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中国七大流域全氟烷基酸污染水平与饮水暴露风险

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摘要: 为探究中国七大流域全氟烷基酸(perfluoroalkyl acids, PFAAs)的污染现状与居民饮水暴露风险, 基于美国国家环保署推荐的风险评估方法, 应用场景风险评估模式, 分析了各流域 PFAAs 的污染水平及特征, 并对中国成人、青少年、儿童的 PFAAs 日均饮水暴露量(average daily dose, ADD)及其健康风险进行了评估。结果表明, 中等暴露水平下, 中国七大流域 $\sum$ PFAAs 中位浓度为 $14 \text{ ng} \cdot \text{L}^{-1}$, 全氟辛酸(perfluorooctanoic acid, PFOA)、全氟丁酸和全氟辛烷磺酸(perfluorooctane sulfonic acid, PFOS)为主要污染物, 松辽、太湖流域 $\sum$ PFAAs 高于整体水平。高等暴露水平下, 碳链 ≤ 6 的全氟羧酸类化合物占 $\sum$ PFAAs 的比例高于中等暴露水平。黄河、长江部分河段污染水平高。风险评估结果显示, 饮水暴露 PFOA、PFOS 对中国各年龄段居民尚无健康风险, 且青少年日均饮水摄入量偏少。

关键词: 中国流域; 全氟烷基酸; 全氟辛烷磺酸; 全氟辛酸; 污染水平; 日均暴露量; 饮水暴露风险; 场景风险评估模式
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Contamination Levels and Exposure Risk via Drinking Water from Perfluoroalkyl Acids in Seven Major Drainage Basins of China

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Abstract: To study the perfluoroalkyl acid (PFAAs) contamination in seven major drainage basins of China and the exposure risk to resident populations via drinking water sourced from these basins, a risk assessment model of the US EPA and a scenario-based risk assessment method were applied to analyze the PFAA pollution characteristics and to evaluate the average daily dose and health risk to adults, adolescents, and children. In the intermediate-exposure scenario, results showed that the $\sum$ PFAAs median for the seven major drainage basins was $14 \text{ ng} \cdot \text{L}^{-1}$, with perfluorooctanoic acid (PFOA), perfluorobutanoic acid (PFBA), and perfluorooctane sulfonic acid (PFOS) the main contaminants, and that the contamination levels were the highest in the Songliao River and Taihu Lake basins. In the high-exposure scenario, the discharge proportion of perfluoroalkyl carboxylic acids with ≤ 6 carbon chains among the $\sum$ PFAAs was higher than that in the intermediate-exposure scenario. In addition, certain sections tended to be more polluted than others in the Yellow River and Yangtze River basins. Risk assessment showed that PFOA and PFOS exposure via drinking water posed no health risk to Chinese residents, and that the average daily ingestion of drinking water of Chinese adolescents was below the suggested amount.

Key words: drainage basins of China; perfluoroalkyl acids (PFAAs); perfluorooctane sulfonic acid (PFOS); perfluorooctanoic acid (PFOA); pollution level; average daily dose (ADD); drinking exposure risk; scenario-based risk assessment model

全氟烷基酸(perfluoroalkyl acids, PFAAs)作为加工助剂和表面活性剂^[1]被广泛应用的同时,所引起的生态污染及对人体健康的潜在威胁也受到了高度关注。有研究表明,水体是PFAAs进入环境的直接受体^[2]。中国河网密布、湖泊众多,根据主要河流覆盖区域可划分为松辽、海河、黄河、淮河、太湖、长江和珠江七大流域。各流域PFAAs污染程度与区域经济发展、自然地理特征等因素密切相关。动物实验已经证实全氟辛烷磺酸(perfluorooctane sulfonic acid, PFOS)和全氟辛酸(perfluorooctanoic acid, PFOA)具有神经毒性、生殖毒性和免疫毒性^[3],饮水暴露PFAAs^[4]的健康风险评价势在必行。因此,明确中国水资源污染现状,是评估国民饮水暴露PFAAs健康风险的重要基础。

基于美国环境保护署(United States Environmental Protection Agency, US EPA)健康风险

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评估方法,应用场景风险评估(scenario-based risk assessment, SceBRA)模式,结合迄今已发表的PFAAs检测数据,分析了中国七大流域PFAAs的污染水平和特征,进而对中国成人、青少年、儿童的PFAAs日均饮水暴露量(average daily dose, ADD)及健康风险进行了评估,以期为我国PFAAs的人体健康风险评价提供基础数据。

1 材料与方法

1.1 数据来源及其统计

以中英文检索词“全氟烷基酸”、“全氟化合物”、“河流”、“水”检索《Web of Science》、《中文学术期刊数据库》、《中文科技期刊数据库》、《中国学位论文全文数据库》等数据库,获得发表于2006年3月至2016年12月的文献共31篇(图1),排除原始数据中污染水样的检测数据,获得覆盖中国七大流域主要河流、湖泊、水库、地下水、自来水中18种PFAAs的检测数据约18000条涉及水样共1013个。涉及的18种PFAAs化合物有13种全氟羧酸类化合物(perfluoroalkyl carboxylic acids,

