

Factors influencing the occurrence and distribution of organophosphate esters in sediments by cascade reservoirs of the Wujiang River in Southwest China

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Abstract An artificial reservoir, as a temporary host for various materials in a basin, faces the potential risk of organophosphate ester (OPE) enrichment in the sediment. In this study, in order to investigate the impacts of dam-related water impoundment on OPEs, seven reservoirs in the Wujiang River (WJR) were investigated in January, April, July, and October 2017, and the occurrence and distribution of eight OPEs were evaluated. The results showed that the content of the eight OPEs ranged from 0.83 to 2745 ng/g dw. The main component was tris(2-chloroethyl) phosphate (TCEP). Spatially, the OPEs decreased from upstream to downstream. Temporally, the OPE content showed a trend of July > October ≥ January > April. Socioeconomic and hydrological factors had significant effects on the distribution of OPEs, and the empirical model of OPEs with gross domestic product (GDP) and reservoir age (RA) as parameters was established. This provided a basis for OPE estimation and

treatment direction for the reservoir. In addition, the relevant data regarding OPEs and total organic carbon (TOC) in terrigenous sediments from previous studies showed a significant correlation ($r=0.63$, $P<0.01$). The significantly high risk quotient (RQ) estimated for OPEs, especially tris(methylphenyl) phosphate (TMPP) and triphenyl phosphate (TPHP), suggest potential adverse risk.

Keywords Organophosphate esters (OPEs) · Cascade reservoirs · Surface sediment · Wujiang River · TOC · Reservoir hydrology

1 Introduction

Following the phase-out of polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), organophosphate esters (OPEs) have emerged as widely utilized alternatives in applications such as flame retardants, plasticizers, polymers, foaming agents, stabilizers, and defoamers (Shi et al. 2020; Marklund et al. 2003). In 2018, the global production of OPEs accounted for 30% of the

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overall flame retardant production (Li et al. 2019a), demonstrating a consistent annual growth rate of 4.6% (Pan et al. 2022). However, recent research has revealed that certain OPEs possess carcinogenic and cytotoxic properties and reproductive toxicity. For instance, chlor-OPEs have been found to induce abnormalities in animals, while tris(1,3-dichloro-2-propyl) phosphate (TDCIPP) has been linked to changes in male hormone levels and a decrease in sperm quality (Zhang et al. 2022). Additionally, tris(2-butoxyethyl) phosphate (TBOEP) has been investigated for its potential carcinogenic effects (Wang et al. 2020b). Moreover, OPEs can be easily discharged into the environment via multiple pathways, including wear, evaporation, and dissolution (Pantelaki and Voutsas 2019). These compounds are ubiquitous in the environment (Wu et al. 2022b; Zeng et al. 2020; Ma et al. 2022; Zhang et al. 2022; Fang et al. 2022; Pang et al. 2016), particularly in aquatic ecosystems (Lai et al. 2019; Li et al. 2019a; Luo et al. 2020). Because of their lipophilic nature, OPEs tend to accumulate within the food chain, posing potential risks to both human health and the environment.

Until now, OPE contaminants have been found to be widespread in atmospheric particles, water, soil, wetlands, and sediment (Wu et al. 2022b; Ma et al. 2022; Yin et al. 2021; Zhang et al. 2022; Hu et al. 2017; Lai et al. 2019). OPEs exhibit a broad hydrophobic nature, as evidenced by their octanol–water partition coefficient ($\log K_{OW}$) ranging from 0.8 to 9.49. This characteristic plays a crucial role in their distribution disparities within aquatic environments (Cristale et al. 2013). The highly hydrophobic monomeric constituents of OPE compounds tend to undergo adsorption onto particulate matter, leading to their accumulation in sediment (Wang et al. 2018). Worldwide application of these highly persistent phosphorus chemicals has led to widespread sedimental environmental contamination, raising concerns about the environmental implications of OPEs in sediments (Huang et al. 2024). Moreover, numerous studies have substantiated the presence of OPEs in various sedimentary environments across China, including but not limited to Taihu Lake, Liaohe River, Shandong Peninsula, Yangtze River Estuary, Pearl River Delta, Taiwan Strait, and China's Yellow Sea (Wang et al. 2018; Luo et al. 2020; Lian et al. 2022; Zha et al. 2018; Tan et al. 2016; Zeng et al. 2020; Lin et al. 2024; Fang et al. 2022). The sedimentary OPE content in lake systems with longer hydraulic retention time (HRT) is 76 ± 377 ng/g dry weight [dw] (median 9.80 ng/g dw), and it is 91.3 ± 271 ng/g dw (median 33.9 ng/g dw) in river systems with shorter HRTs (Table S1), indicating hydrodynamic effects. As a unique kind of ecosystem, reservoirs have different types of regulation and may have a complex distribution of OPEs. Therefore, the occurrence of OPEs in reservoirs with different regulatory types is the focus of this study. In addition, sedimentary organic matter is an important factor affecting the distribution of OPEs (Pang et al.

2013; Wang et al. 2018; Xing et al. 2018). For example, sedimentary OPEs tend to increase with the total organic carbon (TOC) content (Liu et al. 2018). In addition, reservoir age (RA) is a key factor affecting reservoir sediments (Bao et al. 2025; Chen et al. 2024). Newly constructed reservoirs release material from submerged soil to be discharged downstream. The aging reservoirs receive material input from different sources, which intensifies the geochemical reaction of sedimentary organic matter and makes the process of pollutant accumulation more complicated (Bao et al. 2025; Shi and Qin 2023; Yin et al. 2023). Hence, studying the effect of reservoirs with different hydrological characteristics on sedimentary OPEs is critical in order to formulate effective pollution control measures.

Artificial reservoirs possess unique attributes in contrast to natural aquatic ecosystems such as oceans, lakes, and rivers (Wu et al. 2022a; Wang et al. 2020c). An understanding of the migration and transformation dynamics of OPEs in artificial reservoirs is imperative. Firstly, the different regulation types of reservoirs lead to different water retention times (Wu et al. 2020), with different effects on the migration and accumulation of OPEs in the reservoirs. Furthermore, the potential impact of seasonal thermal stratification in artificial reservoirs on the secondary migration of OPEs in sediments and its consequent alteration of the physicochemical state of the sediment–water interface can significantly influence the occurrence of OPEs in sediments (Chen et al. 2024; Dueri et al. 2009; Guo et al. 2023; Han et al. 2018; Xu and Miliman 2009; Wang et al. 2015). Additionally, artificial reservoirs frequently demonstrate a high recharge coefficient (Wang 2020; Zhao et al. 2024), facilitating the accumulation of OPEs from the basin in reservoir sediment and increasing the risk to the safety of water quality. Water quality safety of artificial reservoirs is of utmost importance for socioeconomic factors and public health, as reservoirs frequently function as essential sources of drinking water.

Over the past six decades, nearly 70,000 large dams (higher than 15 m) have been constructed in rivers worldwide, in particular for the development of cascade reservoirs applied to more rivers (<https://www.icold-cigb.org/>). Unlike single reservoir systems, cascade reservoirs can compound the impact of an individual dam on the aquatic environment, resulting in transmission and superposition effects that span the entirety of the basin (Ma et al. 2020; Zhao et al. 2024). However, the impact of cascade dams on OPEs is unknown. The cascade reservoirs on the Wujiang River (WJR) exhibit different characteristics such as regulation patterns, water depths, and operational ages (Wang et al. 2020c; Yang et al. 2025), thus serving as an ideal site for studying the variations in and factors influencing sedimentary OPEs in cascade reservoirs. The WJR, the largest river in Guizhou Province, has multiple reservoirs that have different regulation types and are a crucial source of drinking water for the local

population, yet it has very limited information available on the content, fate, and sources of OPEs. In the present study, sediment samples were collected quarterly from seven reservoirs within the WJR and analyzed for eight OPEs. The study aims to achieve the following objectives: (1) examine the temporal and spatial distribution of eight OPEs in surface sediments of cascade reservoirs; (2) analyze the factors that influence the dispersion of these eight OPEs; and (3) evaluate the ecological risk posed to aquatic organisms.

2 Materials and methods

2.1 Sampling areas

The Wujiang River (WJR) is the largest tributary on the south side of the Yangtze River. It is located in the middle reaches, with a total length of 1037 km (Yang et al. 2020). WJR is the main channel transporting pollutants from Guizhou (Wu et al. 2022a). There are 11 reservoirs on the mainstream of WJR, generating 50.8 billion kW·h/year of electricity, which promotes the economic development of Guizhou province (Li et al. 2009). However, industrial development has also led to frequent discharge of OPE contaminants, while urban sewage, agriculture, and animal husbandry are also important sources of sewage pollution in the basin (Miao et al. 2023). WJR plays a major role as a source of drinking water, making its water quality—especially with respect to micro-contaminants—highly significant.

