialized coastal areas: Bay of Algeciras, Spain. *Environ Earth Sci* 66:1175–1181
- Hay KL, Dearing JA, Baban SMJ, Loveland P (1997) A preliminary attempt to identify atmospherically-derived pollution particles in English topsoils from magnetic susceptibility measurements. *Phys Chem Earth* 22:207–210
- Jaffar STA, Chen LZ, Younas H, Ahmad N (2017) Heavy metals pollution assessment in correlation with magnetic susceptibility in topsoils of Shanghai. *Environ Earth Sci* 76:277–294
- Jiang Y, Chao S, Liu J, Yang Y, Chen Y, Zhang A, Cao H (2017) Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China. *Chemosphere* 168:1658–1668
- Jordanova D, Hoffmann V, Fehr KT (2004) Mineral magnetic characterization of anthropogenic magnetic phases in the Danube river sediments (Bulgarian part). *Earth Planet Sci Lett* 221:71–89
- Jordanova D, Goddu SR, Kotsev T, Jordanova N (2013) Industrial contamination of alluvial soils near Fe–Pb mining site revealed by magnetic and geochemical studies. *Geoderma* 192:237–248
- Kapička A, Petrovský E, Jordanova N (1997) Comparison of in-situ field measurements of soil magnetic susceptibility with laboratory data. *Stud Geophys Geod* 41:391–395
- Karimi A, Haghnia GH, Ayoubi S, Safari T (2017) Impacts of geology and land use on magnetic susceptibility and selected heavy metals in

- surface soils of Mashhad plain, northeastern Iran. *J Appl Geophys* 138:127–134
- Krishnamoorthy N, Mullainathan S, Mehra R, Chaparro MA, Chaparro MA (2014) Radiation impact assessment of naturally occurring radionuclides and magnetic mineral studies of Bharathapuzha river sediments, South India. *Environ Earth Sci* 71:3593–3604
- Krmar M, Slivka J, Varga E, Bikit I, Vesković M (2009) Correlations of natural radionuclides in sediment from Danube. *J Geochem Explor* 100:20–24
- Kukier U, Ishak CF, Sumner ME, Miller WP (2003) Composition and element solubility of magnetic and non-magnetic fly ash fractions. *Environ Pollut* 123:255–266
- Liu W, Lu X, Chen C, Zhou X (2013) The indicating significance of magnetic susceptibility of soil around coal-fired power plant for heavy metal pollution. *Chin J Soil Sci* 44:993–997 (in Chinese)
- Lu SG, Bai SQ, Xue QF (2007) Magnetic properties as indicators of heavy metals pollution in urban topsoils: a case study from the city of Luoyang, China. *Geophys J Int* 171:568–580
- Lu X, Wang L, Lei K, Huang J, Zhai Y (2009) Contamination assessment of copper, lead, zinc, manganese and nickel in street dust of Baoji, NW China. *J Hazard Mater* 161:1058–1062
- Lu X, Wang L, Li LY, Lei K, Huang L, Kang D (2010) Multivariate statistical analysis of heavy metals in street dust of Baoji, NW China. *J Hazard Mater* 173:744–749
- Lu X, Yang G, Ren C (2012) Natural radioactivity and radiological hazards of building materials in Xianyang, China. *Radiat Phys Chem* 81:780–784
- Lu X, Chao S, Yang F (2014a) Determination of natural radioactivity and associated radiation hazard in building materials used in Weinan, China. *Radiat Phys Chem* 99:62–67
- Lu X, Wu X, Wang Y, Che H, Gao P, Fu Y (2014b) Risk assessment of toxic metals in street dust from a medium-sized industrial city of China. *Ecotoxicol Environ Saf* 196:154–163
- Lu X, Zhang X, Li YY, Chen H (2014c) Assessment of metals pollution and health risk in dust from nursery schools in Xi'an, China. *Environ Res* 128:27–34
- Lu X, Pan H, Ren C, Yang L (2016) Natural radioactivity in reservoir sediment near an industrial park of northwest China. *J Radiol Prot* 36:N26–N33
- Magiera T, Jabłońska M, Strzyszczyk Z, Rachwał M (2011) Morphological and mineralogical forms of technogenic magnetic particles in industrial dusts. *Atmos Environ* 45:4281–4290
