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PAPER

Review: Micro-organic contaminants in groundwater in China

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Abstract

Micro-organic contaminants (MOs) in groundwater, which may have adverse effects on human health and ecosystems worldwide, are gaining increased attention in China. A great deal of research has been conducted to investigate their sources, occurrences and behavior in aquifers. This paper reviews the main sources, distribution, concentrations and behavior of a wide range of MOs in groundwater in China. These MOs include well-established persistent organic pollutants—polycyclic aromatic hydrocarbons (PAHs), hexachlorocyclohexanes (HCHs), polychlorinated biphenyls (PCBs), endocrine disrupting chemicals (poly brominated diphenyl ethers (PBDEs), phthalic acid esters (PAEs), bisphenol A (BPA)—and some contaminants of emerging concern such as pharmaceutical and personal care products (antibiotics, caffeine, shampoos) and perfluorinated compounds (PFCs). The results reveal that the main MOs in groundwater are PAHs, organochlorine pesticides (OCPs), PBDEs, PAEs, and antibiotics. Moreover, some PFCs such as perfluorobutane sulfonic acid (PFBS), perfluorobutanoic acid (PFBA) and perfluorooctanoic acid (PFOA) have only recently been observed in groundwater as emerging organic contaminants. Additionally, most MOs are distributed in populated and industrialized areas such as the southeast coast of China. Finally, industrial emissions, wastewater treatment plant effluents and agricultural wastewater are found to be dominant sources of MOs in groundwater. Based on the existing pollution levels, regulation and amelioration of MOs are warranted.

Keywords Contamination · Groundwater · Environmental behavior · Review · China

Introduction

With rapid industrialization, micro-organic contaminants (MOs) and emerging organic contaminants (EOCs) have attracted a great deal of attention. Micro-organic contaminants are organic substances that have numerous sources (e.g. pesticides, hormones, drug residues, personal care products, flame retardants, surfactants and engineered nano-materials) in the environment (Manamsa et al. 2016b; Stuart et al. 2012; Stuart and Dan 2013; Jurado et al. 2012; Lapworth et al. 2012), while emerging organic contaminants are compounds newly found in the environment that were not previously detectable or thought to be significant (Stuart and Dan 2013). Most of these organic contaminants can impede biological behavior such as the synthesis, storage, secretion and transport processes of the related hormones. In recent years, analytical methods, environmental fate, and contamination control have been the focus of considerable research in the field of environmental hydrogeology—for example, the addition of some pollutants, such as perfluorooctane sulfonate (PFOS), perfluorooctane sulfonamide (PFOSA), perfluorooctane sulfonyl fluoride (PFOSF), polybrominated diphenyl ethers (PBDEs), and endosulfans, to the Stockholm Convention (2009, 2011) list presented new challenges for research regarding persistent organic pollutants and pollution control.

Currently, the pollution status of organic contaminants in groundwater is being widely investigated because of advanced technologies and global concern for the environment. When compared to surface water, pollutants in groundwater may be detrimental for longer periods of time. This is because the underground redox and degradation conditions make these

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MOs more persistent and difficult to eliminate (Lapworth et al. 2012; Peng et al. 2014); moreover, MOs in groundwater may accumulate in crops and humans through plant growth and consumption of groundwater, respectively. Human activities have increased the prevalence of various MOs in the environment (Adeel et al. 2016; Koroša et al. 2016; Jurado et al. 2012; Wang et al. 2015).

Globally, many studies have focused on the occurrences and concentrations of MOs in groundwater, as well as their impacts on the biosphere (Stuart and Dan 2013; Balakrishna et al. 2016; Adeel et al. 2016; Jurado et al. 2012; Houtz et al. 2013; Giesy et al. 2010). High concentrations and different types of MOs (antibiotics, pesticides, estrogens, etc.) have been detected in groundwater in several countries, including the United States, England (UK), Germany, India, Iran, Spain, Slovenia, and France (Balakrishna et al. 2016; Boiteux et al. 2012; Dodgen et al. 2016; Javid et al. 2016; Menchen et al. 2017; Mali et al. 2017; Reh et al. 2013; Stuart et al. 2014). The first systematic review of MOs in groundwater was conducted by Lapworth et al. (2012). Several subsequent studies reviewed MOs in groundwater as well as specific regional research (Lapworth et al. 2015; Koroša et al. 2016; Pitarch et al. 2016; Schaider et al. 2014) and sampling and analysis methods (Mali et al. 2017; Mirasole et al. 2016; Locatelli et al. 2016). In recent studies, pharmaceutical and personal care products have been reported in groundwater from the United States, India, Spain, and Slovenia (Balakrishna et al. 2016; Dodgen et al. 2016; Koroša et al. 2016; Menchen et al. 2017). The concentrations of detectable MOs in groundwater from the aforementioned regions were: ND (not detectable)–0.142, 0.021–28, 0.001–0.9, and 0.004–0.273 μg/L, respectively. While progress has been made with respect to regional investigation and detection and analysis techniques, the overall distribution and spatio-temporal variations of most MOs are still poorly understood (Balakrishna et al. 2016); therefore, it is important to continue to identify new MOs and work towards improving appropriate monitoring strategies.

Currently, the Chinese government is paying increasing attention to the pollution problems associated with MOs in the water environment. Since the Stockholm Convention on Persistent Organic Pollutants (POPs) in 2001, China has been faced with the challenges of implementing the conditions agreed in the convention and of managing the pollutants. A series of research projects have been sponsored by the National Natural Science Foundation of China since 1998 to explore the impacts of various MOs on humans and the environment. In May of 2001, more than 90 countries worldwide, including China, signed the Stockholm Convention on POPs and, by 2013, China had initiated production capacity for substitute pesticide POPs. A pilot plant has been built to develop substitutes for decabromodiphenyl ether, responding to the National '863' High Tech Program in China on substitute products and technologies of precedent-controlled POPs (Wang et al. 2013a, b). In 2015, the Ministry of Environmental Protection and the World Bank jointly launched a project designed to reduce and eliminate PFOS/PFOSF from priority industries, and this project has been ongoing in the electroplating and pesticide industry in Guangdong and Hubei provinces. Significant progress with respect to data availability and technological developments in China has facilitated studies of analysis methods, environmental behavior, ecotoxicology, and environmental risk assessment of new POPs found in the environment. Researchers from the environmental analysis and toxicology research group of the State Key Laboratory of Environmental Chemistry and Ecotoxicology at the Chinese Academy of Sciences have conducted a range of studies to understand regional pollution features, biological enrichment, long-distance migration, and toxicological effects, and to undertake ecological and human health risk assessments associated with PBDEs, short chain chlorinated paraffins (SCCPs), and perfluorinated compounds (PFCs). In particular, the identification of previously unknown MOs (new brominated flame retardants, polyfluorinated iodine alkanes (PFIs), benzotriazole UV stabilizer (BZTs), etc.) has received a great deal of attention (Wang et al. 2013a, b).

In China, groundwater resources account for about one-third of the total water resources. Nearly 70% of the population uses groundwater as a source of drinking water. However, about 60% of groundwater in China is reportedly seriously polluted (National Land Resources Bulletin in China, 2015). To date, most studies on MOs in China have focused on the regional pollution status or reviewed specific pollutants in groundwater (Kong et al. 2016a, b; Zhang et al. 2014; Xu et al. 2013; Wang et al. 2010). To better understand the pollution status of MOs in groundwater in China, this article reviews the occurrences and sources of well-established MOs and EOCs in groundwater and discusses their behavior in the subsurface environment. Finally, the paper presents a preliminary summary of existing concerns and the prospects of future work for promoting further research on MOs in groundwater.

Sources of MOs

The primary sources of MOs in the environment are municipal sewage treatment plants, wastewater discharge from hospitals and pharmaceutical factories, chemical plants, emissions from high-tech industries, drinking-water disinfection by-products, food additives, metal plating, textile treatment, and leachate from landfills and agricultural nonpoint source pollution (Liu et al. 2017; Wang et al. 2013a, b; Stuart and Dan 2013; Loos et al. 2009). Generally, environmental MOs come from all production and consumption processes associated with industry, agriculture and daily life, and then migrate to groundwater

via different pathways. The main sources of MOs and their pathways into groundwater are presented in Fig. 1.

Different pollution pathways exist for MOs entering the groundwater environment, some of which continue to be in the investigatory phase because of diverse pollutant characteristics and intricate subsurface environments. Currently, the major reported pathways of pollutants include eluviation (farmland, storage tank, landfill, and septic tank), industrial discharge and leaking municipal sewers (Table 1); moreover, pollutants are widespread in the subsurface environment because of anthropogenic activities. As shown in Table 1, the groundwater from southeastern coastal cities in China has multiple types of MOs.

Recent occurrences of MOs in groundwater

A series of studies published since 2004 that reported MOs in groundwater in China were reviewed. Most study areas were distributed in southeastern regions or other developed and populated cities.

Well-established micro-organic contaminants

Persistent organic pollutants (POPs)

Persistent organic pollutants are natural or synthetic toxic organic pollutants that can persist in the environment for long periods and migrate long-distances or accumulate in humans (Loos et al. 2009). The existence of POPs has been investigated globally for many years, and it is known that those in groundwater primarily originate from municipal sewage, industrial wastewater, municipal landfills, petrochemical pollution, and agricultural application of chemicals (Luo et al. 2016). Currently, the most thoroughly researched POPs (OCPs, PCBs, PAHs, and dioxins) are those that were classified as top priority pollutants at the Stockholm Convention (Mu et al. 2016). Among OCPs, DDTs and HCHs have been widely utilized in agricultural activities because of their low cost and high insecticidal effectiveness.

Current research on POPs is primarily focused on the detection of pollutants in groundwater and the process of contaminant transportation in China. Most reported areas of POPs pollution are distributed in the developed southern industrial and agricultural areas, as well as the southwestern karst regions, where aquifers are relatively vulnerable to pollution. In eastern China, regions of intensive industrialization have been found to be responsible for extensive discharge of POPs into the water environment.

Analysis of groundwater samples collected from the Pearl River Delta region (Huang et al. 2008) indicated widespread distribution of a variety of OCPs—hexachlorobenzene (HCB), HCHs, DDTs, heptachlor epoxide, aldrin and dieldrin—in groundwater; however, their concentrations were generally low. In Nanning, fluoranthene, pyrene, and HCHs were found in offshore groundwater by Kong et al. (2016a), who concluded that they originated from industrial and domestic coal combustion, historical polluted soil, and aquifer runoff. A variety of OCPs (p, p′-DDT, α-HCHs, γ-HCHs, δ-HCHs, heptachlor epoxide, p, p′-DDE, and p, p′-DDD) were found in representative groundwater from typical functional areas in Hangzhou (Yu et al. 2007), and it was speculated that landfill leachate and effluent discharge of industrial and mining enterprises were the main sources of these pollutants.