A total of seven reservoirs located in the WJR were selected to represent various types of regulation. These included an annually regulated reservoir (Hongjia Du, HJD), two seasonally regulated reservoirs (Dongfeng, DF; and Wujiangdu, WJD), and four daily regulated reservoirs (Suofengying, SFY; Silin, SL; Pengshui, PS; and Yinpan, YP) (Fig. 1). Surface sediment samples were collected from these seven reservoirs during the months of January, April, July, and October in 2017. More comprehensive information regarding the sampling areas can be found in Table S2.

2.2 Sample preparation and analysis

In this study, concentrations were measured for eight OPEs, including tris(2-chloroethyl) phosphate (TCEP), TCIPP, TDCIPP, triethyl phosphate (TEP), TBOEP, tris(2-ethylhexyl) phosphate (TEHP), triphenyl phosphate (TPHP), and tris(methylphenyl) phosphate (TMPP). The chemical structure and basic information for each of the eight OPEs are summarized in Table S3. Sediment samples (sample preparation is detailed in Text S1) underwent ultrasonic-assisted extraction for the analysis of OPEs. The method used for analysis was modified from previous publications (Cai et al. 2022; Li et al. 2017). Briefly, approximately 2 g dry sediment for each sample

was spiked with 200 μ L of surrogate standards (d_{15} -tripropyl phosphate, d_{15} -TPP; and triallyl phosphate, TAP), followed by 30 min of ultrasonic extraction with *n*-hexane and acetone solution (1:1, v/v) at 1 mg/L and then ultrasonic-assisted extraction with 10 mL of *n*-hexane and acetone solution (1:1, v/v) for 30 min. The extract was centrifuged at 4000 rpm for 5 min, and the supernatant was decanted into a flask (three times). After a prewash, the combined extracts were fractionated through activated silica gel column chromatography with 25 mL of acetone and DCM solution (7:3, v/v), followed by 5 mL each of ethyl acetate and *n*-hexane. The eluant was concentrated to a volume of 250 μ L and analyzed using gas chromatography–mass spectrometry (GC/MS). An Agilent GC/MS (7890 A/5975 C, USA) with a DB-5MS (30 m $\times$ 0.25 mm i.d. $\times$ 0.25 μ m film thickness) capillary column was used to identify and quantify target OPEs in the extracts. GC/MS was used to identify and quantify target OPEs in the extracts. Details of the instrumental analysis are provided in the Supporting Information (Text S2).

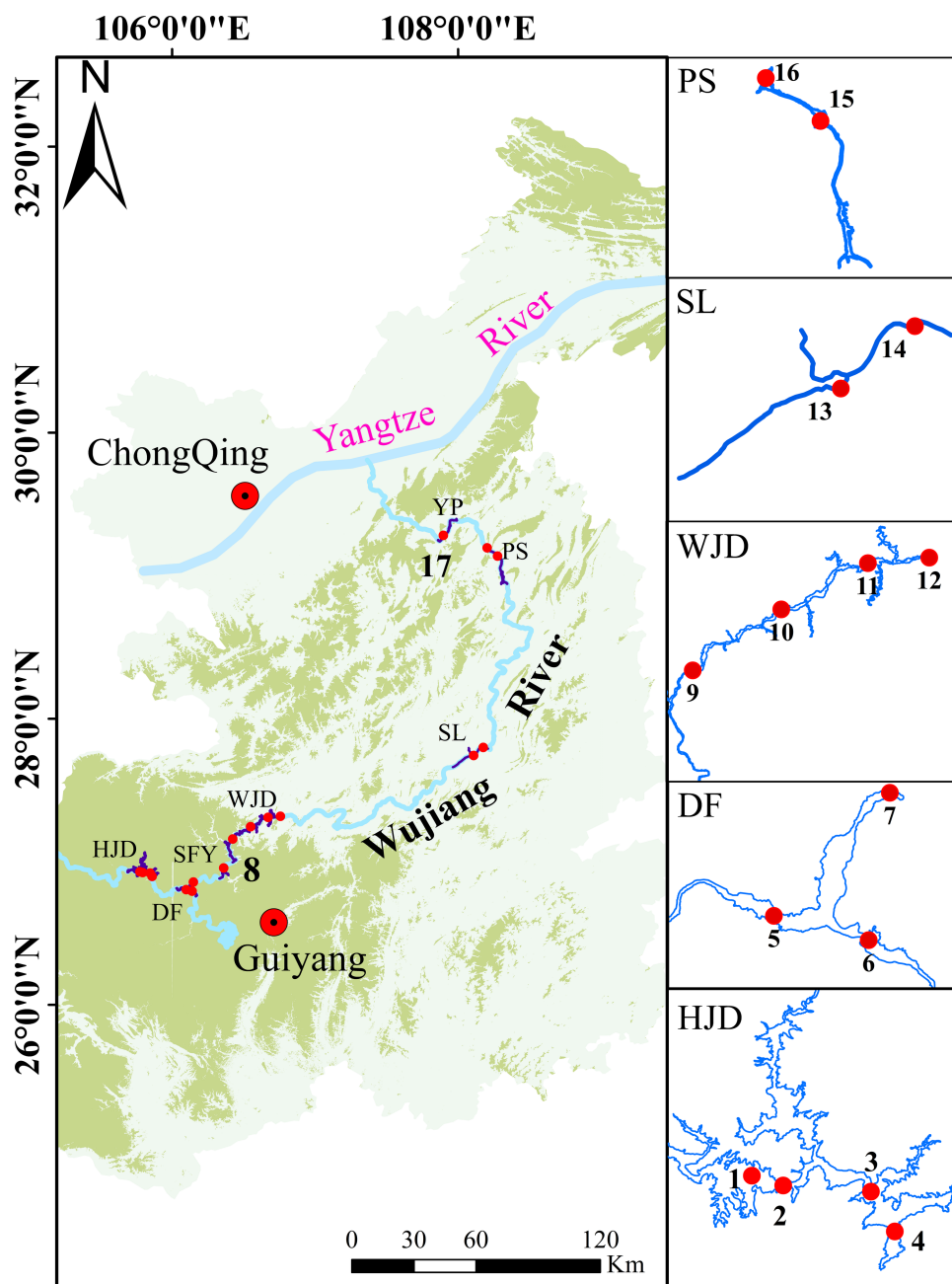
For purposes of quality assurance/quality control, for each batch of ten samples, a procedural blank and a solvent blank were subjected to the same treatment and analysis as the actual samples. The concentrations of the samples were determined using external calibration curves prepared with concentrations ranging from 0.5 to 5000 ng/mL for individual OPEs. These calibration curves exhibited excellent linearity, with regression coefficients exceeding 0.99. The stability of the instrument and the calculation of recovery were monitored by analyzing a quality control standard (d_{15} -TPP, TAP) after every five samples. The recoveries of deuterated OPEs spiked into individual samples were $100\% \pm 12\%$ for d_{15} -TPP, and $90\% \pm 11\%$ for TAP. All samples were subjected to duplicate extraction and analysis. Procedural blanks contained trace levels of OPEs, and the average blank levels were subtracted from all samples. The limit of quantification (LOQ) was set at the standard deviation of the concentrations in the procedural blanks, which ranged from 0.21 (TEP) to 7.01 (TEHP) ng/g dw for OPEs (Table S6). All concentration data are presented on a dry weight basis. For statistical analysis, values below the LOQ were assigned half the value of the LOQ, and non-detection (ND) was set to zero.

The samples were pretreated with 2 M HCl to remove carbonates in order to determine the TOC, following the methodology outlined in previous studies (Zhang et al. 2021; Jia et al. 2017). All samples were analyzed using a EuroVector EA3000 elemental analyzer (Italy).

2.3 Ecological risk assessment

The risk quotient (RQ) method was used to estimate the potential hazards of aquatic organisms. This was done by employing the following equation (Park and Jeon 2021).

Fig. 1 Map of sampling sites in the WJR (five reservoirs with more than one sampling site are depicted by small figures on the right side)



$$RQ = \frac{MEC}{PNEC} = \frac{MEC_{\text{porewater}}}{PNEC} = \frac{\left[\frac{1000 \times C_s}{K_{oc} \times f_{oc}} \right]}{PNEC}, \quad (1)$$

where MEC is the analytical concentration of OPEs found in water samples, and PNEC is the predicted no-effect concentration. $MEC_{\text{porewater}}$ (the concentration of pollutants in the pore water of sediments) was substituted for the MEC in the ecological risk assessment of sediments (Yadav et al. 2018; Luo et al. 2020). Based on the content of the pollutant

in sediment (C_s), the organic carbon partitioning coefficient of pollutant (K_{oc}), and the fraction of organic carbon in sediment (f_{oc}), the $MEC_{\text{porewater}}$ can be estimated by the equilibrium partitioning method (Di Toro et al. 1991).

The PNEC of individual OPEs on algae, daphnia magna, and fish were determined using the data employed by previous studies (Yan et al. 2023; Zhang et al. 2023), as shown in Table S3. The K_{oc} of individual OPEs and f_{oc} in each sediment sample are documented in Tables S3 and S2, respectively.

