One-Century Sedimentary Record, Sources, And Ecological Risk of Polycyclic Aromatic Hydrocarbons in Dianchi Lake, China

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Abstract

In this study, the sedimentary records, sources, and ecological risks of polycyclic aromatic hydrocarbons (PAHs) in Dianchi Lake were analyzed. The concentration ranges of ΣPAH_{16} in the sediments of Dianchi Lake were 368–990 ng/g, with an average value of 572 ng/g, peaking in 1988. Economic development and rapid population growth, as well as the rapid growth of coal consumption, have a greater impact on the HMW PAHs than on the LMW PAHs in the sedimentary environment. The results of the diagnostic ratios and PCA model show that the main sources of PAHs were coal and biomass combustion, as well as fossil fuel combustion sources in individual years. The risk assessment results showed that the PAH concentrations in the sediment were within a safe range. In the past 100 years of sediment pore water, except for Phe, which reached chronic toxic pollution levels in some years, other 2-3 ring LMW PAHs have been within a safe range. With the development of industrialization and urbanization, the burning of fossil fuels such as coal and petroleum has increased, and some of the 4-6 ring HMW PAHs have reached chronic toxicity or even acute toxicity in the sediment pore water.

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants (POPs) that exist in different environmental media (Gregg et al., 2015; Lu et al., 2012; Sandro et al., 2018; Walker et al., 2005). PAHs can originate from natural processes such as forest fires (Freeman and Catell 1990; Ma et al., 2020), volcanic eruptions (Kim et al., 2003; Morillo et al., 2007; Ma et al., 2018), and diagenesis of organic matter in oxygen-deficient sediments (Baumard et al., 1998; Van et al., 2000). However, human activities such as garbage incineration (Mastral and Callén, 2000), fossil fuel combustion (Blumer and Youngblood, 1975; Ma et al., 2021b), and wood burning for household heating and cooking (Lima et al., 2005; Zhang et al., 2007) are generally considered to be the main source of PAHs entering the environment (Viguri et al., 2002).

Lake sediment is an important source and sink of pollutants (Li et al., 2021). PAHs enter the lake aquatic ecosystem through various processes, such as urban and agricultural runoff, automobile exhaust emissions, and fossil fuel leakage (Rinawati et al., 2012; Wang et al., 2020). Owing to the low solubility and strong hydrophobicity of polycyclic aromatic hydrocarbons (Boehm et al., 1984; Mouhri et al., 2008), they are easily combined with particles and eventually accumulate in lake sediments (Donahue et al., 2006; Gogou et al., 2000; Liu et al., 2007). However, as the main source and sink of PAHs, sediments may also cause secondary pollution to the aquatic ecosystem of Dianchi Lake through pore water transportation, posing a substantial threat to animals, plants, and humans (Rockne et al., 2002; Tao et al., 2019; Tao, 2021). PAHs have attracted worldwide attention due to their potential carcinogenicity, mutagenicity, and teratogenicity, as well as their persistence in the environment and possible health risks (Han et al., 2019; Jia et al., 2021; Meyer et al., 2011).

Dianchi Lake is the largest freshwater lake in Yunnan Province. Due to its low replenishment coefficient and long lake water retention period, pollutants are concentrated in the lake (He et al., 2015). Since the reform and opening up, especially after the 1990s, rapid urbanization and industrialization have promoted an increase in human activities, such as industrial and agricultural development, deforestation, and tourism (Gu et al., 2017; Liu et al., 2008; Zeng and Wu 2009; Zhang et al., 2015). These activities have led to a sharp increase in the discharge of pollutants, a decline in water quality, and serious threats to Dianchi Lake and its ecological environment, making Dianchi Lake one of the most polluted lakes in China (Li et al., 2003b). The investigation of the sediments in Dianchi Lake and the risk assessment of PAHs in sediments and pore water can provide a scientific basis for pollution control and risk management of PAHs in lakes.

Although some studies have investigated the deposition records and sources of PAHs in Chinese plateau lakes (Guo et al., 2010; Yang et al., 2016; Zhao et al., 2014), information on persistent organic pollutants in lakes in the western plateau is still limited. Dianchi Lake is an important water supply area for industrial development and human use in Kunming (Ma et al., 2021a); the quality of water is directly related to the development of surrounding industries and affects people's health. Therefore, it is necessary to evaluate the concentration levels, sources, and ecological risk of PAHs in Dianchi Lake. The present study was designed to: (1) study the depositional records of polycyclic aromatic hydrocarbons in the sediments of Dianchi Lake and their relationship with human activities, (2) explore the source of PAHs in Dianchi Lake, and (3) assess the ecological risk of PAHs in sediments and pore water from 1860 to 2014.

2. Materials And Methods

2.1 Sampling and experimental analysis

Dianchi Lake (24°40'-25°03'N, 102°37'-102°48'E) is located on the Yunnan-Guizhou Plateau in China, southwest of Kunming (Fig. 1). The Dianchi Lake basin covers an area of 2,920 km^2, with an average depth of 4.7 m (Du et al., 2011). It is approximately 40 km long from north to south and 12.5 km wide (Gu et al., 2017; Ma et al., 2020). Sediment cores (102.67E, 24.69N) were collected in July, 2014, from the eastern part of Dianchi Lake using a gravity sampler with an internal diameter of 8.3 cm (Fig. 1). The sediment core (length: 39-cm) was cut into 1 cm segments, and each section was sealed in polygon bags at -4°C and transported to the laboratory, where they were stored at -50°C until further analysis.

2.2 Sediment core dating

The dating of each sediment core was based on the activity of ^{210}Pb. Briefly, the activity of ^{210}Pb and ^{226}Ra in the samples was measured using an Ortec HPGe GWL series, well-type, coaxial, low background, intrinsic germanium detector. The activities of ^{210}Pb and ^{226}Ra were determined from the gamma emissions at 46.5 or 295 keV, and 352 keV, respectively. These were emitted in gamma rays by the daughter isotope (^{214}Pb), which was stored for three weeks prior to dating in sealed containers to enable radioactive equilibration. Unsupported ^{210}Pb ($^{210}Pb_{ex}$) was calculated as the difference between the measured total ^{210}Pb at 46.5 keV and an estimate of the supported ^{210}Pb activity determined by the parent nuclide at 351 keV [$^{210}Pbex = ^{210}Pb_{tot}$-214Pb] (Huang et al. 2018; Ma et al. 2018).