PFCAs),包括全氟丁酸(perfluorobutanoic acid, PFBA),全氟戊酸(perfluoropentanoic acid, PFPeA),全氟己酸(perfluorohexanoic acid, PFHxA),全氟庚酸(perfluoroheptanoic acid, PFHpA),全氟辛酸(perfluorooctanoic acid, PFOA),全氟壬酸(perfluorononanoic acid, PFNA),全氟癸酸(perfluorodecanoic acid, PFDA),全氟十一酸(perfluoroundecanoic acid, PFUdA),全氟十二酸(perfluorododecanoic acid, PFDoA),全氟十三酸(perfluorotridecanoic acid, PFTTrDA),全氟十四酸(perfluorotetradecanoic acid, PFTTeDA),全氟十六酸(perfluorohexadecanoic acid, PFHxDA)和全氟十八酸(perfluorooctadecanoic acid, PFoDA),以及5种全氟磺酸类化合物(perfluoroalkane sulfonic acids, PFSA),包括全氟丁烷磺酸(perfluorobutanesulfonic acid, PFBS),全氟己烷磺酸(perfluorohexanesulfonic acids, PFHxS),全氟庚烷磺酸(perfluoroheptanesulfonic acid, PFHpS),全氟辛烷磺酸(perfluorooctanesulfonic acid, PFOS)和全氟癸烷磺酸(perfluorodecane sulfonic acid, PFDS)。

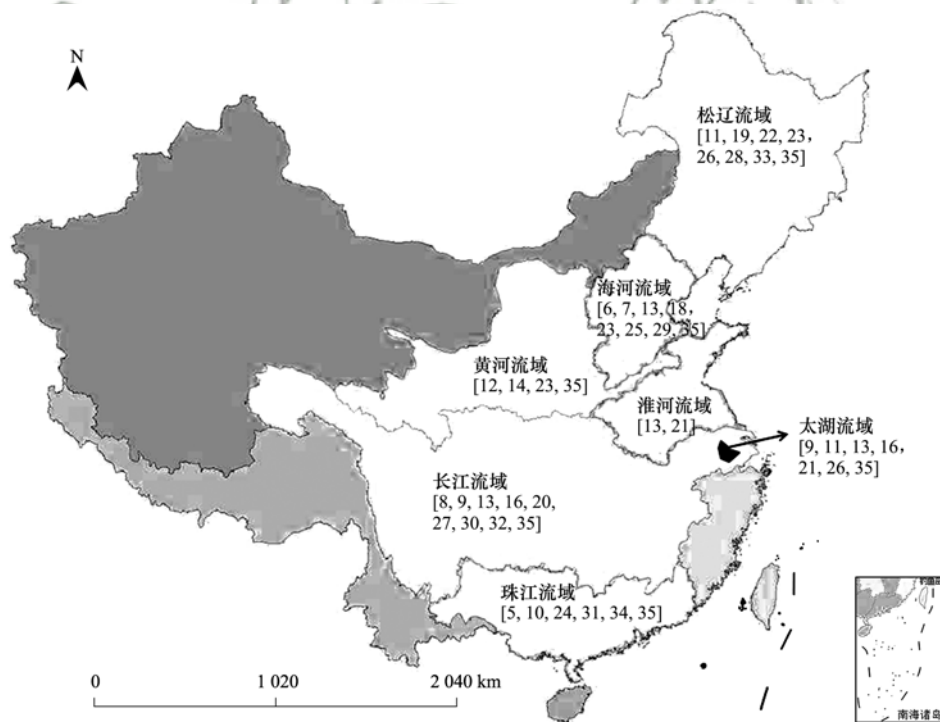


图1 中国七大流域^[36]及其PFAAs数据来源

Fig. 1 Sources of PFAAs data for seven major drainage basins of China

七大流域1013个水样本的分布为松辽流域223个、海河流域136个、黄河流域80个、淮河流域57个、太湖流域118个、长江流域219个、珠江流域180个。依照风险评估最大化原则,原始数据小于

检测限(limit of detection, LOD)的以其1/2 LOD计入统计分析^[37],同时根据拉依达准则(3σ)剔除异常值,分别计算七大流域18种PFAAs的5百分位(P_5)、50百分位(P_{50})、95百分位(P_{95})浓度作为风

险评估基础参数.

1.2 风险评估方法

饮水暴露 PFAAs 的健康风险评估采用 US EPA 推荐的健康风险评价方法. 由于 PFOS、PFOA 为疑似致癌物, 尚无确定的致癌强度系数, 因此基于污染物参考剂量值 (reference dose, RfD) 对 PFOS [RfD_{PFOS}: 25 ng·(kg·d)⁻¹]、PFOA [RfD_{PFOA}: 333 ng·(kg·d)⁻¹]^[38] 进行非致癌物人体暴露健康风险 (R) 评价^[39]:

$$R = \frac{ADD \times 10^{-6}}{RfD} \tag{1}$$

$$ADD = \frac{c \times IR \times EF \times ED}{BW \times AT}$$
$$= \frac{c \times IR \times 365 \times ED}{BW \times 365 \times ED} = \frac{c \times IR}{BW} \tag{2}$$

式中, ADD: 污染物日均暴露量, ng·(kg·d)⁻¹; c: 某污染物浓度, ng·L⁻¹; IR: 日均饮水摄入量, L·d⁻¹; EF: 饮水暴露频率, d·a⁻¹, 取值 365 d·a⁻¹^[40]; ED: 饮水暴露持续时间, a; BW: 体重, kg; AT: 平均终生饮水暴露时间, d, 取值 365 ED^[40].