3 Results and discussion

3.1 Spatial distribution and seasonal variation of eight OPEs

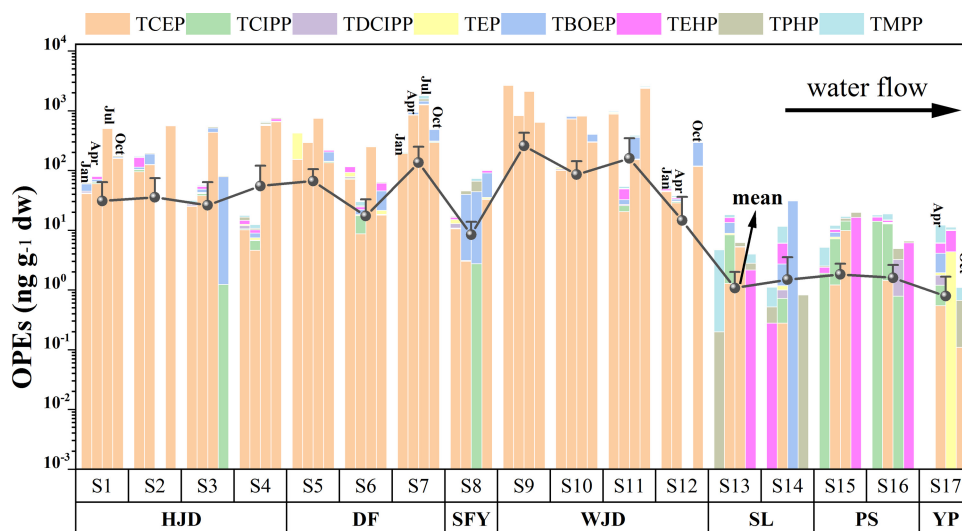
The sediment samples collected from the seven reservoirs of the WJR exhibited a wide range of content for the eight OPEs, from 0.83 to 2745 ng/g dw, with a mean value of 313 ng/g dw (Table S4). Among these compounds, chlor-OPEs (TCEP, TCIPP, and TDCIPP), alkyl-OPEs (TEP, TEHP, and TBOEP), and aryl-OPEs (TPHP and TMPP) accounted for $55.9\% \pm 35.0\%$, $28.0\% \pm 29.6\%$, and $16.2\% \pm 22.5\%$ of the total, respectively. TCEP was the predominant monomer, constituting $46.1\% \pm 37.2\%$. Notably, the WJD reservoir exhibited the highest OPE content among the seven reservoirs, ranging from 72.1 to 570 ng/g dw. The OPE content in the sediments gradually decreased downstream along the river (Fig. 2). For instance, the mean OPE content in the HJD sediment upstream was 305 ng/g dw, whereas it decreased significantly to a mean value of 6.9 ng/g dw in YP sediment downstream. This variation can be ascribed to multiple factors. Firstly, the hydrophobic nature of the OPEs renders them susceptible to adsorption onto particulate matter. Previous studies have indicated that the content of OPEs in suspended particulates in the Minjiang River is significantly higher than that in water and sediment (Yin et al. 2021). Secondly, the interception action of the cascade reservoirs enhances the sedimentation of suspended particle matter, leading to the accumulation of OPEs in sediments. Additionally, the type of reservoir regulation also influences the accumulation of OPEs in sediment. Based on the findings of this study, it was observed that the content of OPEs in sediments were higher in the reservoirs characterized by longer HRTs than in those with shorter HRTs. Reservoirs can exacerbate pollution due to the increase in

water residence, settling of suspended particles, and OPE build-up in sediment (Kumwimba et al. 2022).

The sediment samples from the study area exhibited distinct seasonal diversity in the content of OPEs, with July (mean 346 ng/g dw) > October (mean 226 ng/g dw) > January (mean 186 ng/g dw) > April (mean 135 ng/g dw) being the overall trend. This pattern aligns with the findings in Hangzhou Bay, where the OPE content ratios in sediments were higher during the summer than during autumn (Dou et al. 2022). Similar to OPEs, TCEP, TCIPP, TDCIPP, TPHP, and TMPP displayed comparable seasonal distribution patterns (Fig. S1). This observation can be attributed to the increased precipitation during the summer season. OPE deposition from atmospheric particles is an important approach to sedimentation (Ma et al. 2022). Pan et al. (2022) found that OPEs in atmospheric particulates in summer affected by rainfall are significantly less than those in winter. In addition to atmospheric deposition, OPEs enter the reservoirs through wastewater treatment plant (WWTP) effluents, riverine runoff, and so on (Rodgers et al. 2018; Wang et al. 2015). Moreover, the accumulation of OPEs in sediments can be attributed to upstream sources for transporting OPEs, which are subject to runoff brought by summer rainfall (Li et al. 2017; Ma et al. 2022).

The accumulation of OPEs in sediment can be ascribed to the greater deposition of OPEs originating from atmospheric particulate matter or the transportation of OPEs from upstream sources. Additionally, the seasonal thermal stratification of the reservoirs may exert an influence on the redistribution of OPEs. The most pronounced thermal stratification was observed in July, impeding the vertical mixing and exchange of substances between the upper and lower water layers. The condition of the bottom water deteriorated, leading to a decrease in the dissolved oxygen (DO) to its minimum level. This change in the redox conditions of surface

Fig. 2 The cumulative content of the eight OPEs (ng/g dw) in sediments from each individual sampling site during January, April, July, and October 2017



sediments resulted in an increased presence of oxidized organic pollutants known as transparent exopolymer particles (TEP), due to their release from the water column (Chen et al. 2019). In contrast, the dissipation of thermal stratification in reservoirs led to a sudden decrease in temperature, prompting the mixing of the oxygen-rich cold-water mass in the upper water column with the anaerobic water mass in the lower section. This vigorous exchange between the upper and lower water bodies disrupted the sediment, resulting in the discharge of secondary organic pollutants (Dueri et al. 2009). Consequently, this may be the reason for the decreased content of OPEs in surface sediments of the reservoir during the colder season.

3.2 Socioeconomic impact on the distribution of OPEs

This study gathered economic evaluation indicators from the regions hosting the seven reservoirs in 2017 in order to examine the impact of regional socioeconomic activities on the distribution of OPEs (Table S5). These indicators include the gross domestic product (GDP), primary industry index (PI), secondary industry index (SI), tertiary industry index (TI), and population activity (PA) (Text S3). Significant positive correlations ($P < 0.05$) were observed between the OPEs and various economic indicators including GDP, SI, TI, and PA in the study area (Fig. S2). Among these indicators, PA and SI were found to have the most influence on the OPEs. Previous studies conducted in China (Pearl River, South China Sea, Haihe River) and Japan (Tokyo Bay) also reported significant correlations between OPEs and local per capita GDP and SI (Lai et al. 2019). Notably, chlor-OPEs exhibited positive correlations with economic factors, with TCEP demonstrating the strongest correlation ($P < 0.01$) with GDP, SI, and PA. In contrast, the alkyl-OPEs and aryl-OPEs showed a lower correlation with economic evaluation indicators. In particular, TEP demonstrated no significant correlation with GDP, PI, SI, TI, or PA. This suggests that the distribution of the OPEs in sediment is influenced by a multitude of factors. The alteration of natural organic matter composition and sorption kinetics is among plausible explanations. There is a negative correlation between OPEs and $\log K_{ow}$ ($P = 0.02$, see Fig. S3). Moreover, chlor-OPEs are more persistent than alkyl- and aryl-OPEs in the environment, and with higher production and consumption in recent decades in China (Li et al. 2019b; Ji et al. 2022). OPEs are predominantly derived from anthropogenic sources (Cao et al. 2012; Liu et al. 2018), with pollution levels intricately linked to the actions of the local populace and the industrial sectors operating in the region. The content of sedimentary OPEs in tributaries near industrial agglomeration is obviously higher than that in other sampled locations in Taihu basin (Chen et al. 2018; Zhou et al. 2016). Cao et al. (2017) found a statistically significant correlation between urban

distance and OPEs in sediments in the Great Lakes of the United States, indicating that the content of OPEs at locations near urban and industrialized areas was higher. In this study, the high content of sedimentary OPEs in DF (site 7) and WJD located near Guiyang City suggests that OPEs in these sampling sites originated from human activities. In addition, there are several OPE producers located around the middle and upper reaches of the WJR, producing 100,000 t of OPEs annually with chlor-OPEs. It can be speculated that the discharge of industrial wastewater leads to higher levels of sedimentary TCEP (Fan et al. 2023). However, the distribution of highly water-soluble Cl-OPEs tends to dissolve in water (Cristale et al. 2013; Liu et al. 2018). TCEP in the present study is quite high, suggesting that much higher concentrations tend to be distributed in the water. WJR serves as a water source for the surrounding population, and the fact that these compounds can remain in drinking water is of great concern for human exposure and human health risk.