2.3 Microwave extraction and Analysis by GC-MS

A detailed description of the extraction and cleanup methods for the samples is provided in our previous research (Ma et al., 2020; Ma et al., 2021b; Zhang et al., 2017), and the experimental procedure is briefly explained in this study. First, 25 ml hexane/acetone (1:1, v/v) solution was mixed with each sample and then subjected to microwave extraction for each sample. Next, the extract was centrifuged at 3000 rpm for 15 min and repeated three times, after which 20 mL hexane/acetone (1:1, v/v) solution was added. Third, the concentrated extract was reduced to 1 mL by rotary evaporation. Fourth, the extracts were purified by a chromatography column (1.5 g of 100-200 alumina mesh and 1.5 g of 80-100 silica gel mesh, 1 g of sodium sulfate) with a 50 mL solution of hexane/acetone (1:1, v/v). Finally, the extracts were reduced again to 1 mL by rotary evaporation, and 1 mL of the extract was protected from light by amber glassware (Ma et al., 2020).

Shimadzu QP2010plus gas chromatography-mass spectrometry (GC-MS) was used to determine the concentration of PAHs. The PAHs were separated at a set temperature in a silica capillary column (HP-5MS; diameter, 30 m × 0.25 mm; film thickness, 0.25 μm). Helium was used as the carrier gas (99.999%) at a constant pressure of 20.06 psi. Approximately 1 μL of each sample was added using the splitless injection method. The injector temperature, detector temperature, and initial oven temperature were 250°C, 280°C, and 90°C, respectively. The initial oven temperature was first increased to 160°C at a rate of 20°C/min, then increased to 200°C at a rate of 6°C/min, maintained for 1 min, increased to 230°C at 2°C/min, maintained for 2 min, and finally increased to 280°C at a rate of 20°C/min and maintained for 2 min. The mass spectrum was scanned in electron ionization mode (70 eV) (from 45 to 600) and then scanned in the selected ion monitoring mode. Sixteen PAHs were classified based on retention times and m/z values, quantified according to an internal standard peak area calibration, and the GC-MS was auto-tuned via perfluorotributylamine (Ma et al., 2020). Sixteen types of PAHs were analyzed in this study (Table S5).

2.4 Calculation of PAHs concentration in pore water

The relative distribution of PAHs in the solid and liquid phases in the sedimentary environment can be used to predict their bioavailability, environmental changes, behavior, and toxic effects (Bucheli and Gustafsson, 2000; Han et al., 2015). The concentration of ΣPAH16 in pore water reflects the pollution of PAHs in lake water during different periods (Dueri et al., 2008).

The solid-water distribution coefficient (K_d) in sediments is usually estimated using the equilibrium distribution model of TOC and solution. The calculation formula is as follows (1):

$K_d = K_{TOC}.f_{toc}$ (1)

where K_{TOC} represents the normalized distribution coefficient of TOC ((mol/kg organic carbon)/(mol/L solution)), and f_{toc} represents the ratio of TOC in solids (mass of organic carbon/mass of total solids). The formula for calculating the concentration of PAHs (C_w) in pore water is as follows (2):

$$C_w = C_s/K_d \quad (2)$$

where C_w represents the concentration of PAHs in the pore water, and C_s represents the concentration of PAHs in the sediment. The model has been widely used in field samples (Hawthorne et al., 2010; Li et al., 2019; Sun et al., 2003). The octanol-water partition coefficient used in this study, that is, the normalized carbon partition coefficient, and the PAH toxicity values used for risk assessment are shown in Tables S1 and S3.

2.5 Statistical analysis

The sampling map of the Dianchi sedimentary column was completed using Arc GIS 10.0. Correlation analysis was performed using the SPSS 20.0. Data processing and deposition records of economic parameters and PAH were performed using Microsoft Excel 2013 and OriginPro 9.0. Principal component analysis (PCA) was used for source apportionment. Socioeconomic data were available from the Yunnan Statistical Yearbook (2015). Because of the limitation of historical statistics, we only collected total population, GDP, rural population, and urban population data from 1971 to 2014; and coal consumption data from 1975 to 2014.

3. Results And Discussion

3.1 Historical sedimentary records of PAHs and the correlation with human activities

The concentration ranges of ΣPAH_{16} in the sediments of Dianchi Lake were 368–990 ng/g, and the average values were 572 ng/g (Fig. 2 and Table S2). In the profile (Fig. 2), the slight change at the bottom of the sediments before the mid-1950s may reflect background PAH values. The content of PAHs in sediments increased sharply from 1955 to 1988 and peaked at 990 ng/g in 1988. During this period, with the founding of New China, especially the implementation of the reform and opening policy in 1978 (Ma et al., 2018), the energy consumption caused by urbanization and industrialization increased rapidly; therefore, the residual ΣPAH_{16} showed a rapidly increasing trend.

After 1988, the concentrations of PAHs showed a fluctuating downward trend. The decline from the subsurface maximum to the present day in Dianchi Lake was attributed to government regulation and energy structure changes (Guo et al., 2013; Yunnan Statistical Yearbook 2015). This may be because coal and biomass combustion are the main sources of PAH emissions in Yunnan (Xu et al., 2006), while the proportion of total coal consumption has declined, and the proportion of clean energy (oil and natural gas) has increased (Ma et al., 2020; Yunnan Statistical Yearbook 2015); therefore, PAHS emissions were relatively reduced.