18 种 PFAAs 日均饮水总暴露量为:

$$ADD_{\sum PFAAs} = \sum_{i=1}^{18} ADD_i \tag{3}$$

居民按年龄 (儿童: 2~6 岁, 青少年: 7~17 岁, 成人: ≥18 岁)、性别分组, 各组体重与日均饮水摄入量参数 (表 1) 引自文献 [41~43]. 日均饮水摄入量指直接饮水 (水、咖啡、茶、奶等) 与间接饮水 (粥、汤) 摄入量之和.

表 1 中国居民饮水暴露 PFAAs 的风险评估参数

Table 1 Parameters of daily PFAAs intake via drinking water in China

组别		日均饮水摄入量 (IR)/L·d ⁻¹			体重 (BW)/kg
		P ₅	P ₅₀	P ₉₅	
儿童 (2~6 岁)	男	0.26	0.75	1.7	17
	女	0.24	0.75	1.7	16
	全部	0.25	0.75	1.7	16
青少年 (7~17 岁)	男	0.59	1.2	2.6	41
	女	0.55	1.1	2.6	39
	全部	0.57	1.2	2.6	40
成年 (≥18 岁)	男	0.70	2.0	5.4	65
	女	0.60	1.7	4.8	57
	全部	0.64	1.9	5.2	61

SceBRA 模式是一种污染物暴露风险评价的思路, 定义低等暴露水平 (P₅, 最优情景)、中等暴露水平 (P₅₀, 一般情景)、高等暴露水平 (P₉₅, 最差情景) 这 3 种情景, 进行污染物暴露风险评估, 旨在获得更客观的评价结果^[44]. SceBRA 模式在氯代烃职业暴露评估^[45], 及居民多环芳烃非职业暴露评估^[46] 中均有良好应用, 尤其适用于污染水平悬殊的七大流域 PFAAs 的饮水暴露风险评估. 中国幅员辽阔, 七大流域覆盖面广, 流域间与流域内均存在较大的 PFAAs 污染程度差异, 故基于 SceBRA 模式, 分析低、中、高这 3 种暴露水平下各流域 PFAAs 污染现状, 进而计算各组居民的 ADD 及其 R 值.

1.3 蒙特卡罗模拟方法

运用蒙特卡罗算法, 模拟次数为 10 000 次, 分别获得七大流域 18 种 PFAAs 的模拟浓度和中等暴露水平下成人的 ADD 模拟值. 浓度模拟的输入参数包括七大流域 18 种 PFAAs 浓度中位数及其标准偏差 (表 2); ADD 模拟的输入参数包括七大流域

18 种 PFAAs 模拟浓度中位数及其标准偏差 (表 2)、日均饮水摄入量 (中位数: 1.9 L·d⁻¹, 标准偏差: 0.17) 及体重 (中位数: 61 kg, 标准偏差: 3.4). 风险评估结果的可靠性通过比对模拟值与计算值, 进行不确定度分析.

数据统计分析与作图采用 Excel (2007), SPSS (v 19.0), Origin (Pro 8.5) 和 Crystal Ball (v 7.2.2) 软件, α≤0.05.

2 结果与讨论

2.1 中国七大流域 PFAAs 的污染现状

中等暴露水平下, 七大流域整体 ∑ PFAAs 的 P₅₀ 浓度水平为 14 ng·L⁻¹ (图 2), PFOA、PFBA 和 PFOS 为主要污染物. PFCA 占 ∑ PFAAs 的 83%, 碳链 ≤8 的化合物占 ∑ PFAAs 的 92%. 七大流域中, 黄河、珠江流域 ∑ PFAAs 浓度分别为 9.9 ng·L⁻¹、7.1 ng·L⁻¹, 低于整体水平; 海河、淮河、

表 2 浓度模拟输入参数及输出结果
Table 2 Parameters and results of Monte Carlo
simulation for concentrations

参数	实测浓度/ $\text{ng}\cdot\text{L}^{-1}$		模拟浓度/ $\text{ng}\cdot\text{L}^{-1}$	
	中位数	标准偏差	中位数	标准偏差
PFBA	2.3	12	2.2	11
PFPeA	0.88	11	0.97	11
PFHxA	0.99	16	0.99	16
PFHpA	0.65	8.5	0.77	8.6
PFOA	5.6	61	5.0	60
PFNA	0.50	3.6	0.49	3.6
PFDA	0.25	5.2	0.25	5.2
PFUdA	0.10	4.2	0.080	4.2
PFDoA	0.050	1.3	0.050	1.3
PFTTrDA	0.070	3.4	0.080	3.5
PFTeDA	0.025	0.11	0.030	0.11
PFHxDA	0.05	0.071	0.050	0.070
PFOxDA	0.024	0.051	0.020	0.050
PFBS	0.77	51	1.1	51
PFHxS	0.24	7.1	0.21	7.1
PFHpS	0.035	0.10	0.030	0.10
PFOS	1.2	27	1.3	27
PFDS	0.10	0.18	0.10	0.18

长江流域分别为 18、17、14 $\text{ng}\cdot\text{L}^{-1}$ ，与整体水平相当；松辽、太湖流域分别为 92 $\text{ng}\cdot\text{L}^{-1}$ 、57 $\text{ng}\cdot\text{L}^{-1}$ ，污染程度远高于整体水平。其中，太湖流域 PFOA、PFOS 浓度分别为 25 $\text{ng}\cdot\text{L}^{-1}$ 、5.1 $\text{ng}\cdot\text{L}^{-1}$ ，是七大流域整体水平（PFOA：5.6 $\text{ng}\cdot\text{L}^{-1}$ ；PFOS：1.2 $\text{ng}\cdot\text{L}^{-1}$ ）的 4.5 和 4.3 倍，其 P_5 低等暴露水平下