3.3 Hydrological impact on the distribution of OPEs

3.3.1 Hydrodynamic effects

OPEs were found to be widely distributed in sediments, with content ranging from 0.04 to 3866 ng/g dw in various surface water systems, including estuaries, rivers, and lakes (Table S1). In river and estuary systems with active hydrodynamics, the OPE content in sediments showed an increasing trend with longer HRT. Specifically, OPE content in rivers ($0.31\text{--}3867$ ng/g dry weight, mean 91.3 ± 271 ng/g dry weight) was higher than in estuarine areas ($0.12\text{--}470$ ng/g dry weight, mean 34.1 ± 66.8 ng/g dry weight). In the lake systems with the longest HRT, OPE content ($0.04\text{--}3804$ ng/g dry weight, 76.0 ± 377 ng/g dry weight) fell between that of rivers and estuaries (Fig. 4). The same trend was shown in this study: seasonal regulation reservoirs (674 ± 768 ng/g dry weight) > daily regulation reservoirs (18.6 ± 24.3 ng/g dry weight), while annual regulation reservoirs had OPE content (248 ± 267 ng/g dry weight) between that of seasonal and daily regulation reservoirs, particularly for the highest chlorinated OPEs (Cl-OPEs) (Fig. 3a, b). The distribution of OPEs in sediments was also influenced by HRT, as depicted in Fig. 3a–d. Furthermore, the sedimentary OPE content in reservoirs was significantly higher than that in estuary, lake, and river systems (Fig. 4). This could be attributed to several factors, the first of which is the hydrodynamic effect on the accumulation and differentiation of OPEs in sediments. With the weakening of hydrodynamic force, the accumulation of OPEs in sediments increased. Second, OPEs adsorb to suspended particles and accumulate as they settle by dam interception (Huang et al. 2024; Yin et al. 2021). Notably, as a tributary of the Yangtze River in the middle reaches, the content of sedimentary OPEs in the WJR is significantly

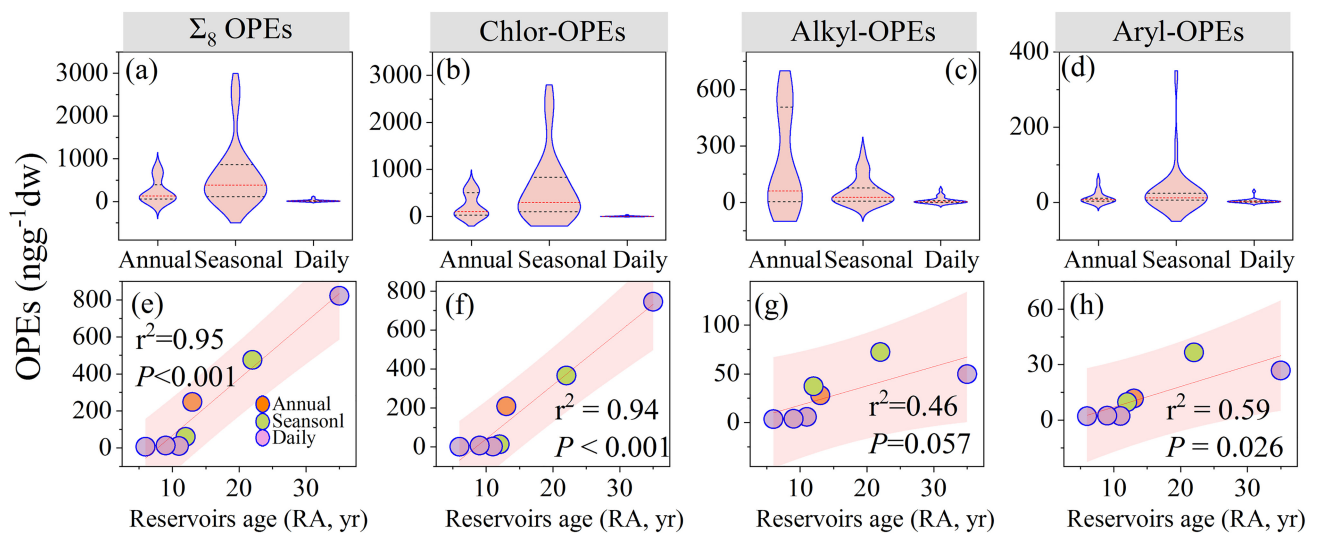


Fig. 3 The relationship between hydrological characteristics and OPEs (ng/g dw) in the study area. **a–d** Distribution of OPEs (ng/g dw) in reservoirs of different regulation types (Annual = annual regulation reservoir, refers to HJD; Seasonal = seasonal regulation reservoir, includes DF and WJD; Daily = daily control reservoir, includes SFY, SL, PS, and YP); **e–h** correlation between reservoir age (RA, years) and OPEs (ng/g dw)

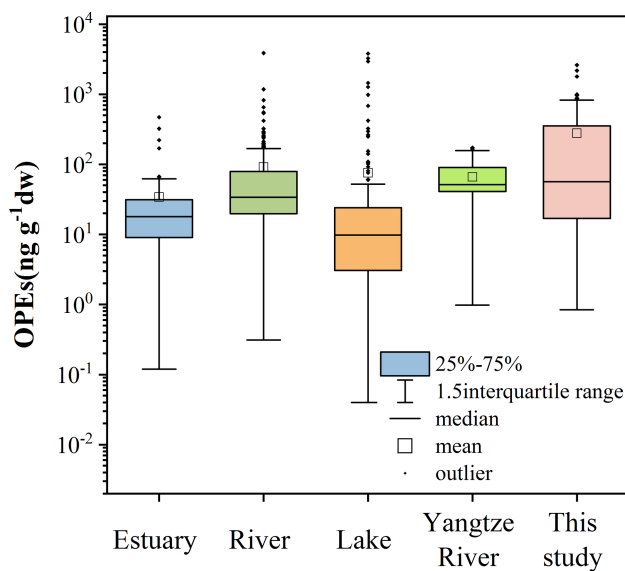


Fig. 4 Comparison and classification of the OPEs (ng/g dw) in sediment from terrestrial water systems with previous studies

higher than that in the Yangtze River (mean 65.9 ± 43.9 ng/g dw), intercepted by the cascade damming effect, which indicates a classification of high pollution levels. Third, the variations observed in OPEs from different sediment types can be attributed to the specific properties of individual compounds as well as the characteristics of the sediment itself. Specifically, the alkyl-OPE content exhibited an increasing trend with longer HRT, while the aryl-OPE content showed no significant difference at lower levels (Fig. 3c, d). These

findings indicate that alkyl-OPEs and aryl-OPEs, which were relatively stable, pose challenges for degradation (Dang et al. 2023). They tend to accumulate with the weakening of hydrodynamic force by dam blocking. In contrast, Cl-OPEs have high water solubility (Huang et al. 2024); the lower the hydrodynamic force, the higher the Cl-OPE saturation in water. The greater input of Cl-OPEs precipitated into the sediment and accumulated. However, in tranquil water bodies, such as lakes and annually regulated reservoirs, thermal stratification alters the redox conditions in the water phase, promoting the release of Cl-OPEs into the water from sediment. The content of chlor-OPEs in reservoirs with longer HRT showed a decreasing trend, which may be caused by microbial degradation (Ye et al. 2024). With the extension of HRT, the enhanced thermal stratification effect accelerated the dechlorination of sulfate-reducing bacteria in the anaerobic environment at the bottom of the water column, increasing the degradation of chlor-OPEs (Badea et al. 2009).

3.3.2 Effect of sedimentary organic matter

Reservoir age (RA) is an important factor affecting the maturity of sedimentary organic matter (Bao et al. 2025). With the growth of RA, the aging, porosity, and polymer organic matter in the sediments increased, which accelerated the adsorption and retention rate of OPEs (Skic et al. 2023), reducing the availability of OPEs to microorganisms. Therefore, the positive correlation between RA and OPEs in reservoirs (Fig. 3e–h), especially chlor-OPEs ($P < 0.001$), also confirmed this conclusion. Moreover, the presence of TOC in sediment plays a crucial role in influencing the behavior

of pollutants (Fang et al. 2022), as one of the important evaluation indexes of sedimentary organic matter. It has been established that when the TOC in sediment exceeds 0.1%, it becomes the primary medium for the distribution of hydrophobic organic pollutants (Chiou et al. 1998; Morillo et al. 2007; Chen et al. 2017). The analysis of sediment data collected from different water systems, including estuary, rivers, and lakes, revealed a robust nonlinear relationship between OPEs and TOC in sediments ($r = 0.63$, $P < 0.01$) (Fig. 5), as in reservoirs of WJR ($r = 0.67$, $P < 0.01$) (Fig. S4). Specifically, a positive correlation between OPEs and TOC was observed when the TOC was below 2.5%. However, as the TOC surpassed 2.5%, the OPEs exhibited a decreasing pattern with increasing TOC. This phenomenon can be attributed to multiple factors. First, the presence of organic matter played a significant role in the adsorption of OPEs in sediment with low TOC levels (Cristale et al. 2017). The adsorption capacity by TOC increased with higher $\log K_{OW}$ values (Liu et al. 2016; Pang et al. 2013, 2016). Secondly, as the TOC levels in the sediment increased, the proportion of autochthonous labile organic matter gradually became more prominent. Notably, the presence of aquatic plants has been observed to substantially facilitate the removal of tris-(2-chloroisopropyl) phosphate (TCPP) from wetland sediments (Qin et al. 2020). Thirdly, the loading and subsequent degradation processes of autochthonous organic matter resulted in anaerobic and weakly