The vertical distributions of the different ring PAH concentrations in the sediments are listed in Fig. 2. The concentrations of 2-3 rings, 4 ring, and 5-6 rings PAHs in the sediments were 240–634, 57–285, and 66–182 ng/g, respectively (Figs. 2, 3). Table 1 shows that 2-3 ring PAHs were significantly correlated with the total population, GDP, and urban population from 1971 to 2014, and the correlation coefficients were 0.661, 0.673, and 0.696 ($P<0.05$), respectively. The results show that increasing population and GDP are the main factors affecting the concentration of LMW PAHs (2-3 rings).

Furthermore, 4 ring PAHs were significantly correlated with the total population, GDP, and urban population from 1971 to 2014, and the correlation coefficients were 0.439, 0.450, and 0.474 ($P<0.01$), respectively. The correlation coefficient between 4 ring and coal consumption was 0.344 ($P<0.01$) between 1975 and 2014 (Tab. 1). This indicates that population, GDP, and coal consumption are the main factors for the 4 rings PAHs, which is consistent with previous research results (Guo et al., 2007; Hafner et al., 2005; Karina et al., 2014; Liu et al., 2012a; Ma et al., 2021b; Zhang et al., 2009). With the establishment of New China, especially the implementation of the reform and opening policy in 1978, rapid economic development and rapid population growth, as well as the rapid growth of coal consumption, have led to a rapid increase in 4 ring PAH residues in the sedimentary environment.

Table 1
Correlation coefficients between PAHs and human activities

	Total population	**GDP**	**Rural Population**	**Urban population**	**coal**
2-3 rings	0.357*	0.368*	0.029	0.392*	0.191
4 rings	0.439**	0.450**	0.135	0.474**	0.344**
5-6 rings	0.661**	0.673**	0.193	0.696**	0.632**
** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed)					

However, after 1988, with an increase in population, GDP, and coal consumption, the 2-3 ring and 4 ring PAHs decreased to a certain extent (Figs. 2, 3). Previous studies have shown that the household energy usage structure in Yunnan Province is dominated by coal and biomass, and biomass combustion is used for cooking and basic heating purposes for household needs (Ma et al., 2020; Zhang et al., 2007). With the rapid development of society and economy, people's lifestyles have undergone significant changes, especially via substituting some coal combustion and biomass for household needs with cleaner energy (Han et al., 2016; Liu et al., 2012; Tian et al., 2017). In addition, the proportion of coal consumption in Yunnan has declined, while the proportion of clean energy (oil and natural gas consumption) has increased (Ma et al., 2020). These may be the main reasons for the decline in 2-3 ring and 4 ring PAHs.

Table 1 shows that 5 ring PAHs were also significantly correlated with the total population, GDP, urban population, and coal consumption. Many studies have shown that traffic sources are the main source of 5-6 ring HMW (4-6 ring PAHs) (Mai et al., 2002; Ma et al., 2021b; Yuan et al., 2001). With the rapid development of society and economy, motor vehicle emissions caused by urbanization and industrialization have increased significantly, resulting in an increase in the concentration of 5-6 ring PAHs. After 2005, the concentration of 5-6 ring PAHs has declined (Figs. 2, 3), which may have been caused by the increase in vehicle emission standards in China in recent years (Ma et al., 2020; Tang et al., 2015).

According to the correlation coefficients between PAHs and human activities, the correlation coefficients between population, GDP, and coal consumption and 2-3 ring LMW PAHs are smaller than the correlation coefficients with 4-6 ring HMW PAHs (Table 1). This indicates that from 1971 to 2014, population, GDP, and coal combustion had a greater impact on HMW PAHs than on LMW PAHs. This may be because HMW PAHs are mainly derived from the burning of fossil fuels at high temperatures, such as coal, coke combustion, and motor vehicle exhaust emissions (Mai et al., 2002; Yuan et al., 2001). With economic development and population increase, the increase in fossil fuel combustion caused by industrialization and urbanization has led to an increase in HMW-PAH emissions (Ma et al., 2020; Ma et al., 2021b).

3.2 Source apportionment and identification of PAHs

3.2.1 Diagnostic ratios of PAHs

The diagnostic ratios of Ant/(Ant+Phe), BaA/(BaA+Chr), and InP/(InP+BghiP) were used to analyze the possible sources of PAHs in Dianchi Lake (Colombo et al., 2006; Guo et al., 2010; Guo et al., 2011b; Han et al., 2021; Yim et al., 2005). Fig. 4 shows that the ratio of BaA/(BaA+Chr) is mostly >0.35, except for individual years, which are between 0.2–0.35. This shows that PAHs in Dianchi Lake are mainly derived from coal and biomass combustion, and fossil fuel combustion occurs in several years. The ratios of InP/(InP+BghiP) were all >0.5 (Fig. 4), which indicates that coal and biomass combustion are the main sources of PAHs in Dianchi Lake. Therefore, the ratios of BaA/(BaA+Chr) and InP/(InP + BghiP) suggest that coal and biomass combustion mainly contribute to the PAH concentrations in Dianchi Lake, and fossil fuel combustion sources exist in individual years.

However, the ratios of Ant/(Ant+Phe) were all <0.1, indicating that PAHs mainly originated from petroleum sources (Fig. 4). The difference between the ratios of Ant/(Ant+Phe), BaA/(BaA+CHR), and InP/(InP+BghiP) has also been observed in previous studies (Yan et al., 2005; Yan et al., 2006). This discrepancy is caused by the difference in the environmental behavior of the Ant and Phe isomers (Hwang et al., 2003; Yan., 2005). Previous studies have shown that Ant has a higher photolytic ability than Phe (Ma et al., 2021b; Sanders et al., 1993). Therefore, the applicability of Ant/(Ant+Phe) in diagnosing PAH sources is questionable. Overall, the PAHs in Dianchi Lake are mainly derived from coal and biomass combustion, as well as fossil fuel combustion sources in individual years.

3.2.2 Principal component analysis (PCA) for source apportionment

Three principal components were extracted using PCA: PC1, PC2, and PC3 (Fig. 5 and Table 2). PC1 accounted for 53.14% of the total variance, of which Acy, Flo, Ant, Flu, Pyr, BaA, Chr, and BKF had higher loading values. Acy and Flo are generally believed to be characteristic indicators of wood burning (Ravindra et al., 2008; Zhang et al., 2013), and Ant, Flu, Pry, BaA, Chr, and BKF are molecular indicators of coal burning (Duval and Friedlander., 1981; Harrison et al., 1996; Li et al., 2003a; Wang et al., 2009a). Therefore, PC1 was determined to be the source of biomass and coal combustion.