In central and northern populated areas of China, industrial and mineral construction and agricultural developments have resulted in widespread application of various chemicals—for example, based on analysis of groundwater data collected in 2014 and 2015, groundwater quality at a chemical site in Hebei province was surveyed (Kang et al. 2016). In that study, o-toluidine reached a maximum detection rate of 36.99%, followed by 16.44% for aniline and 15.07% for phenol. Additionally, aniline and 2, 4-dichlorophenol were detected at the highest concentrations of 1,620 and 144 μg/L, respectively. A study conducted in the southern plain of the Huaihe River basin (Shandong) showed that halohydrocarbon, OCPs,

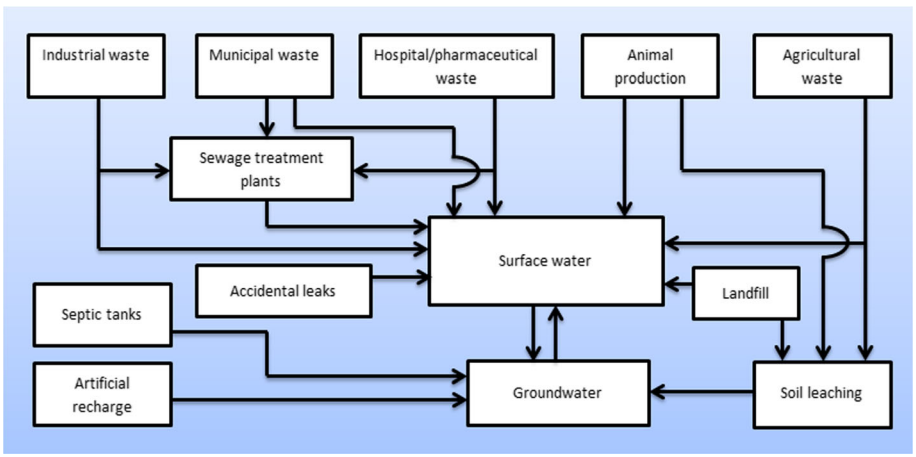

Fig. 1 Sources and pathways for groundwater pollution by MOs

Table 1 Sources and possible pathways of MOs in groundwater in China

Sources	Compounds	Pathways	Examples: town (compound and concentration range)	Reference
Rivers	PAEs, BPA, estrogens, PBDEs, HCHs	Infiltration of river water to subsurface water; industrial discharge; eluviation	Wuhan (DEHP, ND–278.6 ng/L; DBP, ND–812.2 ng/L); Beijing (EDCs, 1–390 ng/L); Nanning (FIL, ND–38.2 ng/L; Pyr, ND–29.3 ng/L; HCHs, ND–55.3 ng/L)	Wang et al. (2009), Li et al. (2013a), Kong et al. (2016a, b)
Rural areas	PBDEs, BPA, PCBs, PAHs, carbamazepine, halohydrocarbon, sulfa antibiotics, ASs, PFOS, diethyltoluamide, PFOA, PFBA	Eluviation; karstic fissure; surface-water seepage	Inner Mongolia (BDE209, 5.3 μg/L); Shenyang (PCBs, 0.03–5.89 ng/L; OCPs, 0.17–21.2 ng/L); Ji'nan (OCPs, 2–179 ng/L; PAHs, 1.2–317 ng/L); Xuzhou (BPA, 26.45 ng/L); Guangzhou (salicylic acid, ND–2014.7 ng/L; methyparaben, ND–83.2 ng/L); Qingyuan (PPCPs, 0.68–3.14 ng/L); Yangzhou (PFOA, 18.3 ng/L); Changshu (PFBA, 58.5 ng/L)	Shan et al. (2013), Luo et al. (2011), Xu et al. (2009), Du et al. (2016), Peng et al. (2014), Gan (2014), Huang et al. (2016), Ding (2015), Chen et al. (2016)
Urban areas	PCBs, PPCPs, OCPs, PFOS, trimethylchlorotin, PFOA, PFNA, PFHpA, PFHxA, PFHxS	Industrial discharge; eluviation; surface-water seepage	Chongqing (HCHs, 39.14 ng/L; DDTs, 24.99 ng/L); Yueyang (OCPs, ND–185.6 ng/L); Guizhou (HCHs, 14.87–21.38 ng/L; DDTs, 12.55–16.21 ng/L); Guangzhou (PPCPs, 1.9–28.09 ng/L; PFOA, 7.76 ng/L; PFHpA, 1.492 ng/L); Dongguan (PPCPs, ND–2.67 ng/L); Foshan (PPCPs, 0.60–23.72 ng/L; PFHxA, 0.676 ng/L);	Xu et al. (2013), Qiu et al. (2008), Yu et al. (2007), Huang et al. (2008), Zhang et al. (2014), Ding (2015); Liu (2014)
Industrial areas	Trichloroethane, caffeine, PFOS, sulpiride, ketoprofen, metoprolol, BPA, nalidixic acid, estrone, halohydrocarbon, PAHs, OCPs, PFOA, PFBS, PFHpA	Industrial discharge; eluviation; wastewater seepage; artificial groundwater recharge with reclaimed water	Hangzhou (acenaphthenylidene, 1660 ng/L; acenaphthene, 99.12 ng/L); Jiangmen (PPCPs, ND–33.54 ng/L); Nanyang (EDCs, ND–12.63 ng/L); Changzhou (EDCs, > 20 ng/L); Ji'nan (EDCs, > 20 ng/L); Fuxin (PFOA, 524 ng/L; PFBS, 872 ng/L); Dongguan (PFNA, 1.274 ng/L)	Yu et al. (2007), Ding (2015), Li et al. (2015); Bao et al. (2011); Liu (2014)

PAEs phthalate esters; *BPA* bisphenol A; *DEHP* diethylhexyl phthalate; *DBP* dibutyl phthalate; *HCHs* hexachloro-cyclohexane; *FIL* fluoranthene; *Pyr* pyrene; *PCBs* polychlorinated biphenyls; *ASs* artificial sweeteners; *DDTs* dichloro-diphenyl-trichloroethane; *PFOA* perfluorooctanoic acid; *PFNA* perfluorononanoic acid; *PFBS* perfluorobutane sulfonate; *PFBA* perfluorobutanoic acid; *PFHpA* perfluoroheptanoic acid; *PFHxA* perfluorohexanoic acid; *PFHxS* perfluorohexane sulfonate; *ND* not detectable

and PAHs existed in shallow groundwater (Zhu et al. 2014). Among 210 sampled wells, the most commonly detected organic pollutants were PAHs, with rates of 5.71, 5.71, 4.29, 3.33 and 2.86% being observed for naphthalene, fluorine, pyrene, phenanthrene, and fluoranthene, respectively. In northeast Liaoning province, PCBs and OCPs were detected at relatively high detection rates (77.8 and 100%, respectively) in groundwater of the Xihe River basin (Luo et al. 2011); however, their concentrations were below the standards for drinking-water quality of the People's Republic of China (GB5749 2006).

The presence of POPs in karst spring basins has also been widely investigated in China. PAHs and OCPs are the most frequently detected pollutants in spring water from Huozhou, Ji'nan, Chongqing, Guangxi, Yunnan, and Guizhou (Shao 2014; Xu et al. 2013; Wei et al. 2011; Zhang et al. 2011a; Hu et al. 2010; Sun 2012). In general, the concentrations of organic pollutants in karst groundwater are relatively low. Systematic sampling and analysis of karst groundwater conducted in the Ji'nan spring system indicated that the detection rates of OCPs and halohydrocarbon categories were 60 and 57.8%, respectively. Among 45 sampled wells, two water

samples had organic contents (carbon tetrachloride and PAHs) over the limits of the standards for drinking-water quality of the People's Republic of China (GB5749- 2006; Xu et al. 2009).

In the aforementioned studies, the most commonly reported compounds were fluoranthene, naphthalene, phenanthrene, HCHs, and DDTs; for commonly reported OCPs, the concentrations were lower than 300 ng/L. The maximum concentration was selected for comparison since it was the most prevalent reference value. The study plots the results with selected interval data (10–300 ng/L) on account of the long span of data. The concentrations and distributions of these POPs in groundwater are presented in Fig. 2 (original data for histogram were provided in Table 2.

Endocrine disrupting chemicals (EDCs)

The United States Environmental Protection Agency (USEPA) has defined environmental EDCs as the disruption of "synthesis, secretion, transport, binding, action, or elimination of natural hormones in the body that are responsible for the maintenance of homeostasis, reproduction, development, and/or behavior" (USEPA 1997). Currently, increasing amounts of EDCs (e.g. PAEs, PBDEs, BPA) are released into groundwater through artificial groundwater recharge, atmospheric sedimentation, surface runoff, and soil leaching (Li et al. 2013a, 2015; Wang and Zhang 2005). Furthermore, water shortages have led to use of reclaimed water containing EDCs for irrigation and groundwater recharge, which can introduce EDCs to soil or groundwater (Li et al. 2013b). In recent years, a wide variety of EDCs have been reported in groundwater environments. Research regarding EDCs in groundwater primarily pertains to first-tier cities and densely populated second-tier cities in China. Most studies conducted to date have reported concentration distributions, sources of pollution, and ecological risk assessments.

In Beijing, spatial and seasonal variations of EDCs in confined and unconfined aquifers recharged using Chaobai River water, which originated from reclaimed water, were studied (Li et al. 2013a). Bisphenol A, estrone (E1), 17α-ethinyl estradiol (EE2), 17β-estradiol (E2), and estriol (E3) were detected in groundwater, with BPA making the largest contribution to EDCs and being the most frequently detected compound in the unconfined/confined aquifer. In