acidic reducing conditions at the sediment–water interface, thereby expediting the degradation of OPEs. Saint et al. (2011) reported that reduced sulfur promotes the elimination of TCEP under anoxic conditions. Finally, the presence of autochthonous organic matter in sediment has the potential to act as co-metabolic substrates for the microbial degradation of OPEs. It has been observed that increased loading of organic matter promotes the degradation of OPEs. The introduction of organic matter to anaerobic sewage sludge can greatly enhance the efficiency of OPE biodegradation through microbial co-metabolism (Pang et al. 2018). Zhang et al. (2023) further substantiated the role of organic acids as co-metabolic substrates in iron-containing environments, enhancing the removal rate of polycyclic aromatic hydrocarbons. Therefore, changes in the composition and environmental conditions of sedimentary organic carbon emerged as pivotal factors influencing the occurrence and conversion of OPEs.

3.3.3 The model of sedimentary OPEs in reservoirs

In this study, the influence of economic factors and reservoir hydrological factors cannot be ignored. Based on GDP (billion yuan) and RA (years), the multi-factor regression model of OPEs in reservoir sediments was established as follows:

$$\sum_8 \text{OPEs} = 64.772 \ln(\text{GDP}) + 26.488 \text{RA} - 389.891 \quad (r^2 = 0.96, P = 0.001). \quad (2)$$

In this model, this study found that GDP and RA are positive feedback for hydrophobic OPE accumulation in the reservoir. With economic development and the extension of reservoir operation period, OPEs in sediment are increasing, which poses a serious risk to the environment. This phenomenon is more prominent as more reservoirs are built. The parameters selected in this model (GDP, RA) are easy to obtain, and also provide a new idea for the direction of treatment for sedimentary OPEs. In summary, this model can quickly assess the occurrence of OPEs in reservoir sediments, and provide a basis for policies governing the control of OPEs pollution in reservoirs.

3.4 Ecological risk assessment

This study assessed the potential ecological risks of the eight OPEs in the study area. This assessment was based on the calculated risk quotient (RQ) values, considering both median and high exposure scenarios (Fig. 6). The average RQs obtained for the OPEs in sediments ranged from 1.4×10^{-5} to 5.68, exhibiting noticeable seasonal variations. The RQ values for TCIPP, TEP, and TEHP were below 0.1,

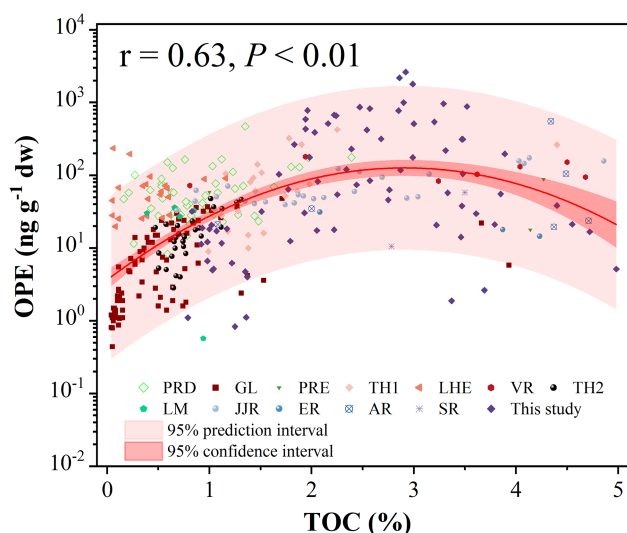


Fig. 5 The relationship between OPEs (ng/g dw) and TOC (%) in sediment samples from surface water sources around the world. Note: PRD (Pearl River Delta, Tan et al. 2016), GL (Great Lakes, Cao et al. 2017), PRE (Pearl River Estuary, Hu et al. 2017), TH1 (Taihu, Liu et al. 2018), LHE (Liao River estuary, Luo et al. 2020), VR (Vaal River, Chokwe and Okonkwo 2019), TH2 (Taihu, Wang et al. 2018), LM (Luoma Lake, Xing et al. 2018), JJR (Jinjiang River, Hou et al. 2019), ER, AR, and SR (Evrotas, Adige, and Sava; Giulivo et al. 2017)

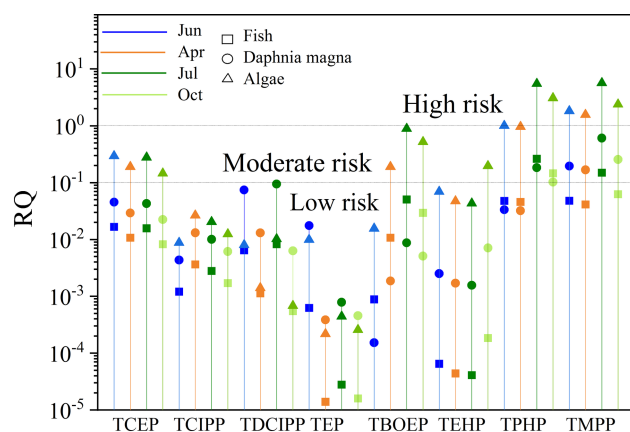


Fig. 6 RQ of the eight OPEs (ng/g dw) from sediments in this study

indicating no significant risk to aquatic organisms (Blair et al. 2013). However, it was observed that TPHP and TMPP, owing to their greater toxicity (lower PNEC), were present in relatively low content, thereby indicating high ecological risk, with average RQ values exceeding 1. TCEP, despite its high exposure, posed minimal risk to *Daphnia magna* and fish, as indicated by average RQ values below 0.1, while demonstrating moderate risk to algae, with RQ values ranging from 0.1 to 1. Similarly, TBOEP showed moderate risk to algae, with average RQ values falling between 0.1 and 1. In particular, 58.8% of the samples had RQ values below 0.1, indicating low ecological risk, while the RQ value of the eight OPEs varied from 0.01 to 7.1 (Fig. S5), with a median of 0.09. Four reservoirs located in the middle reaches had RQ values greater than 1 in RQ_{Algae} , indicating that the highest ecological risk had arisen due to OPE content. The presence of abundant organic matter in the sediment is of significance, as its release into the water has the potential to induce secondary pollution in aquatic organisms by introducing toxic contaminants. Considering the potential exposure of aquatic organisms to the cumulative toxicity of different compound mixtures, the situation necessitates ongoing attention.

4 Conclusion

This study examined the presence of eight OPEs in sediment samples collected from seven cascade reservoirs belonging to the WJR basin. The findings of this investigation revealed that distribution of OPEs is influenced by various direct factors, including the region's GDP, population activity, and regional industry ($P < 0.05$), implying the increasing contribution of anthropogenic activities. Reservoir characteristics (HRT and RA, $P < 0.05$) are key factors affecting sedimentary OPEs. This is because the HRT and RA affect

the biogeochemical process of sedimentary organic matter, which makes the distribution of OPEs more complicated. An empirical model containing the parameters GDP and RA was established to predict OPEs in reservoir sediments with high accuracy ($r^2 = 0.96$), underscoring the importance of these factors in water quality management, which can provide a mathematical basis and treatment direction for reservoir pollution management. Notably, although reservoirs with different regulation types were selected in this work, the number is limited, and more long-term measurement data are lacking. Ultimately, an assessment of the ecological risk revealed potential adverse effects for aquatic organisms, with specific emphasis on TMPP and TPHP. The prosperity of industry and human activity in the WJR is accompanied by the large yield and flow of OPEs. Therefore, the management of OPE contaminants needs to focus on the emission source and reduce the transport in river ecosystems. In addition, periodic monitoring of OPEs in drinking water sources for WJR is critical.

Author contributions XL: conceptualization, data curation, formal analysis, software, writing—original draft, review & editing; YW: conceptualization, data curation, formal analysis, investigation, methodology, project administration, writing—review & editing, XL and YW contributed equally; YQ: data curation, formal analysis, investigation, writing—review; YC: data curation, formal analysis, investigation, Writing—review; XC and MY: conceptualization, investigation, writing—review; JM and FW: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, writing—review & editing.

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Data availability All data that support the findings of this study are included in this manuscript and its supplementary information files.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose. All authors declare no competing interests.