$\sum$ PFAAs 浓度（7.5 $\text{ng}\cdot\text{L}^{-1}$ ）高达七大流域整体水平（0.68 $\text{ng}\cdot\text{L}^{-1}$ ）的 11 倍，表明太湖流域 PFAAs 本底较高。太湖流域在七大流域中面积最小，仅是黄河流域的二十分之一，但人口密度为全国平均值的 7 倍，是我国人口最集中的地区之一。作为我国最大的综合工业基地，涉氟行业如电子、机械、化工、冶金、纺织和食品等占太湖流域工业总产值的比例高达 85%^[47]，应是该流域水资源 PFAAs 含量较高的原因。而松辽流域受气候影响较大，降水量为七大流域最小，水资源储量呈逐年减少趋势，水质污染问题较严重。据文献[48]的报道，该流域水质随着水资源管理制度的实施正逐年改善。

高等暴露水平下，七大流域整体 $\sum$ PFAAs 的 P_{95} 浓度水平为 204 $\text{ng}\cdot\text{L}^{-1}$ （图 2），是其中等暴露水平的近 15 倍。其中松辽、海河、淮河、太湖、珠江流域高等暴露水平下 $\sum$ PFAAs 浓度为其中等暴露水平的 2~5 倍，而黄河、长江流域高等暴露水平下 $\sum$ PFAAs 浓度则为其中等暴露水平的 18 倍。由于黄河、长江流域中等暴露水平下， $\sum$ PFAAs 浓度（黄河：9.9 $\text{ng}\cdot\text{L}^{-1}$ ；长江：14 $\text{ng}\cdot\text{L}^{-1}$ ）均未高于七大流域整体（14 $\text{ng}\cdot\text{L}^{-1}$ ）水平，同时 P_5 低等暴露水平下 $\sum$ PFAAs 浓度（黄河：0.55 $\text{ng}\cdot\text{L}^{-1}$ ；长江：0.69

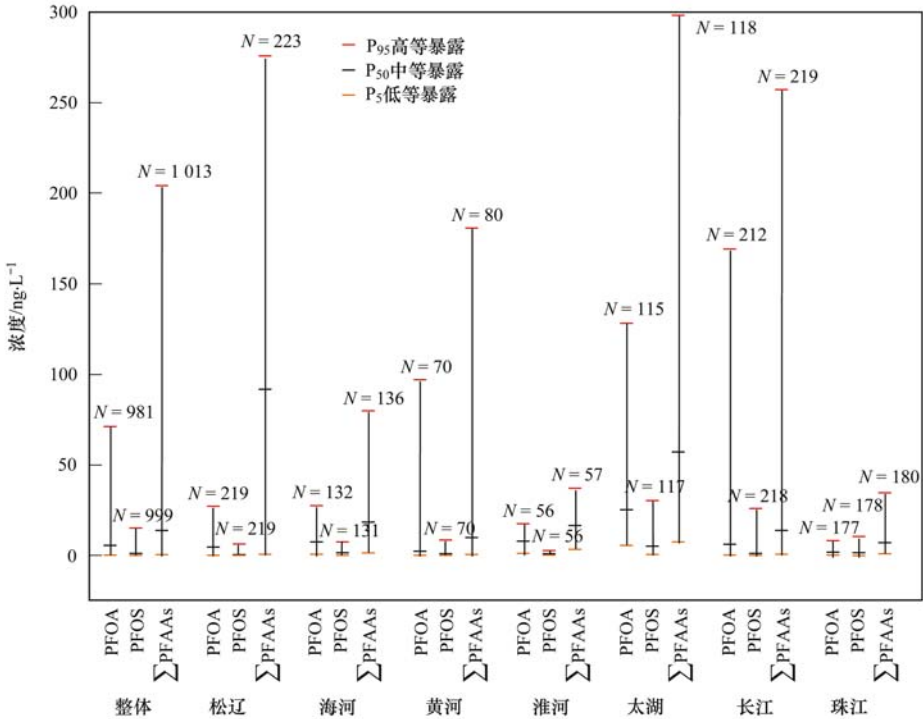


图 2 中国七大流域 PFAAs 的污染水平

Fig. 2 PFAAs concentrations in seven major drainage basins of China

ng·L⁻¹)与七大流域整体(0.68 ng·L⁻¹)水平相当,故其高等暴露水平下高企的 $\sum$ PFAAs浓度(黄河:181 ng·L⁻¹;长江:257 ng·L⁻¹)应由流域内部分河段PFAAs污染造成,而非本底所致.黄河、长江流域面积大、覆盖城市多、工业密布是造成流域部分河段污染较严重的原因.此外,高等暴露水平下PFOA和PFOS占 $\sum$ PFAAs比例较中等暴露水平有所减少,相反,PFBA、PFPeA、PFHxA等短链PFCAs化合物比例均有所增加,表明碳链 ≤ 6 PFCAs化合物的排放趋于上升.这与2014年以来PFOS及其盐逐步被淘汰,碳链 ≤ 6 的PFCAs作为替代品增加使用有关.