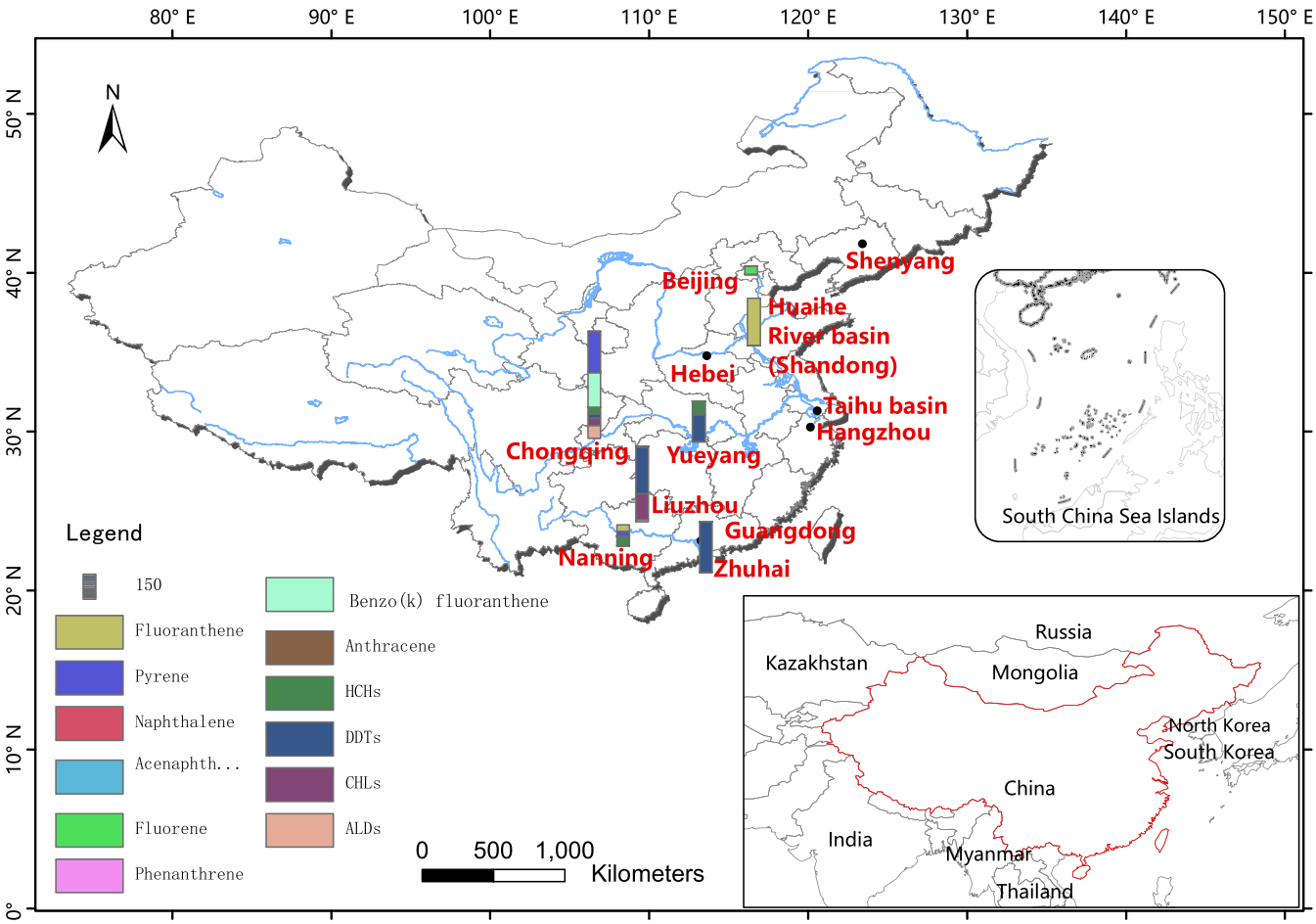

Fig. 2 Maximum concentrations of POPs in groundwater in China

Table 2 POPs concentrations and distribution in groundwater in China

Compound	Region	Lithology/aquifer	Maximum concentration (ng/L)	Reference
PAHs				
Fluoranthene	Nanning	Pore phreatic water	38.2	Kong et al. 2016a
	Chongqing	Karst spring	392.37	Sun 2012
	Hangzhou	Pore phreatic water	57.37	Yu et al. 2007
	Huaihe River basin (Shandong)	Clayey sand	280	Zhu et al. 2014
Pyrene	Nanning	Pore phreatic water	29.3	Kong et al. 2016a
	Chongqing	Karst spring	242.84	Sun 2012
	Hangzhou	Pore phreatic water	120	Yu et al. 2007
Naphthalene	Chongqing	Karst spring	2,440.00	Sun 2012
	Hebei	Silt, silty clay, silty soil	2,800	Kang et al. 2016
	Hangzhou	Pore phreatic water	78.25	Yu et al. 2007
	Huaihe River basin (Shandong)	Clayey sand	170,000	Zhu et al. 2014
	Beijing	–	2,425	Kong et al. 2016b
Acenaphthylene	Chongqing	Karst spring	339.23	Sun 2012
	Hangzhou	Pore phreatic water	99.12	Yu et al. 2007
Acenaphthene	Chongqing	Karst spring	573.25	Sun 2012
	Hangzhou	Pore phreatic water	4,550	Yu et al. 2007
	Huozhou	Karst spring	1,320	Shao 2014
Fluorene	Chongqing	Karst spring	4,289.39	Sun 2012
	Huaihe River basin (Shandong)	Clayey sand	940	Zhu et al. 2014
	Huozhou	Karst spring	2,407	Shao 2014
	Beijing	–	49	Kong et al. 2016b
Phenanthrene	Chongqing	Karst spring	1,524.17	Sun 2012
	Hangzhou	Pore phreatic water	130	Yu et al. 2007
	Huaihe River basin (Shandong)	Clayey sand	910	Zhu et al. 2014
	Huozhou	Karst spring	4,258	Shao 2014
Benzo(k) fluoranthene	Chongqing	Karst spring	208.72	Sun 2012
Anthracene	Hangzhou	Pore phreatic water	69.65	Yu et al. 2007
	Henan	–	>500	Duo et al. 2004
	Huozhou	Karst spring	2,003	Shao 2014
OCPs				
HCHs	Nanning	Pore phreatic water	55.3	Kong et al. 2016a
	Chongqing	Underground river	39.14	Xu et al. 2013
	Liuzhou	Underground river	715.14	Wei et al. 2011
	Yueyang	Phreatic water	80.90	Zhang et al. 2014
	Guangdong	Pore phreatic water	8.11	Huang et al. 2008
	Taihu basin	Phreatic water	450	Li et al. 2007
DDTs	Chongqing	Underground river	24.99	Xu et al. 2013
	Liuzhou	Underground river	279.20	Wei et al. 2011
	Yueyang	Phreatic water	159.00	Zhang et al. 2014
	Shenyang	–	1.20	Luo et al. 2011
	Guangdong	Pore phreatic water	3.41	Huang et al. 2008
	Taihu basin	Phreatic water	1,370	Li et al. 2007
	Zhuhai	–	300	Qiu et al. 2008
	Hangzhou	Pore phreatic water	798	Yu et al. 2007
	Huaihe River basin (Shandong)	Clayey sand	8.3	Zhu et al. 2014

Table 2 (continued)

Compound	Region	Lithology/aquifer	Maximum concentration (ng/L)	Reference
CHLs	Liuzhou	Underground river	153.21	Wei et al. 2011
	Chongqing	Karst spring	42.19	Sun 2012
	Shenyang	–	1.38	Luo et al. 2011
ALDs	Liuzhou	Underground river	12.11	Wei et al. 2011
	Chongqing	Karst spring	78.34	Sun 2012
	Shenyang	–	1.24	Luo et al. 2011
Others				
PCBs	Shenyang	–	5.89	Luo et al. 2011
	Zhuhai	–	93,100	Qiu et al. 2008

CHLs trans-chlordane, cis-chlordane, heptachlor, oxychlordane isomer, heptachlor epoxide; *ALDs* aldrin, isodrin, dieldrin, endrin

Zhuhai, high concentrations of trimethyltin (0.107 mg/L) and total tin (105.4 μg/L) were detected in surficial groundwater (Qiu et al. 2008). These pollutants, especially the hypertoxic trimethyltin are big threats to human health.

Apart from the small-scale districts of the preceding studies, Li et al. (2015) conducted a nation-wide investigation of the occurrence of five EDCs (BPA, EE2, E1, E2, and E3) in reclaimed water and groundwater that originated from reclaimed water. Among 12 cities (Beijing, Baotou, Changzhou, Hefei, Ji'nan, Nantong, Nanyang, Shenyang, Tianjin, Taiyuan, Xi'an and Xi'ning), the total concentrations of EDCs in groundwater ranged between 0.433 and 36.80 ng/L. Moreover, BPA was the dominant compound among EDCs in groundwater, being present at a median concentration of 5.01 ng/L, which was followed by E3 (0.067 ng/L).

Additionally, PAEs and PBDEs have been widely used in plastic products as plasticizers or flame retardants, and several studies have found these compounds in various environmental media (Adams et al. 1995). Representative groundwater samples from the Hutuo River alluvial-proluvial fan in Shijiazhuang (Hebei province), certain counties in Jiangsu province, peripheral areas of Dongguan, and the junction of the Yangtze and Hanjiang rivers in Wuhan have been investigated (Chang et al. 2016; Jiang et al. 2013; Zhang et al. 2011b; Wang et al. 2009), and the results of these studies indicated that high pollution levels occurred largely in the Pearl River Delta and Huaihe River basin. In comparison, the mean concentration (12,245 ng/L) of PAEs in groundwater in Jiangsu province was higher than in other surveyed areas, followed by Dongguan (11,080 ng/L) and Shijiazhuang (ND–28,873.1 ng/L). Among the aforementioned regions, the most commonly detected pollutants were DBP and DEHP. Industrial wastewater, landfills, and plastic products were the main sources of PAEs in groundwater. PBDEs in groundwater in the typical Yellow River water irrigation area of Hetao Plain were also studied (Shan et al. 2013) with BDE209 being the major pollutant and PBDEs released from plastic films comprising a nonignorable source of PBDEs pollution. In 2014, PBDEs in the soil-groundwater system in Taiyuan was studied (Shan 2014), and the main pollutants in the shallow groundwater were BDE47 and BDE28, which also originated from plastic films.

The results from the aforementioned studies indicate that the most commonly reported compounds in groundwater were PBDEs, BPA, and PAEs. To date, the pollution status has been effectively monitored and controlled by governmental regulations in China. With the exception of individual areas (the cities of Wuhan, Shijiazhuang and Guangdong), the detectable concentrations of EDCs in groundwater were usually less than 500 ng/L. The study plots the results with selected interval data (10–1000 ng/L) on account of the long span of data. The proportions and distributions of these EDCs in groundwater are presented in Fig. 3 (original data for histogram were provided in Table 3).

Emerging organic contaminants (EOCs)

Pharmaceutical and personal care products (PPCPS)

Pharmaceutical and personal care products comprise a new type of micro-pollutant with low concentration and multiformity that are difficult to volatize and biodegrade. Sources of PPCPs in the environment include personal care products released from cleaning, bathing, and swimming, original or metabolic products of pharmaceuticals after human or animal intake, and infiltration from landfills containing medical and solid waste. Currently, the major detectable PPCPs in groundwater are antibiotics, anti-inflammatory drugs, psychiatric drugs, β-blockers, environmental estrogens, lipid regulators, and shampoos (Miege et al. 2009; Ratola et al. 2012; Qiu et al. 2016). In China, research regarding PPCPs began in the year 2000 after a related conference was held in North America (USEPA 1999). Most initial studies were conducted in developed coastal or offshore areas.

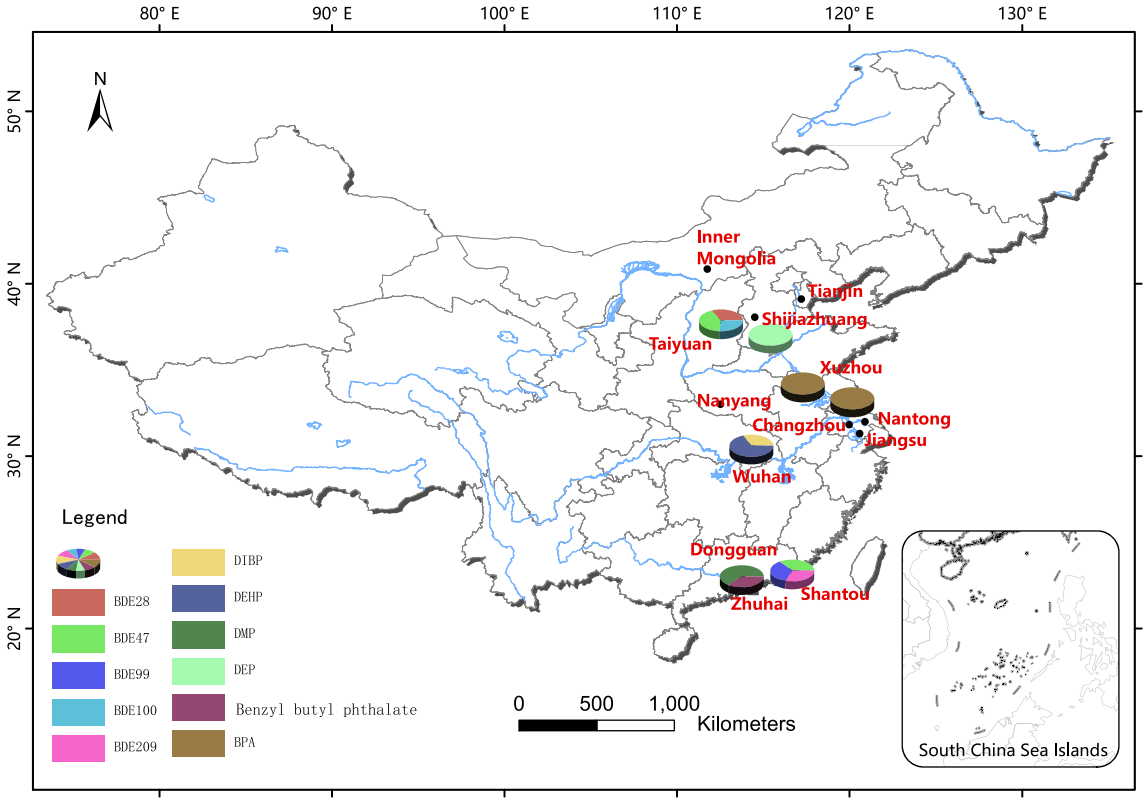

Fig. 3 Proportions of EDCs in groundwater in China

High concentrations of PPCPs have been detected because of their extensive use in the leather, electronic, printing and dyeing, and textile industries (Hu et al. 2005). In recent years, technology for detection of PPCPs has become more accurate, resulting in increased research into their occurrence in groundwater. The total usage of antibiotics in China reportedly reached 162,000 tons in 2013, with those used by humans accounting for 48% and the remainder being veterinary antibiotics (Zhang 2015). In a study by Peng et al. (2014), antibacterial, azole antifungals, pharmaceuticals, and endocrine disrupting PPCPs were detected from groundwater in the vicinity of municipal landfills in Guangzhou; however, the concentrations were generally low (ng/L level), and no significant seasonal differences or spatial distribution laws of pollutants in groundwater were observed. With the exception of landfill leachates, a few home-built septic tanks were inferred as other PPCPs sources. In Guangdong province, the pollution status of PPCPs in groundwater was found to be Guangzhou (1.9–28.09 ng/L) > Foshan (0.6–23.72 ng/L) > Zhongshan (0–12.71 ng/L) > Qingyuan (0.68–3.13 ng/L) > Dongguan (0–2.67 ng/L; Ding 2015). Artificial sweeteners were found in groundwater from rural areas of Tianjin (Gan 2014); they were speculated to originate from sewage irrigation and polluted river water infiltration. In northern China, there have been relatively few studies of PPCPs in groundwater. Sulfa antibiotics were detected in groundwater at a study area in Zhaoyuan county, Heilongjiang province (Zhou 2015), whereas among 11 samples, the detection rate of sulfamethoxazole (SMX) was highest, with concentrations of more than 40 ng/L.