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References

- Badea SL, Vogt C, Weber S, Danet AF, Richnow HH (2009) Stable isotope fractionation of γ -hexachlorocyclohexane (lindane) during reductive dechlorination by two strains of sulfate-reducing

- bacteria. *Environ Sci Technol* 43(9):3155–3161. <https://doi.org/10.1021/es801284m>
- Bao YF, Wang YC, Hu MM, Hu P, Wu NP, Qu XD, Liu XB, Huang W, Wen J, Li SZ, Sun M, Zhang Q (2025) Deciphering the impact of cascade reservoirs on nitrogen transport and nitrate transformation: insights from multiple isotope analysis and machine learning. *Water Res* 268:122638. <https://doi.org/10.1016/j.watres.2024.122638>
- Blair BD, Crago JP, Hedman CJ, Klaper RD (2013) Pharmaceuticals and personal care products found in the Great Lakes above concentrations of environmental concern. *Chemosphere* 93(9):2116–2123. <https://doi.org/10.1016/j.chemosphere.2013.07.057>
- Cai L, Shi YW, Pan CY, Zhu F, Wang SQ, Dai JJ, Yang M, Ma J (2022) Occurrence, distribution, and risk of organophosphate flame retardants in sediments from Jiulong River Estuary and adjacent western Taiwan strait, China. *Int J Environ Res Public Health* 19(4):2449. <https://doi.org/10.3390/ijerph19042449>
- Cao SX, Zeng XY, Song H, Li HR, Yu ZQ, Sheng gY, Fu JM, (2012) Levels and distributions of organophosphate flame retardants and plasticizers in sediment from Taihu Lake, China. *Environ Toxicol Chem* 31(7):1478–1484. <https://doi.org/10.1002/etc.1872>
- Cao DD, Guo JH, Wang YW, Li ZN, Liang K, Corcoran MB, Hosseini S, Bonina SMC, Rockne KJ, Sturchio NC, Giesy JP, Liu JF, Li A, Jiang gB, (2017) Organophosphate esters in sediment of the great lakes. *Environ Sci Technol* 51(3):1441–1449. <https://doi.org/10.1021/acs.est.6b05484>
- Chen WX, Wu XY, Zhang HY, Sun JT, Liu WX, Zhu LZ, Li XD, Tsang DCW, Tao S, Wang XL (2017) Contamination characteristics and source apportionment of methylated PAHs in agricultural soils from Yangtze River Delta, China. *Environ Pollut* 230:927–935. <https://doi.org/10.1016/j.envpol.2017.07.035>
- Chen MH, Liu YH, Guo RX, Xu HZ, Song NH, Han ZH, Chen NN, Zhang SH, Chen JQ (2018) Spatiotemporal distribution and risk assessment of organophosphate esters in sediment from Taihu Lake, China. *Environ Sci Pollut Res Int* 25(14):13787–13795. <https://doi.org/10.1007/s11356-018-1434-3>
- Chen MQ, Gan ZW, Qu B, Chen SB, Dai YY, Bao XM (2019) Temporal and seasonal variation and ecological risk evaluation of flame retardants in seawater and sediments from Bohai Bay near Tianjin, China during 2014 to 2017. *Mar Pollut Bull* 146:874–883. <https://doi.org/10.1016/j.marpolbul.2019.07.049>
- Chen QW, Chen YC, Lin YQ, Zhang JY, Ni JR, Xia J, Xiao L, Feng T, Ma HH (2024) Does a hydropower reservoir cascade really harm downstream nutrient regimes. *Sci Bull* 69(5):661–670. <https://doi.org/10.1016/j.scib.2024.01.007>
- Chiou CT, McGroddy SE, Kile DE (1998) Partition characteristics of polycyclic aromatic hydrocarbons on soils and sediments. *Environ Sci Technol* 32(2):264–269. <https://doi.org/10.1021/es970614c>
- Chokwe TB, Okonkwo JO (2019) Occurrence, distribution and ecological risk assessment of organophosphorus flame retardants and plasticizers in sediment samples along the Vaal River catchment, South Africa. *Emerg Contam* 5:173–178. <https://doi.org/10.1016/j.emcon.2019.05.003>
- Cristale J, García Vázquez A, Barata C, Lacorte S (2013) Priority and emerging flame retardants in rivers: Occurrence in water and sediment, *Daphnia Magna* toxicity and risk assessment. *Environ Int* 59:232–243. <https://doi.org/10.1016/j.envint.2013.06.011>
- Cristale J, Álvarez-Martín A, Rodríguez-Cruz S, Sánchez-Martín MJ, Lacorte S (2017) Sorption and desorption of organophosphate esters with different hydrophobicity by soils. *Environ Sci Pollut Res Int* 24(36):27870–27878. <https://doi.org/10.1007/s11356-017-0360-0>
- Dang Y, Tang KX, Wang ZH, Cui HP, Lei JQ, Wang DH, Liu N, Zhang XD (2023) Organophosphate esters (OPEs) flame retardants in water: a review of photocatalysis, adsorption, and biological degradation. *Molecules* 28(7):2983. <https://doi.org/10.3390/molecules28072983>
- Di Toro DM, Zarba CS, Hansen DJ, Berry WJ, Swartz RC, Cowan CE, Pavlou SP, Allen HE, Thomas NA, Paquin PR (1991) Technical basis for establishing sediment quality criteria for nonionic organic chemicals using equilibrium partitioning. *Environ Toxicol Chem* 10(12):1541–1583. <https://doi.org/10.1002/etc.5620101203>
- Dou WK, Zhang ZM, Huang W, Wang XN, Zhang RR, Wu YY, Sun AL, Shi XZ, Chen J (2022) Contaminant occurrence, spatiotemporal variation, and ecological risk of organophosphorus flame retardants (OPFRs) in Hangzhou Bay and East China Sea ecosystem. *Chemosphere* 303:135032. <https://doi.org/10.1016/j.chemosphere.2022.135032>
- Dueri S, Castro-Jiménez J, Zaldívar JM (2009) Modelling the influence of thermal stratification and complete mixing on the distribution and fluxes of polychlorinated biphenyls in the water column of Ispra Bay (Lake Maggiore). *Chemosphere* 75(9):1266–1272. <https://doi.org/10.1016/j.chemosphere.2009.01.066>
- Fan JX, Yang JX, Cheng FL, Zhang SK (2023) The source, distribution, and environmental effects of suspended particulate matter in the Yangtze River system. *Water* 15(19):3429. <https://doi.org/10.3390/w15193429>
- Fang LD, Liu AF, Zheng MG, Wang L, Hua Y, Pan X, Xu HY, Chen XF, Lin YF (2022) Occurrence and distribution of organophosphate flame retardants in seawater and sediment from coastal areas of the East China and Yellow Seas. *Environ Pollut* 302:119017. <https://doi.org/10.1016/j.envpol.2022.119017>
- Giulivo M, Capri E, Kalogianni E, Milacic R, Majone B, Ferrari F, Eljarrat E, Barceló D (2017) Occurrence of halogenated and organophosphate flame retardants in sediment and fish samples from three European river basins. *Sci Total Environ* 586:782–791. <https://doi.org/10.1016/j.scitotenv.2017.02.056>
- Guo JX, Xie Y, Guan AM, Qi WX, Cao XF, Peng JF, Liu HJ, Wu XH, Li C, Wang DC, Qu JH (2023) Dam construction reshapes sedimentary pollutant distribution along the Yangtze River by regulating sediment composition. *Environ Pollut* 316:120659. <https://doi.org/10.1016/j.envpol.2022.120659>
- Han Q, Wang BL, Liu CQ, Wang FS, Peng X, Liu XL (2018) Carbon biogeochemical cycle is enhanced by damming in a Karst river. *Sci Total Environ* 616–617:1181–1189. <https://doi.org/10.1016/j.scitotenv.2017.10.202>
- Hou L, Jiang JY, Gan ZW, Dai YY, Yang P, Yan Y, Ding SL, Su SJ, Bao XM (2019) Spatial distribution of organophosphorus and brominated flame retardants in surface water, sediment, groundwater, and wild fish in Chengdu, China. *Arch Environ Contam Toxicol* 77(2):279–290. <https://doi.org/10.1007/s00244-019-00624-x>
- Hu YX, Sun YX, Li X, Xu WH, Zhang Y, Luo XJ, Dai SH, Xu XR, Mai BX (2017) Organophosphorus flame retardants in mangrove sediments from the Pearl River Estuary, South China. *Chemosphere* 181:433–439. <https://doi.org/10.1016/j.chemosphere.2017.04.117>
- Huang MY, Zeng LJ, Wang C, Zhou X, Peng Y, Shi CL, Wang SS, Li Y, Barceló D, Li H (2024) A comprehensive and quantitative comparison of organophosphate esters: Characteristics, applications, environmental occurrence, toxicity, and health risks. *Crit Rev Environ Sci Technol*. <https://doi.org/10.1080/10643389.2024.2406587>
- Ji BJ, Liu Y, Wu Y, Liang Y, Gao ST, Zeng XY, Yao P, Yu ZQ (2022) Organophosphate esters and synthetic musks in the sediments of the Yangtze River Estuary and adjacent East China Sea: Occurrence, distribution, and potential ecological risks. *Mar Pollut Bull* 179:113661. <https://doi.org/10.1016/j.marpolbul.2022.113661>
- Jia XB, Luo WY, Wu XQ, Wei HB, Wang BL, Phyo W, Wang FS (2017) Historical record of nutrients inputs into the Xin'an Reservoir and its potential environmental implication. *Environ*