2.2 中国居民饮水暴露 PFAAs 风险评估

表3列出了中、高等暴露水平下中国居民饮水的ADD $\sum$ PFAAs值.中等暴露水平下,成人、青少年、儿童饮水的ADD $\sum$ PFAAs分别为0.42、0.41和0.63 ng·(kg·d)⁻¹,PFOA、PFBA、PFOS之和占ADD $\sum$ PFAAs的66%.高等暴露水平下,成人、青少年、儿童的ADD $\sum$ PFAAs分别为18、13、22 ng·(kg·d)⁻¹,是中等暴露水平的32~42倍,碳链 ≤ 6 的PFCAs摄入比例有所增加.各年龄段均未见性别间显著性差异.随着年龄增长,体重(BW)增加远大于饮水量(IR)增加,故IR/BW及ADD $\sum$ PFAAs值均应呈下降趋势.但在中、高等暴露

表3 中国居民 PFAAs 日均饮水暴露量
Table 3 ADD $\sum$ PFAAs of children, adolescents and adults via drinking water in the intermediate- and high-exposure scenarios

化合物	ADD/ng·(kg·d) ⁻¹					
	中等暴露水平			高等暴露水平		
	儿童	青少年	成人	儿童	青少年	成人
PFBA	0.10	6.7×10 ⁻²	6.9×10 ⁻²	3.9	2.4	3.2
PFPeA	4.0×10 ⁻²	2.6×10 ⁻²	2.7×10 ⁻²	2.8	1.7	2.3
PFHxA	4.5×10 ⁻²	2.9×10 ⁻²	3.0×10 ⁻²	2.8	1.7	2.3
PFHpA	2.9×10 ⁻²	1.9×10 ⁻²	2.0×10 ⁻²	0.62	0.38	0.51
PFOA	0.26	0.17	0.17	7.5	4.6	6.1
PFNA	2.3×10 ⁻²	1.5×10 ⁻²	1.5×10 ⁻²	0.29	0.18	0.23
PFDA	1.1×10 ⁻²	7.4×10 ⁻³	7.6×10 ⁻³	0.18	0.11	0.15
PFUDa	4.6×10 ⁻³	3.0×10 ⁻³	3.1×10 ⁻³	0.26	0.16	0.21
PFDoA	2.3×10 ⁻³	1.5×10 ⁻³	1.5×10 ⁻³	0.10	6.2×10 ⁻²	8.1×10 ⁻²
PFTtDA	3.2×10 ⁻³	2.1×10 ⁻³	2.1×10 ⁻³	3.2×10 ⁻²	2.0×10 ⁻²	2.6×10 ⁻²
PFTeDA	1.1×10 ⁻³	7.4×10 ⁻⁴	7.6×10 ⁻⁴	2.5×10 ⁻²	1.6×10 ⁻²	2.1×10 ⁻²
PFHxDA	2.3×10 ⁻³	1.5×10 ⁻³	1.5×10 ⁻³	1.1×10 ⁻²	6.5×10 ⁻³	8.6×10 ⁻³
PFoDA	1.1×10 ⁻³	7.1×10 ⁻⁴	7.3×10 ⁻⁴	1.1×10 ⁻²	6.5×10 ⁻³	8.6×10 ⁻³
$\sum$ PFCAs	0.52	0.34	0.35	19	11	15
PFBS	3.5×10 ⁻²	2.3×10 ⁻²	2.4×10 ⁻²	1.0	0.63	0.83
PFHxS	1.1×10 ⁻²	7.2×10 ⁻³	7.4×10 ⁻³	0.32	0.19	0.26
PFHpS	1.6×10 ⁻³	1.0×10 ⁻³	1.1×10 ⁻³	2.5×10 ⁻²	1.6×10 ⁻²	2.1×10 ⁻²
PFOS	5.5×10 ⁻²	3.6×10 ⁻²	3.7×10 ⁻²	1.6	0.99	1.3
PFDS	4.6×10 ⁻³	3.0×10 ⁻³	3.1×10 ⁻³	2.6×10 ⁻²	1.6×10 ⁻²	2.1×10 ⁻²
$\sum$ PFSA _s	0.11	7.0×10 ⁻²	7.2×10 ⁻²	3.0	1.8	2.4
$\sum$ PFAAs	0.63	0.41	0.42	22	13	18

水平下,青少年饮水ADD $\sum$ PFAAs值低于成人,表明我国青少年饮水量普遍低于建议量,与文献[49]的报道相符.

中、高等暴露水平下各年龄段居民R_{PFOA}、R_{PFOS}值范围分别为5.0×10⁻¹⁰~2.3×10⁻⁸和1.4×10⁻⁹~6.6×10⁻⁸,均低于居民可接受风险值(10⁻⁷~10⁻⁶[50]).由于PFOA、PFOS之和仅占饮水ADD $\sum$ PFAAs的42%~49%,基于风险评估最大化原则,将 $\sum$ PFCAs视为PFOA, $\sum$ PFSA_s视为

PFOS,即ADD $\sum$ PFCAs、ADD $\sum$ PFSA_s分别除以RfD_{PFOA}、RfD_{PFOS}计算人体暴露的R值,结果显示,仅在高等暴露水平下,R $\sum$ PFSA_s上升至4.5×10⁻⁷~7.7×10⁻⁷,接近可接受风险值上限,尚不构成威胁.但考虑饮水只是PFAAs人体暴露途径之一,故环境PFAAs污染物的监测仍需密切关注.