These studies (Peng et al. 2014; Ding 2015; Li et al. 2015; Zhou 2015; Gan 2014; Xu 2014) have shown that the concentrations of PPCPs in groundwater in China were relatively low (e.g. ng/L and μg/L); however, pollutants such as SMX, ofloxacin, erythromycin-H_2O, oxytetracycline, tetracycline, chlortetracycline, roxithromycin, and salicylic acid were still present at significant detectable concentrations in groundwater based on drinking water safety. The species of organic pollutants in groundwater in developed areas such as Guangdong province were found to be more diverse, whereas the contaminant levels of groundwater in Foshan, Qingyuan, Dongguan, Tianjin and Ji'nan were approximately the same. The concentrations and distributions of PPCPs in groundwater are summarized in Table 4.

Perfluorinated compounds (PFCs)

Perfluorinated compounds (PFCs) are a new type of persistent organic pollutant that are widely used in industrial production, consumer products and scientific research products because of their persistence, bio-accumulative properties and potential toxicity (Chen et al. 2016; Taniyasu et al. 2005).

Table 3 EDCs concentrations and distribution in groundwater in China

Compound	Region	Lithology/aquifer	Maximum concentration (ng/L)	Reference
PBDEs				
BDE28	Taiyuan	Pore phreatic water	15.32	Shan 2014
BDE47	Taiyuan	Pore phreatic water	16.89	Shan 2014
	Shantou	–	18.43	Wang et al. 2014
BDE99	Shantou	–	15.12	Wang et al. 2014
BDE100	Taiyuan	Pore phreatic water	11.80	Shan 2014
BDE209	Inner Mongolia	Silty-fine sand	5,300	Shan et al. 2013
	Shantou	–	15.6	Wang et al. 2014
PAEs				
DIBP	Wuhan	Pore phreatic water	237.8	Wang et al. 2009
DBP	Wuhan	Pore phreatic water	1,023.8	Wang et al. 2009
	Shijiazhuang	Pore water	24,579.0	Chang et al. 2016
	Jiangsu	–	32,111.06	Jiang et al. 2013
DEHP	Wuhan	Pore phreatic water	481.0	Wang et al. 2009
	Shijiazhuang	Pore water	2,901.1	Chang et al. 2016
	Dongguan	–	6,200	Zhang et al. 2011b
	Jiangsu	–	10,080.2	Jiang et al. 2013
DMP	Shijiazhuang	Pore water	1,692.2	Chang et al. 2016
	Dongguan	–	800	Zhang et al. 2011b
	Jiangsu	–	1,174.4	Jiang et al. 2013
DEP	Shijiazhuang	Pore water	142.1	Chang et al. 2016
	Dongguan	–	2,100	Zhang et al. 2011b
	Jiangsu	–	2,787.62	Jiang et al. 2013
Benzyl butyl phthalate	Dongguan	–	500	Zhang et al. 2011b
Others				
Trimethyltin	Zhuhai	–	107,000	Qiu et al. 2008
BPA	Xuzhou	Karst water, pore water	26.45	Du et al. 2016
	Changzhou	Loam	35.54	Li et al. 2015
EE2	Nanyang	Sandy soil	0.26	Li et al. 2015
E1	Nantong	Silt, sandy loam	1.08	Li et al. 2015
E2	Taiyuan	Sandy loam	0.11	Li et al. 2015
E3	Tianjin	Loam, sandy loam	2.31	Li et al. 2015

DIBP diisobutyl phthalate; *DMP* dimethyl phthalate; *DEP* diethyl phthalate

Perfluorinated compounds have unique surfactivity, chemical stability, hydrophobicity and lipophobicity. Environmental PFCs are formed from synthetic chemicals and degradation of precursor compounds (Liu 2014). In recent years, perfluorooctanoic acid (PFOA) and PFOS have received increased attention because of their ubiquity in the environment. Although they have been restricted in many developed countries, they are still manufactured or used in certain industries (e.g., metal plating, fire-fighting foams, semiconductors and aviation) to meet the growing demand for surfactants and other surface modification applications in China (Xie et al. 2013). As a result, industrial processes employing PFCs are still a significant source of perfluoroalkyl acids (PFAAs; Wang et al. 2015). Environmental sources of PFCs are considered difficult to identify because of their widespread distribution as a result of mass production, extensive usage and complicated transformation pathways (Qi et al. 2016). The results of the current study revealed that PFCs sources mainly include industrial production—aviation, textile treatment, metal plating, fire-fighting foams and the semiconductor industry (Liu et al. 2017; Xie et al. 2013; Bao et al. 2011)—municipal wastewater treatment plants (WWTPs) and

Table 4 PPCPs concentrations and distribution in groundwater in China

Compound	Region	Lithology/aquifer	Maximum Conc. (ng/L)	Reference
Antibiotics				
Sulfamethoxazole	Guangzhou	Fine-, silt-, and clay-sandstones	124.5	Peng et al. 2014
	Shijiazhuang	–	105.7	Xu 2014
Sulfadiazine	Shijiazhuang	–	46.3	Xu 2014
Trimethoprim	Guangzhou	Fine-, silt-, and clay-sandstones	10.5	Peng et al. 2014
	Guangzhou	Sandstone	1.03	Ding 2015
	Foshan	Sandstone	18.9	Ding 2015
	Qingyuan	Sandstone	2.27	Ding 2015
Ofloxacin	Guangzhou	Fine-, silt-, and clay-sandstones	44.2	Peng et al. 2014
	Shijiazhuang	–	382.2	Xu 2014
Ciprofloxacin	Shijiazhuang	–	26.8	Xu 2014
Norfloxacin	Shijiazhuang	–	32.2	Xu 2014
Enrofloxacin	Shijiazhuang	–	182.2	Xu 2014
Oxytetracycline	Shijiazhuang	–	1364.7	Xu 2014
Tetracycline	Shijiazhuang	–	1082.5	Xu 2014
Chlorotetracycline	Shijiazhuang	–	47,444.5	Xu 2014
Roxithromycin	Shijiazhuang	–	146.2	Xu 2014
Erythromycin-H_2O	Guangzhou	Fine-, silt-, and clay-sandstones	12.4	Peng et al. 2014
Clotrimazole	Guangzhou	Fine-, silt-, and clay-sandstones	1.5	Peng et al. 2014
Chloramphenicol	Guangzhou	Sandstone	2.01	Ding 2015
Nalidixic acid	Dongguan	Sandstone	1.6	Ding 2015
	Foshan	Sandstone	0.63	Ding 2015
	Qingyuan	Sandstone	0.16	Ding 2015
	Ji'nan	Unconfined aquifer	2.7	Li et al. 2015
Sulfa antibiotics	Zhaoyuan	Siltstone, fine sand	98	Zhou 2015
Other drugs				
Ibuprofen	Guangzhou	Fine-, silt-, and clay-sandstones	57.9	Peng et al. 2014
Indomethacin	Guangzhou	Fine-, silt-, and clay-sandstones	11.7	Peng et al. 2014
	Foshan	Sandstone	32.47	Ding 2015
	Qingyuan	Sandstone	0.65	Ding 2015
Naproxen	Guangzhou	Fine-, silt-, and clay-sandstones	86.9	Peng et al. 2014
Salicylic acid	Guangzhou	Fine-, silt-, and clay-sandstones	2014.7	Peng et al. 2014
Clofibric acid	Guangzhou	Fine-, silt-, and clay-sandstones	73.9	Peng et al. 2014
Metoprolol	Guangzhou	Sandstone	1.73	Ding 2015
	Foshan	Sandstone	1.16	Ding 2015
	Qingyuan	Sandstone	0.17	Ding 2015
Sulpiride	Guangzhou	Sandstone	1.21	Ding 2015
	Foshan	Sandstone	1.66	Ding 2015
	Shenyang	Unconfined aquifer	60.1	Li et al. 2015
Propranolol	Guangzhou	Sandstone	0.06	Ding 2015
	Foshan	Sandstone	1.96	Ding 2015
Caffeine	Guangzhou	Sandstone	10.8	Ding 2015
	Dongguan	Sandstone	0.05	Ding 2015
Carbamazepine	Guangzhou	Sandstone	16.85	Ding 2015
	Dongguan	Sandstone	0.05	Ding 2015
Diclofenac	Guangzhou	Sandstone	1.12	Ding 2015
	Dongguan	Sandstone	0.41	Ding 2015
	Foshan	Sandstone	0.61	Ding 2015
	Qingyuan	Sandstone	0.04	Ding 2015
Ketoprofen	Guangzhou	Sandstone	3.08	Ding 2015
	Dongguan	Sandstone	2.08	Ding 2015
	Foshan	Sandstone	0.03	Ding 2015
	Jinan	Unconfined aquifer	4.1	Li et al. 2015
Mefenamic acid	Foshan	Sandstone	0.42	Ding 2015
	Qingyuan	Sandstone	0.07	Ding 2015
	Jinan	Unconfined aquifer	1.1	Li et al. 2015
Sucralose	Tianjin	–	9.6	Gan 2014
Saccharin	Tianjin	–	63	Gan 2014
Sodium cyclamate	Tianjin	–	98	Gan 2014
Acesulfame	Tianjin	–	22	Gan 2014
Personal care products				
Methyparaben	Guangzhou	Fine-, silt-, and clay-sandstones	83.2	Peng et al. 2014
Triclocarban	Guangzhou	Fine-, silt-, and clay-sandstones	36.2	Peng et al. 2014
Diethyltoluamide	Guangzhou	Sandstone	1.51	Ding 2015
	Dongguan	Sandstone	0.05	Ding 2015
	Foshan	Sandstone	0.13	Ding 2015

domestic and farming wastewater in rural areas, as well as atmospheric precipitation (Sun et al. 2011; Chen et al. 2016; Wang and Shih 2011; Wei et al. 2013).

Mass production of PFCs in China began in 2003, and the manufacturers of PFCs are mainly located in central and eastern China (Chen et al. 2016). Investigation of PFCs in China began relatively late, while its development has been remarkably quick in recent years. To date, large numbers of researchers have made achievements in technology enabling their detection in different environmental media, determination of their distribution characteristics, estimation of their sources and emissions, as well as determination of their toxicology to humans and wildlife and risk assessment (Li et al. 2011; Cai et al. 2012; Wang et al. 2012; Zhang et al. 2011c; Zhou et al. 2012). Nevertheless, information regarding the sources and distribution of PFCs in groundwater is limited (Qi et al. 2016).

The consumption of contaminated groundwater is considered an important human exposure route in PFCs-contaminated areas (Bao et al. 2011). Most study areas of PFCs in groundwater in China are in southeast coastal regions that are populated or have intensive industrial activities such as Tianjin, Guangdong, Zhejiang, Shanghai, Shandong and Jiangsu (Chen et al. 2016; Yao et al. 2014; Qi et al. 2016; Bao et al. 2011; Liu 2014; Yan et al. 2015). In general, the concentrations of PFCs, especially PFOS and PFOA, from these areas are much higher than those from inland regions.