- Sci Pollut Res 24(25):20330–20341. <https://doi.org/10.1007/s11356-017-9537-9>
- Kumwimba MN, Bao LL, Jie ZS, Li XY, Huang JL, Wang W, Li XZ, Su JJ, Muyembe DK, Guide A, Dzakpasu M (2022) Nutrients retention of a series of small dam-impacted urban rivers in northern China. *J Environ Chem Eng* 10(3):107967. <https://doi.org/10.1016/j.jece.2022.107967>
- Lai NLS, Kwok KY, Wang XH, Yamashita N, Liu GJ, Leung KMY, Lam PKS, Lam JCW (2019) Assessment of organophosphorus flame retardants and plasticizers in aquatic environments of China (Pearl River Delta, South China Sea, Yellow River Estuary) and Japan (Tokyo Bay). *J Hazard Mater* 371:288–294. <https://doi.org/10.1016/j.jhazmat.2019.03.029>
- Li SX, Zhou LF, Wang HJ, Liang YG, Chang JB, Xiong MH, Zhang YC, Hu JX (2009) Feeding habits and habitats preferences affecting mercury bioaccumulation in 37 subtropical fish species from Wujiang Rive, China. *Ecotoxicology* 18(2):204–210. <https://doi.org/10.1007/s10646-008-0273-2>
- Li RL, Liang J, Duan HL, Gong ZB (2017) Spatial distribution and seasonal variation of phthalate esters in the Jiulong River estuary, South East China. *Mar Pollut Bull* 122(1–2):38–46. <https://doi.org/10.1016/j.marpolbul.2017.05.062>
- Li HR, La Guardia MJ, Liu HH, Hale RC, Mainor TM, Harvey E, Sheng gY, Fu JM, Peng PA, (2019a) Brominated and organophosphate flame retardants along a sediment transect encompassing the Guiyu, China e-waste recycling zone. *Sci Total Environ* 646:58–67. <https://doi.org/10.1016/j.scitotenv.2018.07.276>
- Li J, Wang J, Taylor AR, Cryder Z, Schlenk D, Gan J (2019b) Inference of organophosphate ester emission history from marine sediment cores impacted by wastewater effluents. *Environ Sci Technol* 53(15):8767–8775. <https://doi.org/10.1021/acs.est.9b01713>
- Lian MS, Lin CY, Li Y, Hao X, Wang AH, He MC, Liu XT, Ouyang W (2022) Distribution, partitioning, and health risk assessment of organophosphate esters in a major tributary of middle Yangtze River using Monte Carlo simulation. *Water Res* 219:118559. <https://doi.org/10.1016/j.watres.2022.118559>
- Lin J, Chen XW, Wang T, Zhou HL, Guo HT, Lin WM, Han YH, Tong P, Zhang H, Zhang Y (2024) Unveiling the occurrence and ecological risks of organophosphate esters in seawater of the northern South China Sea. *Environ Technol Innov* 36:103798. <https://doi.org/10.1016/j.eti.2024.103798>
- Liu YH, Song NH, Guo RX, Xu HZ, Zhang Q, Han ZH, Feng MJ, Li D, Zhang SH, Chen JQ (2018) Occurrence and partitioning behavior of organophosphate esters in surface water and sediment of a shallow Chinese freshwater lake (Taihu Lake): Implication for eco-toxicity risk. *Chemosphere* 202:255–263. <https://doi.org/10.1016/j.chemosphere.2018.03.108>
- Liu SL, Zhang H, Hu XH, Qiu YL, Zhu ZL, Zhao JF (2016) Analysis of organophosphate esters in sediment samples using gas chromatography-tandem mass spectrometry. *Chin J Anal Chem* 44(2):192–197 (in Chinese). <https://doi.org/10.11895/j.issn.0253-3820.150600>
- Luo Q, Gu LY, Wu ZP, Shan Y, Wang H, Sun LN (2020) Distribution, source apportionment and ecological risks of organophosphate esters in surface sediments from the Liao River, Northeast China. *Chemosphere* 250:126297. <https://doi.org/10.1016/j.chemosphere.2020.126297>
- Ma C, Xu R, He W, Xia JJ (2020) Determining the limiting water level of early flood season by combining multiobjective optimization scheduling and copula joint distribution function: A case study of Three Gorges Reservoir. *Sci Total Environ* 737:139789. <https://doi.org/10.1016/j.scitotenv.2020.139789>
- Ma YX, Luo YC, Zhu JC, Zhang JH, Gao GP, Mi WY, Xie ZY, Lohmann R (2022) Seasonal variation and deposition of atmospheric organophosphate esters in the coastal region of Shanghai. *China Environ Pollut* 300:118930. <https://doi.org/10.1016/j.envpol.2022.118930>
- Marklund A, Andersson B, Haglund P (2003) Screening of organophosphorus compounds and their distribution in various indoor environments. *Chemosphere* 53(9):1137–1146. [https://doi.org/10.1016/S0045-6535\(03\)00666-0](https://doi.org/10.1016/S0045-6535(03)00666-0)
- Miao XY, Hao YP, Cai JW, Xie YC, Zhang JR (2023) The distribution, sources and health risk of polycyclic aromatic hydrocarbons (PAHs) in sediments of Liujiang River Basin: A field study in typical karstic river. *Mar Pollut Bull* 188:114666. <https://doi.org/10.1016/j.marpolbul.2023.114666>
- Morillo E, Romero AS, Maqueda C, Madrid L, Ajmone-Marsan F, Grcman H, Davidson CM, Hursthouse AS, Villaverde J (2007) Soil pollution by PAHs in urban soils: a comparison of three European Cities. *J Environ Monit* 9(9):1001–1008. <https://doi.org/10.1039/b705955h>
- Pan X, Liu AF, Zheng MG, Liu JX, Du M, Wang L (2022) Determination and environmental risk assessment of organophosphorus flame retardants in sediments of the South China Sea. *Environ Sci Pollut Res Int* 29(46):70542–70551. <https://doi.org/10.1007/s11356-022-20752-7>
- Pang L, Liu JF, Yin YG, Shen MH (2013) Evaluating the sorption of organophosphate esters to different sourced humic acids and its effects on the toxicity to *Daphnia Magna*. *Environ Toxicol Chem* 32(12):2755–2761. <https://doi.org/10.1002/etc.2360>
- Pang L, Yuan YT, He H, Liang K, Zhang HZ, Zhao JH (2016) Occurrence, distribution, and potential affecting factors of organophosphate flame retardants in sewage sludge of wastewater treatment plants in Henan Province, Central China. *Chemosphere* 152:245–251. <https://doi.org/10.1016/j.chemosphere.2016.02.104>
- Pang L, Ge LM, Yang PJ, He H, Zhang HZ (2018) Degradation of organophosphate esters in sewage sludge: Effects of aerobic/anaerobic treatments and bacterial community compositions. *Bioresour Technol* 255:16–21. <https://doi.org/10.1016/j.biortech.2018.01.104>
- Pantelaki I, Voutsas D (2019) Organophosphate flame retardants (OPFRs): A review on analytical methods and occurrence in wastewater and aquatic environment. *Sci Total Environ* 649:247–263. <https://doi.org/10.1016/j.scitotenv.2018.08.286>
- Park N, Jeon J (2021) Emerging pharmaceuticals and industrial chemicals in Nakdong River, Korea: identification, quantitative monitoring, and prioritization. *Chemosphere* 263:128014. <https://doi.org/10.1016/j.chemosphere.2020.128014>
- Qin P, Lu SY, Liu XH, Wang gQ, Zhang YX, Li DL, Wan ZF, (2020) Removal of tri-(2-chloroisopropyl) phosphate (TCPP) by three types of constructed wetlands. *Sci Total Environ* 749:141668. <https://doi.org/10.1016/j.scitotenv.2020.141668>
- Rodgers TFM, Truong JW, Jantunen LM, Helm PA, Diamond ML (2018) Organophosphate ester transport, fate, and emissions in Toronto, Canada, estimated using an updated multimedia urban model. *Environ Sci Technol* 52(21):12465–12474. <https://doi.org/10.1021/acs.est.8b02576>
- Saint-Hilaire D, Ismail KZ, Jans U (2011) Reaction of tris(2-chloroethyl)phosphate with reduced sulfur species. *Chemosphere* 83(7):941–947. <https://doi.org/10.1016/j.chemosphere.2011.02.040>
- Shi WQ, Qin BQ (2023) Sediment and nutrient trapping by river dams: a critical review based on 15-year big data. *Curr Pollut Rep* 9(2):165–173. <https://doi.org/10.1007/s40726-023-00258-7>
- Shi YF, Zhang Y, Du YM, Kong DG, Wu QH, Hong YG, Wang Y, Tam NFY, Leung JYS (2020) Occurrence, composition and biological risk of organophosphate esters (OPEs) in water of the Pearl River Estuary, South China. *Environ Sci Pollut Res Int* 27(13):14852–14862. <https://doi.org/10.1007/s11356-020-08001-1>