Table 2
PCA analysis of PAHs in the sediments of Dianchi Lake

	Component		
	Factor 1	**Factor 2**	**Factor 3**
Nap	0.492	-0.087	0.342
Acy	0.822	0.113	0.217
Ace	0.000	-0.560	-0.455
Flo	0.711	0.492	-0.061
Phe	0.519	-0.089	0.773
Ant	0.895	0.096	0.027
Flu	0.803	-0.020	0.346
Pyr	0.824	-0.131	0.355
BaA	0.910	0.284	-0.247
Chr	0.758	0.336	-0.289
BbF	0.563	0.547	-0.273
BKF	0.834	0.213	-0.463
BaP	0.662	-0.137	-0.279
DBA	-0.762	0.577	0.176
IcdP	-0.434	0.791	0.149
Bghip	-0.825	0.503	0.129

PC2, which explained 14.87% of the total variance, was mainly composed of BbF, DBA, IcdP, and Bghip (Fig. 5 and Table 2). Previous studies have shown that BbF and BghiP are indicators of gasoline combustion emissions (Chen et al., 2011; Motelay-Massei et al., 2007; Qian et al., 2016; Li et al., 2003a;

Sofowote et al., 2008), and Inp and DBA have been identified as indicators of diesel combustion emissions (Fang and Chang, 2004; Li and Kamens, 1993; Liu et al., 2017; Wang et al., 2009b; Wang et al., 2016; Yunker et al., 2002). Therefore, PC2 was classified as the source of the vehicle exhaust emissions.

PC3 accounted for 11.68% of the total variance, which was highly loaded by Phe (Fig. 5 and Table 2). Phe is a typical marker of coal combustion (Cao et al., 2016; Ramdahl, 1983; Ravindra et al., 2008). Therefore, PC2 was identified as the source of coal combustion. According to the analyses above, PAHs in Dianchi Lake are mainly derived from the combustion of coal and biomass, followed by automobile exhaust emissions. This result is consistent with the results of the diagnostic ratio method.

Studies have shown that the household energy utilization structure in Yunnan Province is dominated by coal and biomass (Xu et al., 2006; Zhang et al., 2007). The sampling point is located in the southeast of Dianchi Lake, mainly in rural and mountainous areas. Biomass and coal combustion are the main energy sources for cooking and heating of households in this area, which also shows that the source analysis results are accurate.

3.3 Ecological risk assessment with PAH contamination

In this study, the risk assessment of seven PAHs with potential human carcinogenicity, namely BaA, Chr, BbF, BkF, BaP, DBA, and InP, was conducted. The toxicity of BaP was used as the standard to quantify the toxic equivalent TEQ_{BaP} of the six other carcinogenic PAHs (Table S4) (Han et al., 2021; Qiao et al., 2006; Tsai et al., 2004). The concentration of TEQ_{BaP} in the sediments of Dianchi Lake was calculated, as shown in Table 3. Toxicity equivalent concentration ranges of BaA, Chr, BbF, BkF, BaP, InP, and DBA were 0.72–3.20 ng/g, 0.03–0.55 ng/g, 1.68–0.48 ng/g, 8.85–1.10 ng/g, 65.64–5.25 ng/g, 14.08–8.47 ng/g, and 1.64–1.04 ng/g, respectively, and the average values were 1.52 ng/g, 0.10 ng/g, 1.05 ng/g, 3.39 ng/g, 17.23 ng/g, 11.35 ng/g, and 1.42 ng/g, respectively. The toxicity equivalent concentration range of $\sum$7PAHs was 22.38–87.79 ng/g, and the average value was 36.05 ng/g. Compared with the global average TEQ_{BaP} concentration (804.94 ng/g) in sediments (Li et al., 2014; Sprovieri et al., 2007), the TEQ_{BaP} concentration in Dianchi Lake sediments was much lower than the world's average toxicity level. The PAH concentrations in the sediment were all within a safe range (Liu et al., 2010; Li et al., 2019).

Table 3
Toxicity equivalent concentrations of PAHs in the sediments of Dianchi Lake (TEQ_{Bap}) (ng/g)

	TEQ_{BaP}		
	Mix.	Min.	Mean
BaA	0.72	3.20	1.52
Chr	0.03	0.55	0.10
BbF	1.68	0.48	1.05
BkF	8.85	1.10	3.39
BaP	65.64	5.25	17.23
InP	14.08	8.47	11.35
DBA	1.64	1.04	1.42
∑7PAHs	22.38	87.79	36.05

The concentration of ΣPAH16 in sediment pore water reflects the pollution of PAHs in lake water during different periods (Arp et al., 2009; Chiou et al., 1981; Lücker et al., 2003; Yong et al., 2009). In this study, the risk threshold of PAHs in lake water was used to assess the risk of PAHs in the sediment pore water of Dianchi Lake (Neff et al., 2005). As shown in Fig. 6, the pollution level of 2-3 ring LMW PAHs has been within the safe range in the past 100 years. Only the concentration of Phe in some years has reached the pollution level of chronic toxicity (55 μg/L), which may be related to agricultural development and biomass burning (Li et al., 2018; Simcik et al., 1999; Wang et al., 2015)

Among the 4-6 ring HMW PAHs, most of the concentrations of Flu, Chr, and BbF were within the safe range before the 1980s. After the 1980s, the pollution concentration increased and reached chronic toxicity levels of 11, 2.2, and 2.9 ug/L, respectively. Most of the concentrations of Pyr, BaA, BkF, BaP, and BghiP reached their chronic toxicity levels of 12, 2.0, 1.7, 1.5 ug/L, and 0.49 ug/L, respectively. Furthermore, the concentrations of BkF and BaP on the surface reached their acute toxicity levels of 8.6 ug/L and 7.6 ug/L, respectively. DBA and InP were the two most polluting compounds. In the past 100 years, all concentrations have reached their acute toxicity levels of 1.3 and 0.64 ug/l, respectively. This may be related to the increase in the burning of fossil fuels, such as coal and oil, caused by the development of industrialization and urbanization since the reform and opening up (Ma et al., 2021b; Nemr et al., 2007; Wang et al., 2016).