A recent investigation of the geographical distribution and characteristic PFCs compositions in groundwater from selected rural areas (Changshu, Tianjin, Yangzhou, Yancheng, Tai'an, Liaocheng) in eastern China showed that the sum of PFCs (ΣPFCs) in groundwater ranged from 5.3 to 615 ng/L (Chen et al. 2016). The PFCs most commonly detected in groundwater were PFBA and PFOA, followed by PFNA, PFHpA, and PFHxA. In addition to domestic sewage, the waste from domestic animal production is another source of PFCs; similarly, PFCs in Tianjin were characterized by Qi et al. (2016) and Yao et al. (2014). Tianjin is one of the fastest growing cities in China, and more than 70% of its water supply comes from groundwater (Dong et al. 2013). In the suburbs of Tianjin, the concentration of ΣPFCs in groundwater was found to be 0.32–8.3 ng/L, with the dominant PFCs being PFBS and PFOA (Qi et al. 2016). It is worth noting that the concentration of PFBS was much greater than the PFOS levels in groundwater because of restriction of the production and application of PFOS by international organizations. This phenomenon also appeared in groundwater in shallow aquifers around a fluorochemical industrial park in Fuxin, northwest Liaoning province. PFBS contributed 62% of the total PFCs at this site (Bao et al. 2011). Analysis of the groundwater around Bohai Bay by Yao et al. (2014) showed that PFOA was the dominant PFCs, being present at concentrations of 0.76–1.46 ng/L, followed by PFHpA and PFHxA. The dominant PFCs in groundwater from Weifang were PFOS, PFBA and PFOA; however, their concentrations differed greatly among samples. Moreover, it was inferred there were extra sources of PFOS in groundwater, as PFOA to PFOS ratios were generally lower than those in river water. According to the results presented in the preceding, the concentrations of PFCs in groundwater were generally higher in the Yangtze River Delta region and showed a decreasing trend from south to north (Chen et al. 2016).

The Pearl River Delta Region has advanced manufacturing and modern service industries. A systematic investigation of PFCs levels in groundwater was conducted in the Pearl River Delta area (urban villages of Guangzhou and Foshan, industrial area of Dongguan and Zhongshan, rural areas of Qingyuan). The results showed that the detection rate of PFCs in 36 samples was 100% and the total concentration of PFCs ranged from 0.056 to 54.067 ng/L. The short-carbon-chain-perfluorinated carboxylic acid and sulfonic acid (e.g., PFOA and PFOS) are the PFCs most commonly detected in groundwater. Overall, the groundwater from the Pearl River Delta had a PFCs concentration approximately the same as the pollution levels in some parts of Japan and Europe (Liu 2014). The maximum concentrations of ΣPFCs in groundwater are presented in Fig.4, while the distributions of individual PFCs are provided in Table 5. .

The behavior of MOs in aquifers

The behavior of MOs in an underground environment depends on their physicochemical properties (hydrophobicity, water solubility (S_w), pH dependent n-octanol/water partition coefficient (D_{ow}), octanol-water partition coefficient (K_{ow}), etc.) and subsurface conditions (groundwater residence time, redox conditions, runoff conditions, acid and alkali conditions, etc.; Jurado et al. 2012; Lapworth et al. 2012; Wells 2006; Xie et al. 2013). Other processes controlling migration of MOs in aquifers include ion exchange, sorption to organic matter, clay minerals and transformation (Lapworth et al. 2012; Blackwell et al. 2007; Loffler and Gembarovic 2005; Drillia et al. 2005). Additionally, the presence of conduits and caves in aquifers makes investigation of pollutant behavior in aquifers complex (Keshavarzi et al. 2017). In this section, studies of physicochemical/hydraulic controls and migration and transformation processes of pollutants in groundwater are reviewed.

Physicochemical/hydraulic controls

The transfer process of MOs in groundwater is partly controlled by physicochemical and hydraulic properties (Worrall and Kolpin 2004; Lapworth et al. 2012). It is commonly understood that groundwater is more likely to be contaminated in

areas with intense surface-water/groundwater interactions—for example, most of the drinking water generally comes from groundwater, especially in north China. Considering the local topography and economy, the majority of wells in China have been built along riversides. Large-scale exploitation of groundwater near rivers has induced river water to recharge groundwater. Consequently, the pollutants from river water have the potential to enter the soil-groundwater system.

In a study of the underground river system in Chongqing (Lan 2014), 2–3 ringed PAHs were found to have higher transport capability and a longer migration distance than 4–6 ringed PAHs. Additionally, 4–6 ringed PAHs can be easily adsorbed by sediments or carbonate rocks because of their high particle affinity adsorption and low solubility. Zhang et al. (2013a, b) found that, from 81 selected reproductive health estrogens, when compared for half-life, K_{oc} (organic carbon adsorption coefficient) was the key parameter influencing the adsorption process of estrogens; therefore, leaching and migration ability was mainly controlled by adsorption. Groundwater samples collected from different depths of aquifers (unconfined aquifer at 30 m, confined aquifer I at 50 m, and confined aquifer II at 80 m) in Beijing were analyzed (Li et al. 2013a), and the K_{ow} of five selected EDCs was found to occur in the order: EE2 > E2 > E1 > BPA > E3, indicating that E3 was the most mobile pollutant. However, the results showed that BPA was the most frequently detected compound in groundwater, followed by E1; moreover, EE2, E2, and E3 were not detected in confined aquifer II. The detection rates of BPA and E1 in confined aquifers indicated that EDCs with relatively lower hydrophobicity may more easily migrate to deeper aquifers. Because of the high hydrophobicity, the mobility of long-chained PFCs is lessened by their sorption to soil; therefore, they can be preferentially removed during infiltration; moreover, the short-chained PFCs are more likely to migrate to groundwater (Ahrens et al. 2009). In research conducted in Shandong (Liu et al. 2016), the average relative abundance of PFBA (C4), PFPeA (C5) and PFHxA (C6) increased by 8.04, 5.05, and 3.92%, respectively, during seepage of perfluoroalkyl acids (PFAAs) from the Dongzhulong River to groundwater, while that of PFHpA (C7) and PFOA (C8) decreased by 0.96 and 15.6%, respectively.

The interaction between surface water and groundwater has also received increasing attention. In a study of POPs in offshore groundwater in Nanning (Kong et al. 2016a), the concentration distributions of fluoranthene and pyrene in groundwater gradually increased with increasing distance from river water, while those of HCHs showed the opposite trend. Kong et al. (2016a) speculated that fluoranthene and pyrene were more easily adsorbed onto suspended solids in the aquifer and bottom sediments of the river than HCHs because of their relatively higher hydrophobicity. As a

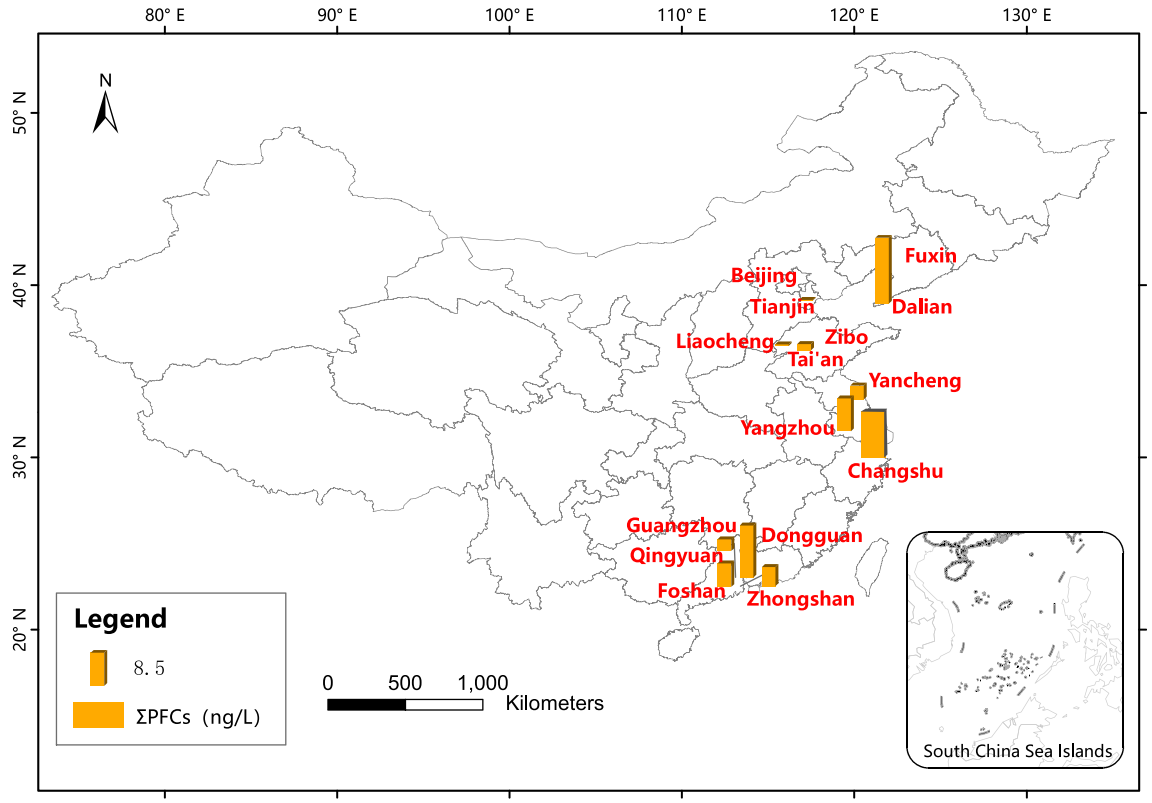

Fig. 4 Total concentrations of PFCs in groundwater in China

Table 5 PFCs concentrations and distribution in groundwater in China

Compound	Region	Maximum concentration (ng/L)	Reference
PFOA	Yangzhou (rural areas)	18.3	Chen et al. 2016
	Yancheng (rural areas)	6.4	Chen et al. 2016
	Changshu (rural areas)	475	Chen et al. 2016
	Tai'an (rural areas)	2.3	Chen et al. 2016
	Liaocheng (rural areas)	0.6	Chen et al. 2016
	Tianjin (rural areas)	0.5	Chen et al. 2016
	Tianjin (suburb)	3.9	Qi et al. 2016
	Zibo (farmland)	239,644	Liu et al. 2016
	Fuxin (FCIP)	524	Bao et al. 2011
	Guangzhou (urban areas)	7.76	Liu 2014
	Dongguan (industrial areas)	6.82	Liu 2014
	Foshan (urban areas)	3.98	Liu 2014
	Zhongshan (industrial areas)	3.98	Liu 2014
	Qingyuan (rural areas)	0.157	Liu 2014
	Beijing	20.3	Gao et al. 2016
PFOS	Zibo (farmland)	37.8	Liu et al. 2016
	Tianjin (suburb)	0.25	Qi et al. 2016
	Fuxin (FCIP)	0.73	Bao et al. 2011
	Guangzhou (urban areas)	4.96	Liu 2014
	Dongguan (industrial areas)	41.4	Liu 2014
	Foshan (urban areas)	3.76	Liu 2014
	Zhongshan (industrial areas)	2.562	Liu 2014
	Qingyuan (rural areas)	0.36	Liu 2014
	Beijing	7.4	Gao et al. 2016
PFBS	Tianjin (suburb)	2.4	Qi et al. 2016
	Fuxin (FCIP)	872	Bao et al. 2011
	Beijing	23.2	Gao et al. 2016
PFBA	Yangzhou (rural areas)	3.9	Chen et al. 2016
	Yancheng (rural areas)	2.6	Chen et al. 2016
	Changshu (rural areas)	58.5	Chen et al. 2016
	Tai'an (rural areas)	1.9	Chen et al. 2016
	Liaocheng (rural areas)	1.0	Chen et al. 2016
	Tianjin (rural areas)	0.4	Chen et al. 2016
	Beijing	42.9	Gao et al. 2016
PFNA	Yangzhou (rural areas)	0.8	Chen et al. 2016
	Yancheng (rural areas)	0.4	Chen et al. 2016
	Changshu (rural areas)	22.0	Chen et al. 2016
	Tai'an (rural areas)	0.3	Chen et al. 2016
	Liaocheng (rural areas)	<0.1	Chen et al. 2016
	Tianjin (rural areas)	<0.1	Chen et al. 2016
	Tianjin (suburb)	0.35	Qi et al. 2016
	Guangzhou (urban areas)	1.746	Liu 2014
	Dongguan (industrial areas)	1.274	Liu 2014
	Foshan (urban areas)	0.492	Liu 2014
	Zhongshan (industrial areas)	0.614	Liu 2014
	Qingyuan (rural areas)	0.013	Liu 2014
	Beijing	6.1	Gao et al. 2016
PFHpA	Yangzhou (rural areas)	2.1	Chen et al. 2016
	Yancheng (rural areas)	0.8	Chen et al. 2016
	Changshu (rural areas)	99.7	Chen et al. 2016
	Tai'an (rural areas)	0.6	Chen et al. 2016
	Liaocheng (rural areas)	<0.5	Chen et al. 2016
	Tianjin (rural areas)	<0.5	Chen et al. 2016
	Tianjin (suburb)	0.5	Qi et al. 2016
	Guangzhou (urban areas)	1.492	Liu 2014
	Dongguan (industrial areas)	0.682	Liu 2014
	Foshan (urban areas)	1.14	Liu 2014
	Zhongshan (industrial areas)	0.682	Liu 2014
	Qingyuan (rural areas)	0.051	Liu 2014
	Beijing	11	Gao et al. 2016