- Skic K, Boguta P, Klimkowicz-Pawlas A, Ukalska-Jaruga A, Baran A (2023) Effect of sorption properties on the content, ecotoxicity, and bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) in bottom sediments. *J Hazard Mater* 442:130073. <https://doi.org/10.1016/j.jhazmat.2022.130073>
- Tan XX, Luo XJ, Zheng XB, Li ZR, Sun RX, Mai BX (2016) Distribution of organophosphorus flame retardants in sediments from the Pearl River Delta in South China. *Sci Total Environ* 544:77–84. <https://doi.org/10.1016/j.scitotenv.2015.11.089>
- Wang FS (2020) Impact of a large sub-tropical reservoir on the cycling of nutrients in a river. *Water Res* 186:116363. <https://doi.org/10.1016/j.watres.2020.116363>
- Wang BL, Liu CQ, Wang FS, Liu XL, Wang ZL (2015) A decrease in pH downstream from the hydroelectric dam in relation to the carbon biogeochemical cycle. *Environ Earth Sci* 73(9):5299–5306. <https://doi.org/10.1007/s12665-014-3779-3>
- Wang XL, Zhu LY, Zhong WJ, Yang LP (2018) Partition and source identification of organophosphate esters in the water and sediment of Taihu Lake, China. *J Hazard Mater* 360:43–50. <https://doi.org/10.1016/j.jhazmat.2018.07.082>
- Wang WF, Yi YB, Zhong J, Kumar A, Li SL (2020a) Carbon biogeochemical processes in a subtropical Karst river–reservoir system. *J Hydrol* 591:125590. <https://doi.org/10.1016/j.jhydrol.2020.125590>
- Wang X, Zhu QQ, Yan XT, Wang YW, Liao CY, Jiang gB, (2020b) A review of organophosphate flame retardants and plasticizers in the environment: analysis, occurrence and risk assessment. *Sci Total Environ* 731:139071. <https://doi.org/10.1016/j.scitotenv.2020.139071>
- Wang WF, Li SL, Zhong J, Maberly SC, Li C, Wang FS, Xiao HY, Liu CQ (2020c) Climatic and anthropogenic regulation of carbon transport and transformation in a Karst river–reservoir system. *Sci Total Environ* 707:135628. <https://doi.org/10.1016/j.scitotenv.2019.135628>
- Wu YL, Wang XH, Ya ML, Li YY, Liu YH, Chen HZ (2020) Spatial-temporal distribution and transport flux of polycyclic aromatic hydrocarbons in a large hydropower reservoir of Southeast China: Implication for impoundment impacts. *Environ Pollut* 257:113603. <https://doi.org/10.1016/j.envpol.2019.113603>
- Wu FX, Wang JF, Jiang SH, Zeng HX, Wu QX, Chen Q, Chen JG (2022a) Effect of cascade damming on microplastics transport in rivers: a large-scale investigation in Wujiang River, Southwest China. *Chemosphere* 299:134455. <https://doi.org/10.1016/j.chemosphere.2022.134455>
- Wu JH, Zhang YF, Song L, Yang M, Liu X, Yu JH, Liang gZ, Zhang YM, (2022b) Occurrence and dry deposition of organophosphate esters in atmospheric particles above the Bohai Sea and northern Yellow Sea, China. *Atmos Environ* 269:118831. <https://doi.org/10.1016/j.atmosenv.2021.118831>
- Xing LQ, Zhang Q, Sun X, Zhu HX, Zhang SH, Xu HZ (2018) Occurrence, distribution and risk assessment of organophosphate esters in surface water and sediment from a shallow freshwater Lake, China. *Sci Total Environ* 636:632–640. <https://doi.org/10.1016/j.scitotenv.2018.04.320>
- Xu KH, Milliman JD (2009) Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. *Geomorphology* 104(3–4):276–283. <https://doi.org/10.1016/j.geomorph.2008.09.004>
- Yadav IC, Devi NL, Li J, Zhang g, Covaci A, (2018) Concentration and spatial distribution of organophosphate esters in the soil–sediment profile of Kathmandu Valley, Nepal: implication for risk assessment. *Sci Total Environ* 613:502–512. <https://doi.org/10.1016/j.scitotenv.2017.09.039>
- Yan ZF, Feng CL, Leung KMY, Luo Y, Wang JD, Jin XW, Wu FC (2023) Insights into the geographical distribution, bioaccumulation characteristics, and ecological risks of organophosphate esters. *J Hazard Mater* 445:130517. <https://doi.org/10.1016/j.jhazmat.2022.130517>
- Yang MD, Li XD, Huang J, Ding SY, Cui GY, Liu CQ, Li QK, Lv H, Yi YB (2020) Damming effects on river sulfur cycle in Karst area: a case study of the Wujiang cascade reservoirs. *Agric Ecosyst Environ* 294:106857. <https://doi.org/10.1016/j.agee.2020.106857>
- Yang YJ, Wang WF, Yu SD, Yi YB, Xu S, Yao YZ, Zhong J, Shi WH, Chen SN, Wu QX, Ou ZH, Ding H, Li SL (2025) Seasonal variations and hydrological management regulate nutrient transport in cascade damming: Insights from carbon and nitrogen isotopes. *Water Res* 271:122894. <https://doi.org/10.1016/j.watres.2024.122894>
- Ye JM, Tang SY, Qiu RL, Chen SN, Liu HL (2024) Biodegradation pathway and mechanism of tri (2-chloropropyl) phosphate by *Providencia rettgeri*. *J Environ Sci* 144:26–34. <https://doi.org/10.1016/j.jes.2023.07.023>
- Yin HL, Liu Q, Deng X, Liu XW, Fang SH, Xiong YM, Song JJ (2021) Organophosphate esters in water, suspended particulate matter (SPM) and sediments of the Minjiang River, China. *Chin Chem Lett* 32(9):2812–2818. <https://doi.org/10.1016/j.ccl.2021.02.023>
- Yin YP, Zhang W, Cao X, Chen XM, Tang JY, Zhou YX, Li QM (2023) Evaluation of sediment phosphorus dynamics in cascade reservoir systems: a case study of Wei Yuan River, China. *J Environ Manag* 346:118980. <https://doi.org/10.1016/j.jenvman.2023.118980>
- Zeng XY, Xu L, Hu QP, Liu Y, Hu JF, Liao WS, Yu ZQ (2020) Occurrence and distribution of organophosphorus flame retardants/plasticizers in coastal sediments from the Taiwan Strait in China. *Mar Pollut Bull* 151:110843. <https://doi.org/10.1016/j.marpolbul.2019.110843>
- Zha DP, Li Y, Yang CM, Yao C (2018) Assessment of organophosphate flame retardants in surface water and sediment from a freshwater environment (Yangtze River, China). *Environ Monit Assess* 190(4):222. <https://doi.org/10.1007/s10661-018-6587-5>
- Zhang Q, Wang YX, Jiang XX, Xu HZ, Luo YQ, Long TT, Li J, Xing LQ (2021) Spatial occurrence and composition profile of organophosphate esters (OPEs) in farmland soils from different regions of China: Implications for human exposure. *Environ Pollut* 276:116729. <https://doi.org/10.1016/j.envpol.2021.116729>
- Zhang QY, Wang Y, Zhang C, Yao YM, Wang L, Sun HW (2022) A review of organophosphate esters in soil: Implications for the potential source, transfer, and transformation mechanism. *Environ Res* 204:112122. <https://doi.org/10.1016/j.envres.2021.112122>
- Zhang L, Ni LF, Wang H, Zhang ZC, Wu YC, Jia RM, He JY, Zhu ZH, Jin HY, Ren X, Zhang DD (2023) Higher ecological risks and lower bioremediation potentials identified for emerging OPEs than legacy PCBs in the Beibu Gulf, China. *Environ Res* 231:116244. <https://doi.org/10.1016/j.envres.2023.116244>
- Zhao BL, Zeng QH, Wang JH, Jiang YZ, Liu H, Yan L, Yang ZF, Yang Q, Zhang FB, Tang JX, Hu P (2024) Impact of cascade reservoirs on nutrients transported downstream and regulation method based on hydraulic retention time. *Water Res* 252:121187. <https://doi.org/10.1016/j.watres.2024.121187>
- Zhou LJ, Zhang BB, Zhao YG, Wu QL (2016) Occurrence, spatiotemporal distribution, and ecological risks of steroids in a large shallow Chinese lake, Lake Taihu. *Sci Total Environ* 557:68–79. <https://doi.org/10.1016/j.scitotenv.2016.03.059>

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