2.3 蒙特卡罗模拟及不确定度分析

中等暴露水平下,成人ADD $\sum$ PFAAs计算值[0.42 ng·(kg·d)⁻¹]与蒙卡模拟值[0.35

$\text{ng} \cdot (\text{kg} \cdot \text{d})^{-1}$] 的相对偏差为 20% (图 3), 同时, 其 R_{PFOA} (5.1×10^{-10})、 R_{PFOS} (1.5×10^{-9}) 与模拟值 ($R_{\text{PFOA}}: 4.6 \times 10^{-10}$; $R_{\text{PFOS}}: 1.6 \times 10^{-9}$) 的相对偏差分别为 11% 和 6.3%, 显示模型计算结果在可

接受水平. 七大流域覆盖面广, 数据群的标准偏差较大, 以及数据源文献中目标化合物数量、检测分析方法及其检测限存在差异是产生偏差的主要原因.

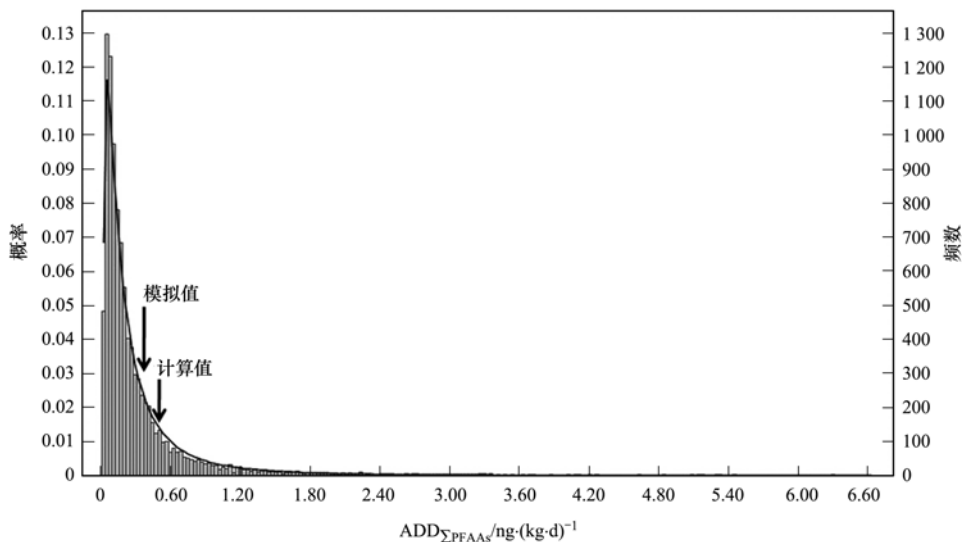


图 3 中等暴露水平下成人饮水的 $\text{ADD}_{\Sigma\text{PFAAs}}$ 频数分布

Fig. 3 Frequency distribution of $\text{ADD}_{\Sigma\text{PFAAs}}$ of adults via drinking water in the intermediate-exposure scenario

3 结论

(1) 中等暴露水平下, 中国七大流域 ΣPFAAs 浓度为 $14 \text{ ng} \cdot \text{L}^{-1}$, 松辽、太湖流域污染水平高于整体, 黄河、长江部分河段污染水平高. 碳链 ≤ 6 的 PFCA 排放有增加趋势.

(2) 中国各年龄段居民饮水 R_{PFOA} 、 R_{PFOS} 值均低于居民可接受风险值, 尚无健康风险. 青少年饮水 $\text{ADD}_{\Sigma\text{PFAAs}}$ 低于成人, 反映其饮水量不足的问题.

参考文献:

- [1] Filipovic M, Woldegiorgis A, Norström K, *et al.* Historical usage of aqueous film forming foam: a case study of the widespread distribution of perfluoroalkyl acids from a military airport to groundwater, lakes, soils and fish [J]. *Chemosphere*, 2015, **129**: 39-45.
- [2] Wang X X, Zhang R B, Zhang H, *et al.* Impact of biological treatment techniques on perfluoroalkyl acids emissions in municipal sewage [J]. *Water, air, & Soil Pollution*, 2016, **227** (5): 149.
- [3] Takahashi M, Ishida S, Hirata-Koizumi M, *et al.* Repeated dose and reproductive/developmental toxicity of perfluoroundecanoic acid in rats [J]. *The Journal of Toxicological Sciences*, 2014, **39** (1): 97-108.
- [4] European Food Safety Authority. Perfluoroalkylated substances in food: occurrence and dietary exposure [J]. *EFSA Journal*, 2012, **10**(6): 2743.
- [5] 王鑫璇, 张鸿, 何龙, 等. 深圳水库群表层水中全氟化合物的分布特征 [J]. *环境科学*, 2014, **35**(6): 2085-2090.
- [6] Wang X X, Zhang H, He L, *et al.* Distribution of perfluorinated compounds in surface water of Shenzhen reservoir groups [J]. *Environmental Science*, 2014, **35**(6): 2085-2090.
- [7] Wang T Y, Chen C L, Naile J E, *et al.* Perfluorinated compounds in water, sediment and soil from Guanting reservoir, China [J]. *Bulletin of Environmental Contamination and Toxicology*, 2011, **87**(1): 74-79.
- [8] 高杰, 李文超, 李广贺, 等. 北京部分地区地下水中全氟化合物的污染水平初探 [J]. *生态毒理学报*, 2016, **11**(2): 355-363.
- [9] Gao J, Li W C, Li G H, *et al.* Preliminary investigation on perfluorinated compounds in groundwater in some areas of Beijing, China [J]. *Asian Journal of Ecotoxicology*, 2016, **11** (2): 355-363.
- [10] 张明, 唐访良, 俞雅云, 等. 钱塘江 (杭州段) 表层水中全氟化合物的残留水平及分布特征 [J]. *环境科学*, 2015, **36** (12): 4471-4478.
- [11] Zhang M, Tang F L, Yu Y Y, *et al.* Residue concentration and distribution characteristics of perfluorinated compounds in surface water from Qiantang River in Hangzhou section [J]. *Environmental Science*, 2015, **36**(12): 4471-4478.
- [12] 王懿. 持久性全氟化合物典型污染源环境污染特性研究 [D]. 南京: 南京农业大学, 2011. 51-63.
- [13] Liu B L, Zhang H, Xie L W, *et al.* Spatial distribution and partition of perfluoroalkyl acids (PFAAs) in rivers of the Pearl River Delta, southern China [J]. *Science of the Total Environment*, 2015, **524-525**: 1-7.
- [14] Yang L P, Zhu L Y, Liu Z T. Occurrence and partition of perfluorinated compounds in water and sediment from Liao River and Taihu Lake, China [J]. *Chemosphere*, 2011, **83**(6): 806-814.