Table 5 (continued)

Compound	Region	Maximum concentration (ng/L)	Reference
PFHxA	Yangzhou (rural areas)	1.6	Chen et al. 2016
	Yancheng (rural areas)	0.9	Chen et al. 2016
	Changshu (rural areas)	132.4	Chen et al. 2016
	Tai'an (rural areas)	0.6	Chen et al. 2016
	Liaocheng (rural areas)	<0.2	Chen et al. 2016
	Tianjin (rural areas)	<0.2	Chen et al. 2016
	Tianjin (suburb)	0.8	Qi et al. 2016
	Guangzhou (urban areas)	1.070	Liu 2014
	Dongguan (industrial areas)	0.818	Liu 2014
	Foshan (urban areas)	0.676	Liu 2014
	Zhongshan (industrial areas)	0.632	Liu 2014
	Qingyuan (rural areas)	0.043	Liu 2014
	Beijing	32.8	Gao et al. 2016
PFHxS	Guangzhou (urban areas)	0.642	Liu 2014
	Dongguan (industrial areas)	2.46	Liu 2014
	Foshan (urban areas)	0.458	Liu 2014
	Zhongshan (industrial areas)	0.129	Liu 2014
	Qingyuan (rural areas)	0.023	Liu 2014
	Fuxin (FCIP)	0.68	Bao et al. 2011
	Beijing	3.4	Gao et al. 2016
ΣPFCs	Changshu (rural areas)	269.1	Chen et al. 2016
	Yangzhou (rural areas)	8.5	Chen et al. 2016
	Yancheng (rural areas)	3.57	Chen et al. 2016
	Tai'an (rural areas)	1.68	Chen et al. 2016
	Liaocheng (rural areas)	0.45	Chen et al. 2016
	Tianjin (rural areas)	0.20	Chen et al. 2016
	Dalian (rural areas)	17	Li et al. 2016
	Guangzhou (urban areas)	6.105	Liu 2014
	Dongguan (industrial areas)	13.40	Liu 2014
	Foshan (urban areas)	3.05	Liu 2014
	Zhongshan (industrial areas)	4.895	Liu 2014
	Qingyuan (rural areas)	0.348	Liu 2014

PFOA perfluorooctanoic acid; *PFOS* perfluorooctane sulfonic acid; *PFBS* perfluorobutane sulfonic acid; *PFBA* perfluorobutyric acid; *PFNA* perfluorononanoic acid; *PFHpA* perfluoroheptanoic acid; *PFHxA* perfluorohexanoic acid; *PFHxS* perfluorohexane sulfonic acid; *FCIP* fluorochemical industrial park

result, HCHs with weak hydrophobicity contaminated the aquifer. Cui et al. (2014) studied the pollution status of water in the Hunhe River and coastal groundwater in Shenyang and found that local hydrogeological characteristics made lateral infiltration from river water a prominent feature. At the same time, uplift of the water level caused by rubber dams or sluices, as well as a regional cone of groundwater depression caused by the large volume of continuous groundwater pumping changed the recharge and runoff conditions of groundwater near the river. As a result, halohydrocarbons and HCHs were detected in both river water and groundwater, and the concentration in groundwater was lower than that in river water. A study by Liu et al. (2016) indicated that seepage from river to groundwater is an important source of subsequent contamination. Near a fluorochemical industrial park (FIP) in Zibo, Shandong province, the concentrations of ΣPFAAs in surface water and groundwater showed a downward trend with increasing distance from the FIP; however, no change in relative abundance of individual PFAAs was evident.

In general, adsorption and degradation processes and the close hydraulic connection between surface water and groundwater have led to lower levels of MOs in groundwater than in surface water. However, occasional counter examples exist in some regions—for example, investigation of the distribution characteristics of PPCPs in a reclaimed water irrigation area (Huang et al. 2016) revealed that the concentrations of CBZ, mefenamic acid, and nalidixic acid in groundwater were higher than in surface water. A similar pattern was observed in the Chalk groundwater in the UK (Manamsa et al. 2016a).

Migration and transformation processes

The migration and transformation processes of MOs can be initiated through volatilization, absorption, hydrolyzation, bioaccumulation, and degradation (Caupos et al. 2011; Liu and Liu 2004). These processes depend on properties of

pollutants and environmental conditions. Adsorption and biodegradation are considered the most important processes influencing the environmental fate of organic pollutants (Li et al. 2013b; Juhasz and Naidu 2000). Some pollutants have low potential to migrate to aquifers via leaching processes when adsorbed onto soil organic matter, resulting in different pollution levels with respect to nearby pollution sources; however, in regions polluted by perfluoroalkyl acids (PFAAs), contamination can continue even if the pollution sources have been cut off. In a study conducted by Xiao et al. (2015), the concentrations of PFOS and PFOA in groundwater beneath a former fluorochemical industrial park (FIP) were still high (24 and 1.6 μg/L, respectively) from the 1940s to 2002.

Some of the studies concentrated on adsorption and degradation features of MOs under different conditions (acid or alkaline environment, redox environment, etc.). The adsorption behavior of most commonly detected DMP, DEP, DBP, DIBP, and DEHP in the shallow aquifer sediment of Jianghan plain, Hubei province, was analyzed by Zhang (2010), who found that the adsorption isotherms of these five PAEs fitted a linear model. The sediment-water distribution coefficient (K_d) followed the order of DEP < DMP < DIBP < DBP < DEHP. The adsorption capacity of aquifer media for DIBP was greater under acidic conditions, while it was suitable for DMP, DEP, DBP, and DIBP under alkaline conditions. Ma et al. (2015) conducted leaching column experiments to investigate the adsorption and biodegradation of EDCs in river-based artificial groundwater recharged with reclaimed water in Beijing. To simulate aquifer behavior, different recharge conditions were set—continual sterilization recharge (CSR), continual recharge (CR), and wetting and drying alternative recharge (WDSR). The results showed that the migration depth of EDCs in the CSR column was longest. The order of both the removal rate and attenuation effect of the three EDCs (E2 > EE2 > BPA) indicated the strong migration and weak adsorption capacity of BPA. In a study by Li et al. (2013b), the adsorption of selected EDCs—E2, EE2, BPA, and nonylphenol (NP)—onto the soil followed the order of NP > E2 > EE2 > BPA, and E2 > NP > BPA > EE2 of the degradation rate. Based on these conclusions, it was inferred that hydrophobicity is the major mechanism for EDCs adsorption onto aquifer media. In China, landfills are widely distributed and the national leakage of ΣPFAAs to groundwater from landfill leachate has been estimated to be 3,110 kg/year (Yan et al. 2015). The leaching processes of PFAAs are affected not only by the properties of PFAAs, but also by the properties of leachate—pH, temperature, total organic carbon (TOC), electrical conductivity (EC), etc. Correlation analysis revealed negative correlations between EC and concentrations of individual PFAAs in raw leachates, which was similar to the decreasing mobility of PFASs observed with increasing ionic strength (You et al. 2010); moreover, some studies showed that PFAAs mobility was enhanced with increasing pH (Benskin et al. 2012; Wang and Shih 2011).

A recent study of the migration and transformation mechanisms of four selected sulfa antibiotics (sulfamethyldiazine, sulfamethazine, sulfathiazole, sulfamethoxazole) through percolation column simulation experiments (Zhou 2015) revealed that the migration rate of the four sulfa antibiotics in aquifers was fine sand > silty sand > silt. Moreover, these compounds were found to be difficult to adsorb and to have strong migration capacity (sulfathiazole < sulfamethazine < sulfamethyldiazine < sulfamethoxazole). The half-life of antibiotics in silt was less than that in silty sand and fine sand because of differences in the soil organic matter content in media; moreover, humus, iron, and manganese ions had greater adsorption capacity towards sulfa antibiotics that facilitated the adsorption process. The pollution status of OCPs in groundwater for different land use types was studied by Zhang et al. (2014), who found that the concentrations of OCPs in paddy field groundwater were considerably higher than those from dry land and woodland because of the higher soil-water content in paddy fields. Based on investigation of the behavior of PBDEs adsorption onto porous media, Shan (2014) showed that colloids acted as the major adsorbent and migration carrier in soil-groundwater systems, which may be the key pathway of migration of PBDEs into groundwater. However, a study in the UK came to the opposite conclusion, indicating that there was no association between colloids and pesticides in deep groundwater from the Chalk aquifer in southern England (Gooddy et al. 2007).

Existing problems and future prospects

China has a large area of farmland, and the application of fertilizers and pesticides is a persistent threat to surface and groundwater. In many studies, the toxicity and environmental occurrence of most pollutants are poorly understood. Although the migration process in soil may attenuate a large proportion of MOs, in some instances groundwater may be contaminated after a certain period of time, after which it becomes a potential pollution source. In addition, artificial groundwater recharge with treated wastewater is a new method to address declining levels and contamination of groundwater. This method can supplement aquifers or be regarded as a storage system for later use, especially in arid regions with shortage of water; however, it can change the natural physical, chemical, and biological equilibrium conditions of aquifers. Accordingly, this technique may become a source of MOs pollution with

time. To date, the national regulations regarding PFCs in drinking water have not been addressed. Although some recommended allowable values have been issued, they are not unified and are primarily limited to PFOA and PFOS. In general, the number of groundwater PFCs samples was much smaller than that of surface water and soil samples; therefore, a better investigation and understanding of the spatio-temporal variation of MOs is imperative. In the coming decades, relevant environmental standards for groundwater management should be improved.

Currently, research on adsorption and desorption behavior of actual aquifer media in subsurface environments is relatively scarce. Both large-scale field research and laboratory simulations are needed for detailed comprehension of the fate of MOs in aquifers. There may be some key properties that can govern contaminant behaviors in the subsurface that remain unknown. Additionally, most Chinese studies of MOs in groundwater have been conducted in southeastern China, while groundwater quality surveys in western and northern China are rare. In these regions, groundwater is the predominant source of domestic water; thus, it is imperative to conduct research on water treatment techniques, monitoring, and detection in these areas.

Conclusions

This paper reviewed existing sources and occurrences of a series of MOs in groundwater in China. Significant environmental concentrations of well-established MOs and EOCs were reviewed. Most of these compounds are potentially hazardous to aquatic environments and human health. Major sources of MOs in groundwater were found to be industrial and domestic effluents from wastewater treatment plants (WWTPs) and agricultural activities. Relatively high concentrations of MOs are mainly distributed in areas with developed industry or intensive agriculture. When compared to the pollution levels of groundwater in parts of the North America and Europe, the concentrations of individual contaminants in groundwater of southeast coastal areas of China were greater, perhaps because of the long production history, the course of urbanization and the lack of regulation. The MOs detected at high concentrations in groundwater were mainly contributed by PAHs, DDTs, PCBs, BDE209, PAEs, antibiotics, PFOA and PFBS. When compared with well-established pollutants, PFCs have relatively less distribution range in groundwater of China. The behavior of MOs in aquifers is influenced by properties of the pollutants and conditions of the subsurface environment. Adsorption behavior is one of the primary processes that impact the fate of organic contaminants in aquifers.

Although research regarding MOs has increased in recent years, it is still in an exploratory stage. MOs could not be thoroughly investigated due to their wide diversities and presence of trace amounts. However, the negative impacts of MOs in the environment will remain a potential threat for ecosystem and human health with rapid urbanization and industrialization; therefore, perfection of legislation for management of MOs, especially EOCs, needs to be further improved in China.