- Ng SL, Chan LS, Lam KC, Chan WK (2003) Heavy metal contents and magnetic properties of playground dust in Hong Kong. *Environ Monit Assess* 89:221–232
- Özmen H, Külahcı F, Çukurovalı A, Dođru M (2004) Concentrations of heavy metal and radioactivity in surface water and sediment of Hazar Lake (Elazığ, Turkey). *Chemosphere* 55:401–408
- Pan H, Lu X, Lei K (2017a) A comprehensive analysis of heavy metals in urban road dust of Xi'an, China: contamination, source apportionment and spatial distribution. *Sci Total Environ* 609:1361–1369
- Pan H, Lu X, Lei K (2017b) Lead in roadway dusts from different functional areas in a typical valley city, NW China: contamination and exposure risk. *Environ Sci Pollut Res* 25:523–532
- Peng X, Shi G, Liu G, Xu J, Tian Y, Zhang Y, Feng Y, Russell AG (2017) Source apportionment and heavy metal health risk (HMHR) quantification from sources in a southern city in China, using an ME2-HMHR model. *Environ Pollut* 221:335–342
- Porsch K, Dippon U, Rijal ML, Appel E, Kappler A (2010) In-situ magnetic susceptibility measurements as a tool to follow geomicrobiological transformation of Fe minerals. *Environ Sci Technol* 44:3846–3852
- Prajith A, Rao VP, Kessarkar PM (2015) Controls on the distribution and fractionation of yttrium and rare earth elements in core sediments from the Mandovi estuary, western India. *Cont Shelf Res* 92:59–71
- Rachwał M, Magiera T, Wawer M (2015) Coke industry and steel metallurgy as the source of soil contamination by technogenic magnetic particles, heavy metals and polycyclic aromatic hydrocarbons. *Chemosphere* 138:863–873
- Rachwał M, Kardel K, Magiera T, Bens O (2017) Application of magnetic susceptibility in assessment of heavy metal contamination of Saxonian soil (Germany) caused by industrial dust deposition. *Geoderma* 295:10–21
- Ramasamy V, Paramasivam K, Suresh G, Jose MT (2014) Role of sediment characteristics on natural radiation level of the Vaigai river sediment, Tamilnadu, India. *J Environ Radioact* 127:64–74
- Saç MM, Ortabuk F, Kumru MN, İçhedef M, Sert Ş (2012) Determination of radioactivity and heavy metals of Bakırçay river in Western Turkey. *Appl Radiat Isot* 70:2494–2499
- Shi D, Lu X, Zhu Y, Yang L, Ren C (2018) Contamination and ecological risk of heavy metal in sediments of a reservoir near an industrial park of northwest China. *Fresenius Environ Bull* 27:1552–1562
- Shilton VF, Booth CA, Smith JP, Giess P, Mitchell DJ, Williams CD (2005) Magnetic properties of urban street dust and their relationship with organic matter content in the West Midlands, UK. *Atmos Environ* 39:3651–3659
- Strakhovenko VD, Shcherbov BL, Malikova IN, Vosel YS (2010) The regularities of distribution of radionuclides and rare-earth elements in bottom sediments of Siberian lakes. *Russ Geol Geophys* 51: 1167–1178
- Strzyszczyk Z, Magiera T (1998) Magnetic susceptibility and heavy metals contamination in soils of southern Poland. *Phys Chem Earth* 23: 1127–1131
- Suresh G, Ramasamy V, Meenakshisundaram V, Venkatachalapathy R, Ponnusamy V (2011) Influence of mineralogical and heavy metal composition on natural radionuclide concentrations in the river sediments. *Appl Radiat Isot* 69:1466–1474
- Suresh G, Sutharsan P, Ramasamy V, Venkatachalapathy R (2012) Assessment of spatial distribution and potential ecological risk of the heavy metals in relation to granulometric contents of Veeranam lake sediments, India. *Ecotoxicol Environ Saf* 84:117–124
- Szarłowicz K, Reczynski W, Misiak R, Kubica B (2013) Radionuclides and heavy metal concentrations as complementary tools for studying the impact of industrialization on the environment. *J Radioanal Nucl Chem* 298:1323–1333