4. Conclusion

The concentration ranges of ΣPAH16 in the sediments of Dianchi Lake were 368−990 ng/g, with an average value of 572 ng/g and peaking in 1988. The concentrations of 2-3 ring, 4 ring, and 5-6 ring PAHs in the sediments were 240–634, 57–285, and 66–182 ng/g, respectively. Population and GDP are the main influencing factors of 2-6 ring PAHs, and coal consumption is the main influencing factor for the 4-6 ring HMW PAHs. Moreover, population, GDP, and coal combustion have a greater impact on HMW PAHs than LMW PAHs. The results of the diagnostic ratios and PCA model show that the main sources of PAHs were coal and biomass combustion, as well as fossil fuel combustion sources in individual years. PAH concentrations in the sediment were within the safe range. In the sediment pore water, except for Phe, which has reached chronic toxic pollution levels in some years, other 2-3 ring LMW PAHs have been within a safe range for the past 100 years. With the development of industrialization and urbanization, the burning of fossil fuels such as coal and petroleum has increased, and some 4-6 ring HMW PAHs have reached chronic toxicity or even acute toxicity in the sediment pore water.

Declarations

Data availability

The research data are available on request: huangchangchun_aaa@163.com.

Author contributions

X.H.M., T.H. and C.C.H. designed the experiments. X.H.M., S.D.L., carried out the experiments and performed the analyses. X.H.M., H.Y., T.H., C.C.H. substantially contributed to interpreting the results and writing the paper.

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Ethics declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests

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Figures

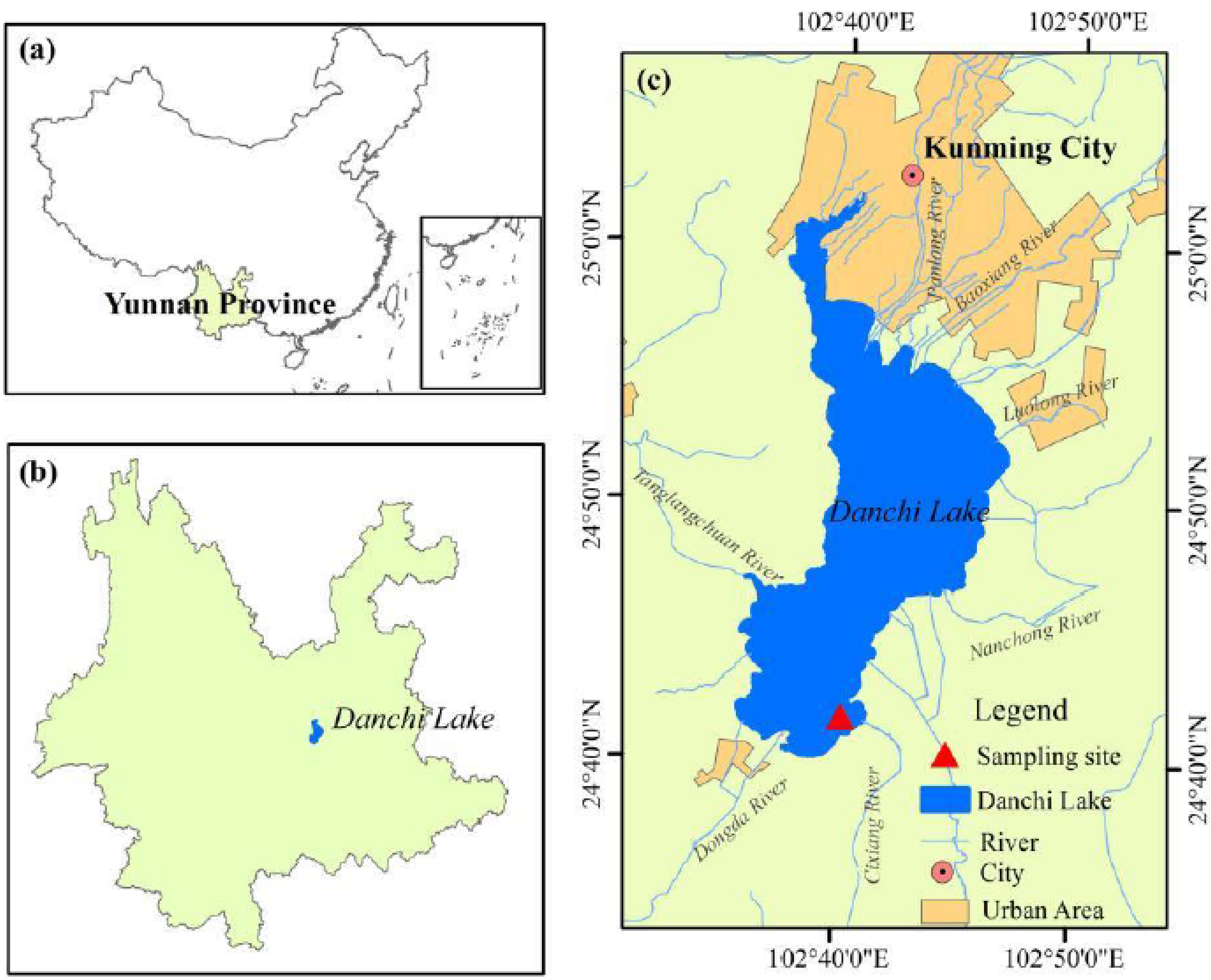

Figure 1

Location of sampling site in Dianchi Lake

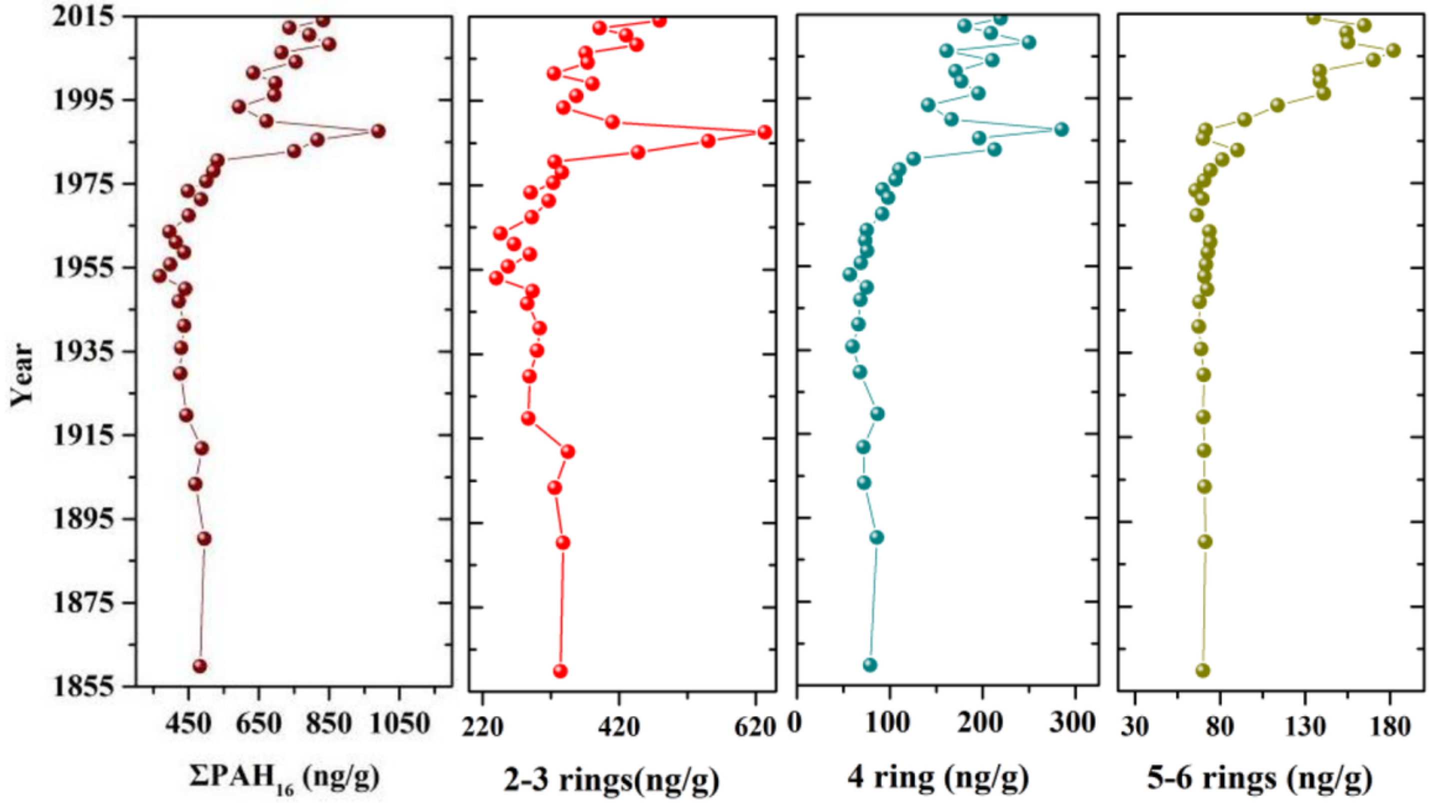

Figure 2

Historical trend of ΣPAH16 and 2-6 rings PAHs concentrations in sediments of Dianchi Lake