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References

Adams WJ, Biddinger GR, Robillard KA, Gousuch JW (1995) A summary of the acute toxicity of 14 phthalate esters to representative aquatic organisms. Environ Toxicol Chem 14(9):1569–1574

Adeel M, Song X, Wang Y, Francis D, Yang Y (2016) Environmental impact of estrogens on human, animal and plant life: a critical review. Environ Int 99:107–119

Ahrens L, Yamashita N, Yeung LW, Taniyasu S, Horii Y, Lam PK, Ebinghaus R (2009) Partitioning behavior of per- and polyfluoroalkyl compounds between porewater and sediment in two sediment cores from Tokyo Bay. Japan Environ Sci Technol 43(18):6969–6975

Balakrishna K, Rath A, Praveenkumarreddy Y, Guruge KS, Subedi B (2016) A review of the occurrence of pharmaceuticals and personal care products in Indian water bodies. Ecotoxicol Environ Saf 137: 113–120

Bao J, Liu W, Liu L, Jin Y, Dai J, Ran X (2011) Perfluorinated compounds in the environment and the blood of residents living near fluorochemical plants in Fuxin, China. Environ Sci Technol 45(19): 8075–8080

Benskin JP, Li B, Ikonomou MG, Grace JR, Li LY (2012) Per- and polyfluoroalkyl substances in landfill leachate: patterns, time trends, and sources. Environ Sci Technol 46:11532–11540

Blackwell PA, Kay P, Boxall ABA (2007) The dissipation and transport of veterinary antibiotics in a sandy loam soil. Chemosphere 67(2): 292–299

Boiteux V, Dauchy X, Rosin C, Munoz JF (2012) National screening study on ten perfluorinated compounds in raw and treated tap water in France. Arch Environ Contam Toxicol 63(1):1–12

Cai MH, Zhao Z, Yang HZ, Yin Z, Hong Q, Sturm R (2012) Spatial distribution of per- and polyfluoroalkyl compounds in coastal waters from the east to South China Sea. Environ Pollut 161:162–169

Caupos E, Mazellier P, Croue JP (2011) Photodegradation of estrone enhanced by dissolved organic matter under simulated sunlight. Water Res 45(11):3341–3350

Chang S, Zhang X, Liu Y (2016) Distribution characteristics and pollution status of phthalate esters in the groundwater of Hutuo River pluvial fan. Environ Sci 37(8):3041–3048

Chen S, Jiao XC, Gai N, Li XJ, Wang XC, Lu GH (2016) Perfluorinated compounds in soil, surface water, and groundwater from rural areas in eastern China. Environ Pollut 211:124–131

Cui J, Du J, Wang X (2014) Contamination characteristics in surface water and coastal groundwater of Hunhe River. Acta Ecol Sin 34(7):1860–1869

Ding Z (2015) Occurrence and distribution of pharmaceutical and personal care products in typical pollution sources and groundwater in the Pearl River Delta (in Chinese). PhD Thesis, Hunan Normal University, Changsha, China

Dodgen LK, Kelly WR, Panno SV (2016) Characterizing pharmaceutical, personal care product, and hormone contamination in a karst aquifer of southwestern Illinois, USA, using water quality and stream flow parameters. Sci Total Environ 578:281–289

Dong DL, Sun WJ, Zhu ZC, Xi S, Lin G (2013) Groundwater risk assessment of the third aquifer in Tianjin city, China. Water Resour Manag 27(8):3179–3190

Drillia P, Stamatelatou K, Lyberatos G, (2005) Fate and mobility of pharmaceuticals in solid matrices. Chemosphere 60 (8):1034-1044

Du J, Hu H, Yang J, Li Z, Han W, Zhu X (2016) Analysis and risk assessment of endocrine disruptors in groundwater in Xuzhou region. Admin Tech Environ Monit 28(6):38–40

Duo K, Wang L, Zhu X, Peng H, Shen J (2004) An investigation and analysis of toxic organic traces in drinking water sources in Henan. J Saf Environ 4(01):32–35

Gan Z (2014) Distribution, fate, and photolysis mechanism of artificial sweeteners in environment (in Chinese). PhD Thesis, Nankai University, Nankai Qu, China

Gao J, Li W, Li G, Huang J, Yu G (2016) Preliminary investigation on perfluorinated compounds in groundwater in some areas of Beijing, China. Asian J Ecotoxicol 2016(2):355–363

GB5749 (2006) Standards for drinking water quality of the People's Republic of China (2006). http://www.nhfpc.gov.cn/zwgkzt/wsbysj/200804/30005.shtml. Accessed March 2018

Giesy JP, Naile JE, Khim JS, Jones PD, Newsted JL (2010) Aquatic toxicology of perfluorinated chemicals. Rev Environ Contam Toxicol 202:1–52

Gooddy DC, Mathias SA, Harrison I, Lapworth DJ, Kim AW (2007) The significance of colloids in the transport of pesticides through chalk. Sci Total Environ 385(1–3):262–271

Houtz EF, Higgins CP, Field JA, Sedlak DL (2013) Persistence of perfluoroalkyl acid precursors in AFFF-impacted groundwater and soil. Environ Sci Technol 47(15):8187–8195

Hu H, Wang C, Guo M (2005) The present status of environmental pollution by pharmaceuticals and personal care products (PPCPs). Ecol Environ 14(6):947–952

Hu Y, Qi S, Lan L, Zhang WJ, Qi SL (2010) Distribution and health risk assessment of HCHs and DDTs in underground river of karst, Southwest China. China Environ Sci 30(6):802–807

Huang G, Sun J, Wang S, Hai-Yan DU, Yao-Dong LU, Zhi BF (2008) Elementary research of organochlorine pesticide in groundwater of Pearl River Delta. J Agro-Environ Sci 27(4):1471–1475

Huang D, He J, Yang L, He B (2016) Distribution characteristics of pharmaceuticals and personal care products in water and soil environment in reclaimed water irrigation area of a city. China Environ Sci 36(9):2614–2623

Javid A, Mesdaghinia A, Nasseri S, Mahvi AH, Alimohammadi M, Gharibi H (2016) Assessment of tetracycline contamination in surface and groundwater resources proximal to animal farming houses in Tehran, Iran. J Environ Health Sci Eng 14(1):1–5

Jiang L, Xu Q, Liang C (2013) Detection and risk assessment of phthalates in groundwater in a country of Jiangsu Province. Environ Monit China 29(4):5–10

Juhasz AL, Naidu R (2000) Bioremediation of high molecular weight polycyclic aromatic hydrocarbons: a review of the microbial degradation of benzo[a] pyrene. Int Biodeterior Biodegrad 45:57–88

Jurado A, Vàzquez-Suñé E, Carrera J, López DAM, Pujades E, Barceló D (2012) Emerging organic contaminants in groundwater in Spain: a review of sources, recent occurrence and fate in a European context. Sci Total Environ 440(3):82–94

Kang B, Wang D, Du S (2016) Source identification and degradation pathway of multiple persistent organic pollutants in groundwater at an abandoned chemical site in Hebei, China. Exposure Health 9(2)135–141

Keshavarzi M, Baker A, Kelly BFJ, Andersen MS (2017) River–groundwater connectivity in a karst system, Wellington, new South Wales. Austral Hydrogeol J 25:557–574

Kong X, Miao Y, Luan R, Qin S, CAGS (2016a) Contamination of persistent organic pollutants in the offshore groundwater of Chaoyangxi River in Nanning City, China. Earth Environ 44(4): 406–413

Kong L, Kadokami K, Duong HT, Hong TCC (2016b) Screening of 1300 organic micro-pollutants in groundwater from Beijing and Tianjin, North China. Chemosphere 165:221–230

Koroša A, Auersperger P, Mali N (2016) Determination of micro-organic contaminants in groundwater (Maribor, Slovenia). Sci Total Environ 571:1419–1431

Lan J (2014) Study on migration, partitioning and ecological risk of PAHs in a karst Underground River system in Southwest China (in Chinese). PhD Thesis, Southwest University, El Paso, TX

Lapworth DJ, Baran N, Stuart ME, Ward RS (2012) Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. Environ Pollut 163(4):287–303

Lapworth DJ, Baran N, Stuart ME, Manamsa K, Talbot J (2015) Persistent and emerging micro-organic contaminants in chalk groundwater of England and France. Environ Pollut 203:214–225

Li B, Ren Z, Chen H, Cao X, Fei L (2007) Residues of organochlorine pesticides in shallow groundwater of agricultural region in Taihu Basin. J Agro-Environ Sci 26(5):1714–1718

Li FS, Sun HW, Hao ZN, He N, Zhao L, Zhang T, Sun T (2011) Perfluorinated compounds in Haihe River and Dagu Drainage Canal in Tianjin, China. Chemosphere 84(2):265–271

Li J, Fu J, Zhang H, Li Z, Ma Y, Wu M (2013a) Spatial and seasonal variations of occurrences and concentrations of endocrine disrupting chemicals in unconfined and confined aquifers recharged by reclaimed water: a field study along the Chaobai River, Beijing. Sci Total Environ 450–451C:162–168

Li J, Jiang L, Liu X, Lv J (2013b) Adsorption and aerobic biodegradation of four selected endocrine disrupting chemicals in soil-water system. Int Biodeterior Biodegrad 76(1):3–7

Li Z, Xiang X, Li M, Ma Y, Wang J, Liu X (2015) Occurrence and risk assessment of pharmaceuticals and personal care products and endocrine disrupting chemicals in reclaimed water and receiving groundwater in China. Ecotoxicol Environ Safety 119:74–80

Li X, Shang X, Luo T, Du X, Wang Y, Xie Q, Matsuura N, Chen J, Kadokami K, (2016) Screening and health risk of organic micropollutants in rural groundwater of Liaodong Peninsula, China. Environmental Pollution 218:739-748

Liu Q (2014) Occurrence and distribution of Perfluorinated compounds in typical pollution sources and groundwater in the Pearl River Delta (in Chinese). PhD Thesis, Lanzhou Jiaotong University, Lanzhou, China

Liu B, Liu X (2004) Direct photolysis of estrogens in aqueous solutions. Sci Total Environ 320(2–3):269–274

Liu Z, Lu Y, Wang T, Wang P, Li Q, Johnson AC (2016) Risk assessment and source identification of perfluoroalkyl acids in surface and ground water: spatial distribution around a mega-fluorochemical industrial park, China. Environ Int 91:69–77

Liu Z, Lu Y, Wang P, Wang T, Liu S, Johnson AC (2017) Pollution pathways and release estimation of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) in central and eastern China. Sci Total Environ 580:1247–1256

Locatelli M, Sciasci F, Cifelli R, Malatesta L, Bruni P, Croce F (2016) Analytical methods for the endocrine disruptor compounds determination in environmental water samples. J Chromatogr A 1434:1–18

Loffler M, Gembarovic J (2005) A new way of modeling transport processes. Thermal Conductivity 123–133

Loos R, Gawlik BM, Locoro G, Rimaviciute E, Contini S, Bidoglio G (2009) EU-wide survey of polar organic persistent pollutants in European river waters. Environ Pollut 157(2):561–568

Luo Q, Sun L, Zhang Y (2011) Health risk assessment of persistent organochlorine pollutants in groundwater from Xihe River area. Res Soil Water Conserv 18(6):119–124

Luo W, Wang S, Fei Q, Sun L (2016) Advances and prospects of pharmaceutical and personal care products in drinking water. J Tianjin Chengjian Univ 22(5):344–351

Ma W, Nie C, Chen B, Cheng X, Lun X, Zeng F (2015) Adsorption and biodegradation of three selected endocrine disrupting chemicals in river-based artificial groundwater recharge with reclaimed municipal wastewater. J Environ Sci 31(5):154–163

Mali N, Cerar S, Koroša A, Auersperger P (2017) Passive sampling as a tool for identifying micro-organic compounds in groundwater. Sci Total Environ 593–594:722–734

Manamsa K, Lapworth DJ, Stuart ME (2016a) Temporal variability of micro-organic contaminants in lowland chalk catchments: new insights into contaminant sources and hydrological processes. Sci Total Environ 568:566