- [12] Wang P, Lu Y L, Wang T Y, *et al.* Shifts in production of perfluoroalkyl acids affect emissions and concentrations in the environment of the Xiaoqing River Basin, China[J]. *Journal of Hazardous Materials*, 2016, **307**: 55-63.
- [13] 陈舒. 中国东部地区典型全氟化合物污染地理分布特征及来源辨析[D]. 北京: 中国地质科学院, 2016. 27-103.
- [14] 路国慧, 沈亚婷, 何俊, 等. 高效液相色谱-串联质谱法测定黄河河口段水中全氟化合物的初步研究[J]. *岩矿测试*, 2012, **31**(1): 147-153.
- Lu G H, Shen Y T, He J, *et al.* Preliminary study on perfluorinated compounds in waters from the Yellow River Estuary Area by utilizing liquid chromatography-mass spectrometry/mass spectrometry[J]. *Rock and Mineral Analysis*, 2012, **31**(1): 147-153.
- [15] Li F S, Sun H W, Hao Z N, *et al.* Perfluorinated compounds in Haihe River and Dagu Drainage Canal in Tianjin, China[J]. *Chemosphere*, 2011, **84**(2): 265-271.
- [16] Lu Z B, Song L N, Zhao Z, *et al.* Occurrence and trends in concentrations of perfluoroalkyl substances (PFASs) in surface waters of eastern China[J]. *Chemosphere*, 2015, **119**: 820-827.
- [17] Zhang Y, Meng W, Guo C S, *et al.* Determination and partitioning behavior of perfluoroalkyl carboxylic acids and perfluorooctanesulfonate in water and sediment from Dianchi Lake, China[J]. *Chemosphere*, 2012, **88**(11): 1292-1299.
- [18] Zhou Z, Shi Y L, Li W H, *et al.* Perfluorinated compounds in surface water and organisms from Baiyangdian Lake in North China: source profiles, bioaccumulation and potential risk[J]. *Bulletin of Environmental Contamination and Toxicology*, 2012, **89**(3): 519-524.
- [19] Bao J, Liu W, Liu L, *et al.* Perfluorinated compounds in the environment and the blood of residents living near fluorochemical plants in Fuxin, China[J]. *Environmental Science & Technology*, 2011, **45**(19): 8075-8080.
- [20] Wang B B, Cao M H, Zhu H D, *et al.* Distribution of perfluorinated compounds in surface water from Hanjiang River in Wuhan, China[J]. *Chemosphere*, 2013, **93**(3): 468-473.
- [21] Yu N Y, Shi W, Zhang B B, *et al.* Occurrence of perfluoroalkyl acids including perfluorooctane sulfonate isomers in Huai River Basin and Taihu Lake in Jiangsu province, China[J]. *Environmental Science & Technology*, 2013, **47**(2): 710-717.
- [22] Sun H W, Li F S, Zhang T, *et al.* Perfluorinated compounds in surface waters and WWTPs in Shenyang, China: mass flows and source analysis[J]. *Water Research*, 2011, **45**(15): 4483-4490.
- [23] Wang T Y, Khim J S, Chen C L, *et al.* Perfluorinated compounds in surface waters from Northern China: comparison to level of industrialization[J]. *Environment International*, 2012, **42**: 37-46.
- [24] So M K, Miyake Y, Yeung W Y, *et al.* Perfluorinated compounds in the Pearl River and Yangtze River of China[J]. *Chemosphere*, 2007, **68**(11): 2085-2095.
- [25] Pan Y Y, Shi Y L, Wang J M, *et al.* Pilot investigation of perfluorinated compounds in river water, sediment, soil and fish in Tianjin, China[J]. *Bulletin of Environmental Contamination and Toxicology*, 2011, **87**(2): 152-157.
- [26] Lu G H, Yang Y L, Taniyasu S, *et al.* Potential exposure of perfluorinated compounds to Chinese in Shenyang and Yangtze River Delta areas[J]. *Environmental Chemistry*, 2011, **8**(4): 407-418.
- [27] Pan G, You C. Sediment-water distribution of perfluorooctane sulfonate (PFOS) in Yangtze River Estuary[J]. *Environmental Pollution*, 2010, **158**(5): 1363-1367.
- [28] 刘冰, 金一和, 于麒麟, 等. 松花江水系江水中全氟辛烷磺酸和全氟辛酸污染现状调查[J]. *环境科学学报*, 2007, **27**(3): 480-486.
- Liu B, Jin Y H, Yu Q L, *et al.* Investigation of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) pollution in the surface water of the Songhua River[J]. *Acta Scientiae Circumstantiae*, 2007, **27**(3): 480-486.
- [29] Zhao X L, Li J D, Shi Y L, *et al.* Determination of perfluorinated compounds in wastewater and river water samples by mixed hemimicelle-based solid-phase extraction before liquid chromatography-electrospray tandem mass spectrometry detection[J]. *Journal of Chromatography A*, 2007, **1154**(1-2): 52-59.
- [30] 金一和, 丁梅, 翟成, 等. 长江三峡库区江水和武汉地区地面水中 PFOS 和 PFOA 污染现状调查[J]. *生态环境*, 2006, **15**(3): 486-489.
- Jin Y H, Ding M, Zhai C, *et al.* An investigation of the PFOS and PFOA pollution in Three Gorges Reservoir areas of the Yangtze River and surface water of Wuhan areas[J]. *Ecology and Environment*, 2006, **15**(3): 486-489.
- [31] 张鸿, 陈清武, 王鑫璇, 等. 自来水处理工艺对溶解相中全氟化合物残留的影响[J]. *环境科学*, 2013, **34**(9): 3467-3473.
- Zhang H, Chen Q W, Wang X X, *et al.* Influence of tap water treatment on perfluorinated compounds residue in the dissolved phase[J]. *Environmental Science*, 2013, **34**(9): 3467-3473.
- [32] Zhou Y S, Tao Y, Li H R, *et al.* Occurrence investigation of perfluorinated compounds in surface water from East Lake (Wuhan, China) upon rapid and selective magnetic solid-phase extraction[J]. *Scientific Reports*, 2016, **6**: 38633.
- [33] Shao M H, Ding G H, Zhang J, *et al.* Occurrence and distribution of perfluoroalkyl substances (PFASs) in surface water and bottom water of the Shuangtaizi Estuary, China[J]. *Environmental Pollution*, 2016, **216**: 675-681.
- [34] Pan C G, Liu Y S, Ying G G. Perfluoroalkyl substances (PFASs) in wastewater treatment plants and drinking water treatment plants; removal efficiency and exposure risk[J]. *Water Research*, 2016, **106**: 562-570.
- [35] Jin Y H, Liu W, Sato I, *et al.* PFOS and PFOA in environmental and tap water in China[J]. *Chemosphere*, 2009, **77**(5): 605-611.
- [36] 中华人民共和国水利部. 开启江河开发治理保护新篇章—聚焦中国七大流域综合规划(修编)[EB/OL]. <http://www.mwr.gov.cn/ztpd/2013ztbd/2013kqjkhfzlbhxpz/>, 2017-03-19.
- [37] Helsel D R. Statistics for censored environmental data using Minitab® and R (2nd ed.)[M]. New Jersey: John Wiley & Sons Inc., 2012. 22-36.
- [38] 刘晓湾, 张鸿, 李静, 等. 中国沿海地区鸡蛋中全氟化合物污染水平及分布[J]. *食品科学*, 2016, **37**(4): 191-196.
- Liu X W, Zhang H, Li J, *et al.* Investigation of contamination levels of perfluorinated compounds in eggs from nine coastal provinces of China[J]. *Food Science*, 2016, **37**(4): 191-196.