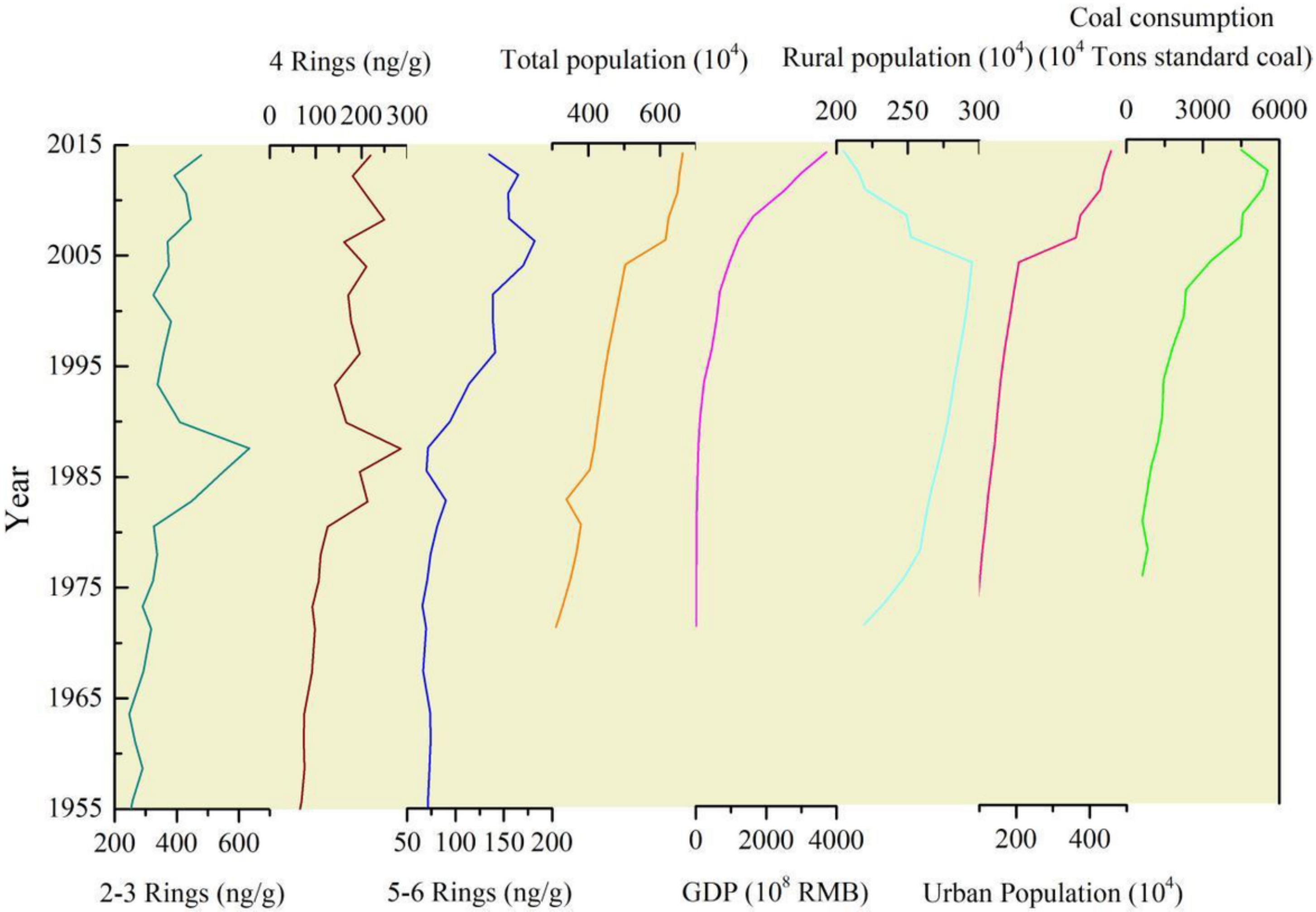

Figure 3

Historical trend of the concentration of individual PAHs in the sediments of Dianchi Lake