Manamsa K, Crane E, Stuart M, Talbot J, Dan L, Hart A (2016b) A national-scale assessment of micro-organic contaminants in groundwater of England and Wales. Sci Total Environ 568:712–726

Menchen A, Heras JL, Alday JJ (2017) Pesticide contamination in groundwater bodies in the Júcar River European Union pilot basin (SE Spain). Environ Monit Assess 189(4):146

Miege C, Choubert JM, Ribeiro L, Eusèbe M, Coquery M (2009) Fate of pharmaceuticals and personal care products in wastewater treatment plants: conception of a database and first results. Environ Pollut 157(5):1721–1726

Mirasole C, Di Carro M, Tanwar S, Magi E (2016) Liquid chromatography–tandem mass spectrometry and passive sampling: powerful tools for the determination of emerging pollutants in water for human consumption. J Mass Spectrom 51(9):814–820

Mu X, Huang Y, Li X (2016) The occurrence of persistent organic pollutants in China and their environmental risk to fish: a review. Chin J Pest Sci 18(1):12–27

Peng X, Ou W, Wang C, Wang Z, Huang Q, Jin J, Tan J (2014) Occurrence and ecological potential of pharmaceuticals and personal care products in groundwater and reservoirs in the vicinity of municipal landfills in China. Sci Total Environ 490:889–898

Pitarch E, Cervera MI, Portolés T, Ibáñez M, Barreda M, Renaupruñonosa A, Morell I, López F, Albarrán F, Hernández F (2016) Comprehensive monitoring of organic micro-pollutants in surface and groundwater in the surrounding of a solid-waste treatment plant of Castellón. Spain Total Environ 548:211–220

Qi Y, Huo S, Hu S, Xi B, Su J, Tang Z (2016) Identification, characterization, and human health risk assessment of perfluorinated compounds in groundwater from a suburb of Tianjin, China. Environ Earth Sci 75(5):1–12

Qiu S, Ruan X, Hu X, Chen J, Bai Y, Tang X (2008) Investigation and solution study of main industry-poisonous chemical pollution of drinking water resources in Zhuhai. Modern Prevent Med 13: 2420–2422

Qiu B, Xiang W, Li Y (2016) A review on detection and removal processes of typical pharmaceuticals and personal care products (PPCPs) in aqueous environment. Environ Sci Technol 29(6):70–75

Ratola N, Cincinelli A, Alves A, Katsoyiannis A (2012) Occurrence of organic micro contaminants in the wastewater treatment process: a mini review. J Hazard Mater 239–240:1–18

Reh R, Licha T, Geyer T, Nödler K, Sauter M (2013) Occurrence and spatial distribution of organic micro-pollutants in a complex hydrogeological karst system during low flow and high flow periods, results of a two-year study. Total Environ 443:438–445

Schaider LA, Rudel RA, Ackerman JM, Dunagan SC, Brody JG (2014) Pharmaceuticals, perfluorosurfactants, and other organic wastewater compounds in public drinking water wells in a shallow sand and gravel aquifer. Sci Total Environ 468–469:384–393

Shan H (2014) Geochemical behavior of PBDEs and their in situ measurement in soil–groundwater system in the sewage irrigation area (in Chinese). PhD Thesis, China University of Geosciences, Beijing

Shan H, Ma T, Du Y, Ning G, Cong X (2013) Distribution of PBDEs in soil and water from Hetao agriculture irrigation area. Environ Sci Technol. 36(6):37–41

Shao Y (2014) The Occurrence and Fate of PAHs in the Guozhuang Karst Water System of Northern China (in Chinese). PhD Thesis, China University of Geosciences, Beijing

Stuart M, Dan L (2013) Emerging organic contaminants in groundwater, vol 4. Springer, Heidelberg, pp 259–284

Stuart M, Lapworth D, Crane E, Hart A (2012) Review of risk from potential emerging contaminants in UK groundwater. Sci Total Environ 416:1–21

Stuart ME, Lapworth DJ, Thomas J, Edwards L (2014) Fingerprinting groundwater pollution in catchments with contrasting contaminant sources using microorganic compounds. Sci Total Environ 468: 564–577

Sun Y (2012) Study on migration and transformation characteristics of OCPs and PAHs in epikarst system (in Chinese). PhD Thesis, Southwest University, El Paso, TX

Sun HW, Li FS, Zhang T, Zhang X, He N, Song Q, Zhao LJ, Sun LN, Sun TH (2011) Perfluorinated compounds in surface waters and WWTPs in Shenyang, China: mass flows and source analysis. Water Res 45(15):4483–4490

Taniyasu S, Kannan K, So MK, Gulkowska A, Sinclair E, Okazawa T, Yamashita N (2005) Analysis of fluorotelomer alcohols, fluorotelomer acids, and short- and long-chain perfluorinated acids in water and biota. J Chromatogr A 1093(1–2):89–97

USEPA (1997) Endocrine Disruptor Screening and Testing Advisory Committee (EDSTAC) final report. https://www.epa.gov/endocrine-disruption/endocrine-disruptor-screening-and-testing-advisory-committee-edstac-final. Accessed March 2018

USEPA (1999) Pharmaceuticals & Personal Care Products in the environment: an emerging concern? USEPA, Washington, DC

Wang F, Shih K (2011) Adsorption of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) on alumina: influence of solution pH and cations. Water Res 45:2925–2930

Wang S, Zhang J (2005) Review on the current contaminative status analysis on environmental endocrine disrupting chemicals in China. J Environ Pollut Control 27(3):228–231

Wang C, Liu H, Cai H, Liang Y, Liang HC, Xiong QH (2009) Source analysis and detection of trace phthalate esters in groundwater in Wuhan. Environ Sci Technol 32(10):118–123

Wang B, Iino F, Yu G, Huang J, Morita M (2010) The pollution status of emerging persistent organic pollutants in China. Environ Eng Sci 27(3):215–225

Wang L, Zhang Z, Zhang XZ, Sun S, Sun H (2011) Removal of perfluorinated compounds by wastewater treatment plants. Acta Sci Circumst 31(7):1363–1368

Wang TY, Khim JS, Chen CL, Naile JE, Lu Y, Kannan K, Park J, Luo W, Jiao WT, Hu WY, Giesy JP (2012) Perfluorinated compounds in surface waters from northern China: comparison to level of industrialization. Environ Int 42:37–46

Wang Y, Wang T, Fu J, Ruan T, Qu G, Wang C, Zeng L, Liu Q, Yuan B, Jiang G (2013a) Recent research progresses of emerging organic pollutants. Chem Bull 76(1):3–14

Wang B, Deng S, Huang J, Yu G (2013b) Environmental risk assessment and control of emerging contaminants in China. Environ Chem 32(7):1129–1136

Wang X, Jiao X, Zhu X, Liu Q, Liu J, Yin X (2014) Distribution characteristics of PBDEs in surface and ground waters of electronic waste dismantling sites and surrounding area. Ecol Environ Sci 23(6): 1027–1033

Wang T, Wang P, Meng J, Liu S, Lu Y, Khim JS, Giesy JP (2015) A review of sources, multimedia distribution and health risks of perfluoroalkyl acids (PFAAs) in China. Chemosphere 129(1):87–99

Wei L, Guo F, Wang J, Kang C (2011) Distribution characteristics of organochlorine pesticides in karst subterranean river in Liuzhou. Carsolog Sin 30(1):16–21

Wei MC, Zhong WJ, Zhao LX, Zhu LY (2013) Distribution and profile of perfluorinated compounds in the environment around a fluorine chemistry industrial park in South China. Acta Sci Circumst 33(7): 1989–1995

Wells MJM (2006) Log Dow: key to understanding and regulating wastewater derived contaminants. Environ Chem 3(6):439–449

Worrall F, Kolpin DW (2004) Aquifer vulnerability to pesticide pollution combining soil, land-use and aquifer properties with molecular descriptors. J Hydrol 293:191–204

Xiao F, Simcik MF, Halbach TR, Gulliver JS (2015) Perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in soils and groundwater of a US metropolitan area: migration and implications for human exposure. Water Res 72:64–74

Xie SW, Wang TY, Liu SJ, Jones KC, Sweetman AJ, Lu YL (2013) Industrial source identification and emission estimation of perfluorooctane sulfonate in China. Environ Int 52:1–8

Xu Y (2014) Pollution characteristics of antibiotics, antibiotic resistance Bacteria and genes in Wangyanggou River, ShiJiaZhuang (in Chinese). MSc Thesis, Shandong Agricultural University, Tai'an, China

Xu J, Zhu H, Xu H, Liu CH, Zhang Z (2009) Study on organic pollution of karst underground water in Jinan spring area. Carsolog Sin 28(3): 249–254

Xu X, Sun Y, Alam MJ (2013) Preliminary study on OCPs in water body of the Laolongdong underground river basin in Chongqing. Carsolog Sin 32(2):189–194

Yan H, Cousins IT, Zhang C, Zhou Q (2015) Perfluoroalkyl acids in municipal landfill leachates from China: occurrence, fate during leachate treatment and potential impact on groundwater. Sci Total Environ 524–525:23–31

Yao Y, Zhu H, Li B, Hu H, Zhang T, Yamazaki E, Taniyasu S, Yamashita N, Sun H (2014) Distribution and primary source analysis of per- and poly-fluoroalkyl substances with different chain lengths in surface and groundwater in two cities, North China. Ecotoxicol Environ Safety 108(1):318

You C, Jia C, Pan G (2010) Effect of salinity and sediment characteristics on the sorption and desorption of perfluorooctane sulfonate at sediment–water interface. Environ Pollut 158:1343–1347

Yu G, Liu H, Zhang T, Su JW, Sheng MT, Li W (2007) Assessment of the organic pollution and its risk for the surficial groundwater in Hangzhou City. Resour Surv Environ 28(3):198–204

Zhang D (2010) Characteristics of sorption of phthalic acid esters on shallow aquifer sediment (in Chinese). MSc Thesis, China University of Geosciences, Beijing

Zhang J, Qi S, Yao H (2011a) The distribution characteristics of OCPs residues in karst underground river of Guangxi. J Environ Pollut Control 33(4):54–57

Zhang Y, Sun J, Chen X, Huang G, Jing J, Liu J, Zhang Y (2011b) The distribution characteristics and source of phthalic acid esters in groundwater of Dongguan. J Environ Pollut Control 33(8):57–61

Zhang T, Sun H, Lin Y, Wang L, Zhang X, Liu Y, Geng X, Zhao L, Li F, Kannan K (2011c) Perfluorinated compounds in human blood, water, edible freshwater fish, and seafood in China: daily intake and regional differences in human exposures. J Agric Food Chem 59(20):11168–11176

Zhang YL, Dang JY, Lv Y, Wang Z (2013a) Evaluation of migration abilities of reproductive health estrogens in the subsurface environment. Sci Technol Rev 31(22):31–35

Zhang L, Pan F, Liu X, Yang L, Jiang X, Yang J, Shi W (2013b) Multi-walled carbon nanotubes as sorbent for recovery of endocrine disrupting compound-bisphenol F from wastewater. Chem Eng J 218:238–246

Zhang G, Wang X, Li Z (2014) Analysis of organochlorine pesticide concentrations and pollution characteristics in groundwater of Yueyang City. Water Resour Protect 30(2):52–56

Zhou A (2015) Research on the migration and transformation mechanism and remediation technique of sulfa antibiotics in phreatic water (in Chinese). PhD Thesis, Jilin University, Changchun, China

Zhang X (2015) Rational use and substitution of veterinary antibiotics. China Animal Industry 2015(22):45–46

Zhou Z, Shi YL, Li WH, Xu L, Cai Y (2012) Perfluorinated compounds in surface water and organisms from Baiyangdian Lake in North China: source profiles, bioaccumulation and potential risk. Bull Environ Contam Toxicol 89(3):519–524

Zhu H, Zeng Q, Xu J, Liu Z, Wang W, Wei C (2014) On organic pollution of shallow groundwater in southern plain of Huaihe River basin (Shandong section). J Geol 38(3):511–516