- Szuskiewicz M, Łukasik A, Magiera T, Mendakiewicz M (2016) Combination of geo-pedo- and technogenic magnetic and geochemical signals in soil profiles—diversification and its interpretation: a new approach. *Environ Pollut* 214:464–477
- Trujillo-González JM, Torres-Mora MA, Keesstra S, Brevik EC, Jiménez-Ballesta R (2016) Heavy metal accumulation related to population density in road dust samples taken from urban sites under different land uses. *Sci Total Environ* 553:636–642
- Tzortzis M, Svoukis E, Tsertos H (2004) A comprehensive study of natural gamma radioactivity levels and associated dose rates from surface soils in Cyprus. *Radiat Prot Dosim* 109:217–224
- Van der Gon HD, Appelmann W (2009) Lead emissions from road transport in Europe: a revision of current estimates using various estimation methodologies. *Sci Total Environ* 407:5367–5372
- Wang B, Xia D, Yu Y, Jia J, Xu SJ (2013) Magnetic properties of river sediments and their relationship with heavy metals and organic matter in the urban area in Lanzhou, China. *Environ Earth Sci* 70:605–614
- Wang L, Lu X, Ren C, Li X, Chen C (2014) Contamination assessment and health risk of heavy metals in dust from Changqing industrial park of Baoji, NW China. *Environ Earth Sci* 71:2095–2104
- Wang B, Xia D, Yu Y, Jia J, Nie Y, Wang X (2015) Detecting the sensitivity of magnetic response on different pollution sources—a case study from typical mining cities in northwestern China. *Environ Pollut* 207:288–298

- Wang G, Liu Y, Chen J, Ren F, Chen Y, Ye F, Zhang W (2017) Magnetic evidence for heavy metal pollution of topsoil in Shanghai, China. *Front Earth Sci* 12:125–133
- Wilding LP (1985) Spatial variability: its documentation, accommodation and implication to soil surveys. In: Nielsen DR, Bouma J (eds) *Soil spatial variability*. PUDOC Publishers, Wageningen, pp 166–194
- Yang T, Liu Q, Chan L, Liu Z (2007) Magnetic signature of heavy metals pollution of sediments: case study from the East Lake in Wuhan, China. *Environ Geol* 52:1639–1650
- Yang G, Lu X, Zhao C, Li N (2013) Natural radioactivity in building materials used in Changzhi, China. *Radiat Prot Dosim* 155:512–516
- Yang P, Ge J, Yang M (2017) Identification of heavy metal pollution derived from traffic in roadside soil using magnetic susceptibility. *Bull Environ Contam Toxicol* 98:837–844
- Yii MW, Zaharudin A, Abdul-Kadir I (2009) Distribution of naturally occurring radionuclides activity concentration in East Malaysian marine sediment. *Appl Radiat Isot* 67:630–635
- Yoshida M, Jedidi N, Hamdi H, Ayari F, Hassen A, M'Hiri A (2003) Magnetic susceptibility variation of MSW compost-amended soils: in situ method for monitoring heavy metal contamination. *Waste Manag Res* 21:155–160
- Zhang C, Qiao Q, Piper JD, Huang B (2011) Assessment of heavy metal pollution from a Fe-smelting plant in urban river sediments using environmental magnetic and geochemical methods. *Environ Pollut* 159:3057–3070
- Zhang C, Appel E, Qiao Q (2013) Heavy metal pollution in farmland irrigated with river water near a steel plant-magnetic and geochemical signature. *Geophys J Int* 192:963–974
- Zhang M, Lu X, Chen H, Gao P, Fu Y (2015) Multi-element characterization and source identification of trace metal in road dust from an industrial city in semi-humid area of Northwest China. *J Radioanal Nucl Chem* 303:637–646
- Zhu Y, Lu X, Yang L, Wang L (2016) Accumulation and source of heavy metals in sediment of a reservoir near an industrial park of northwest China. *Front Earth Sci* 10:707–716
- Zorer ÖS, Ceylan H, Doğru M (2008) Assessment of some trace heavy metals and radioactivity concentration in water of Bendimahi River basin (Van, Turkey). *Environ Monit Assess* 147:183–190