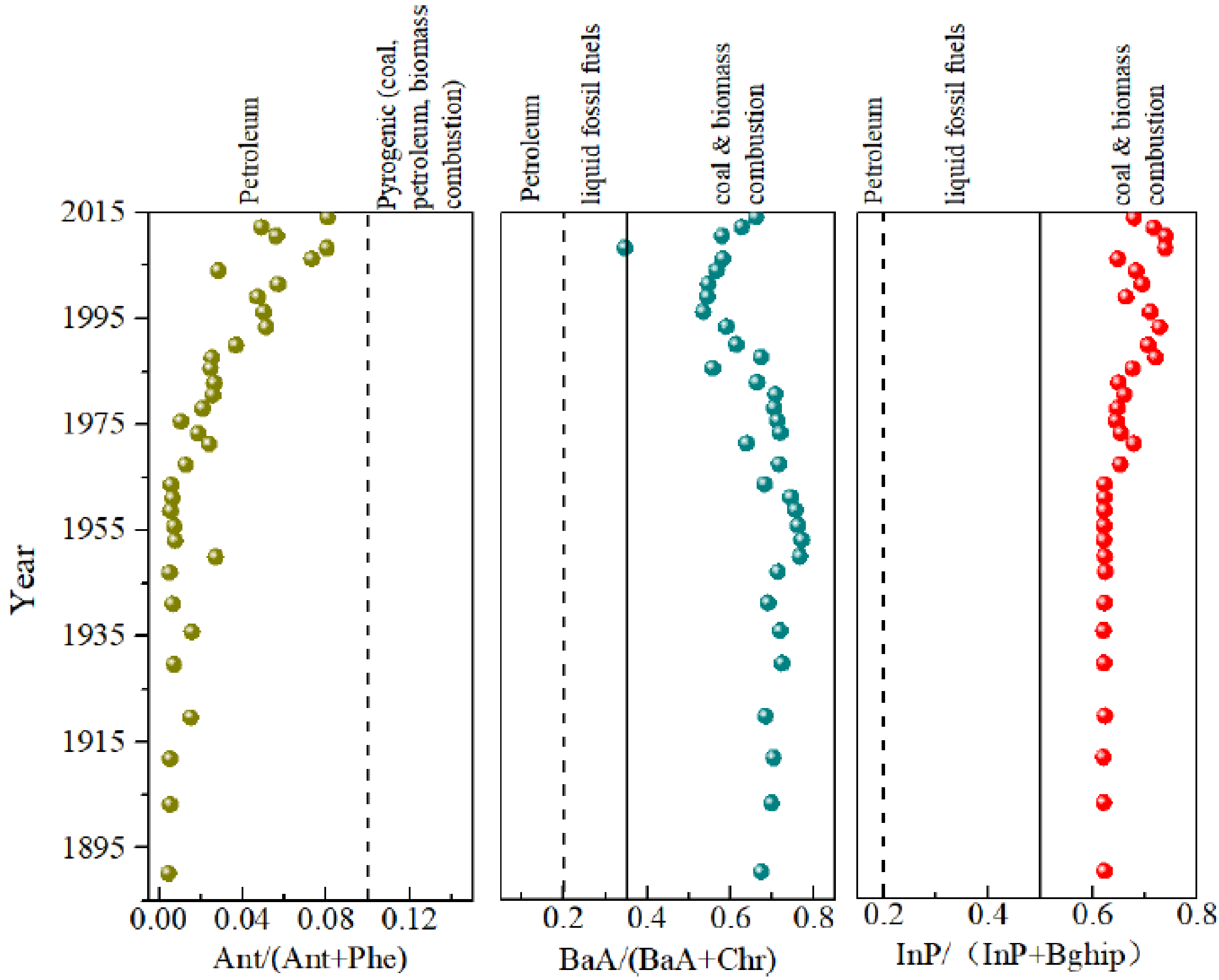

Figure 4

Diagnostic ratios of PAHs in Dianchi Lake

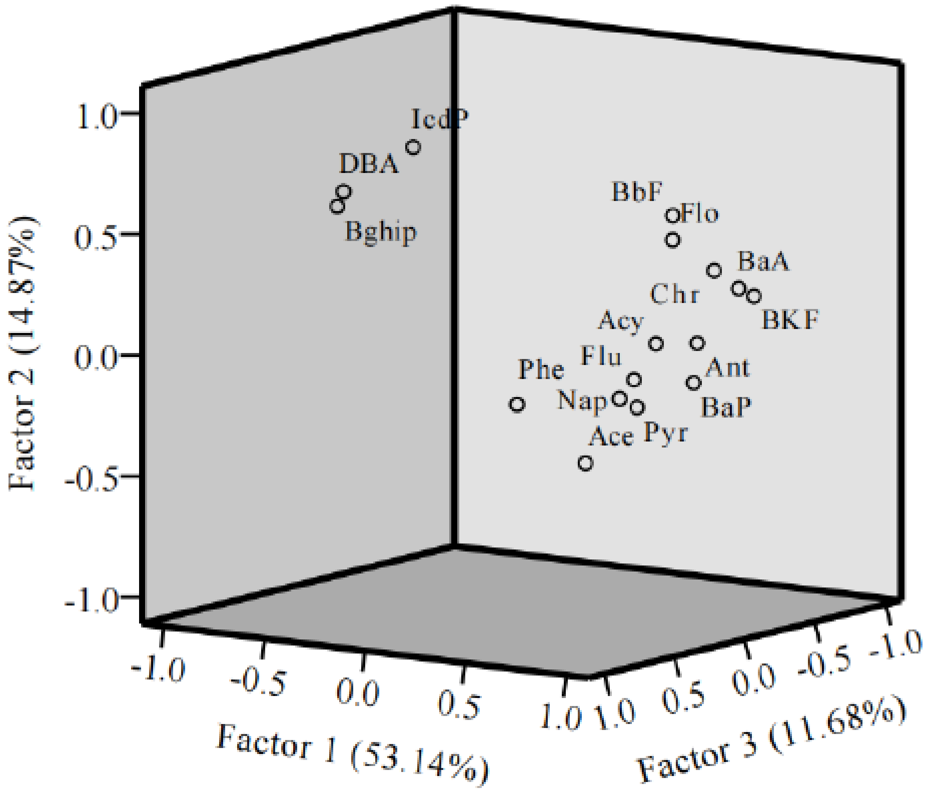

Figure 5

Three-dimensional plot of the principal component loading for the Dianchi sediment core

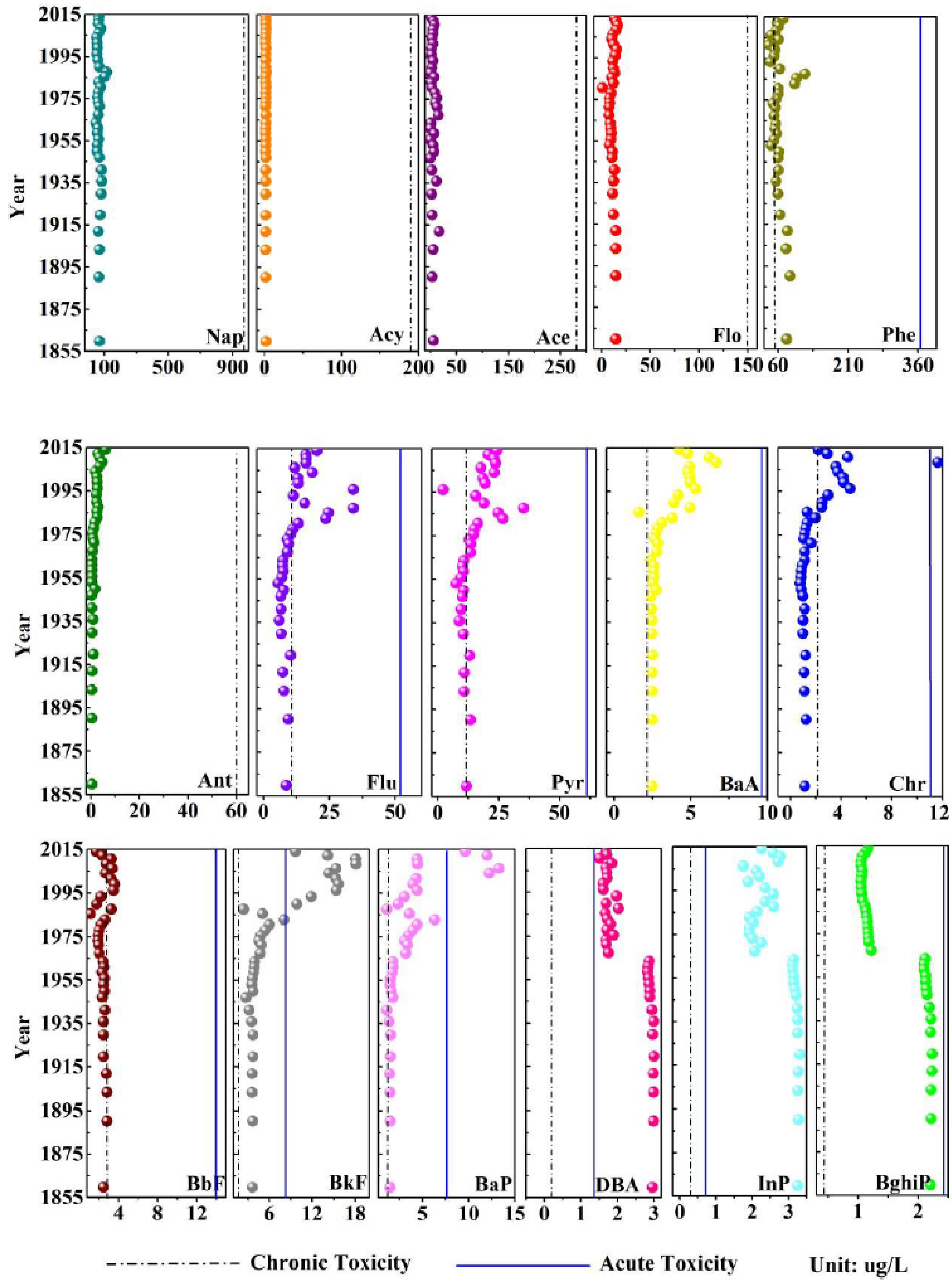

Figure 6

Risk assessment of PAHs in Dianchi Lake pore water

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