- [39] 余葱葱, 赵委托, 高小峰, 等. 电镀厂周边地表水中重金属分布特征及健康风险评价[J]. 环境科学, 2017, **38**(3): 993-1001.
Yu C C, Zhao W T, Gao X F, *et al.* Distribution characteristics and health risk assessment of heavy metals in surface water around electroplating factories [J]. Environmental Science, 2017, **38**(3): 993-1001.
- [40] 唐访良, 张明, 徐建芬, 等. 钱塘江(杭州段)水中有机氯农药残留污染特征及健康风险评价[J]. 环境科学学报, 2015, **35**(11): 3595-3603.
Tang F L, Zhang M, Xu J F, *et al.* Pollution characteristics and health risk assessment of organochlorine pesticides (OCPs) in Qiantang river, Hangzhou Section [J]. Acta Scientiae Circumstantiae, 2015, **35**(11): 3595-3603.
- [41] 环境保护部. 中国人群暴露参数手册(成人卷)[M]. 北京: 中国环境科学出版社, 2013.
- [42] 环境保护部. 中国人群暴露参数手册(儿童卷: 0~5岁)[M]. 北京: 中国环境科学出版社, 2016.
- [43] 环境保护部. 中国人群暴露参数手册(儿童卷: 6~17岁)[M]. 北京: 中国环境科学出版社, 2016.
- [44] Gebbink W A, Berger U, Cousins I T. Estimating human exposure to PFOS isomers and PFCA homologues: the relative importance of direct and indirect (precursor) exposure [J]. Environment International, 2015, **74**: 160-169.
- [45] Von Grote J, Hürlimann C, Scheringer M, *et al.* Reduction of occupational exposure to perchloroethylene and trichloroethylene in metal degreasing over the last 30 years: influences of technology innovation and legislation [J]. Journal of Exposure Analysis and Environmental Epidemiology, 2003, **13**(5): 325-340.
- [46] Wormuth M, Scheringer M, Hungerbühler K. Linking the use of scented consumer products to consumer exposure to polycyclic musk fragrances [J]. Journal of Industrial Ecology, 2005, **9**(1-2): 237-258.
- [47] 中国国家统计局工业统计司. 中国工业统计年鉴 2015 [M]. 北京: 中国统计出版社, 2016.
- [48] 水利部松辽水利委员会. 松辽流域水资源公报 2015 [EB/OL]. <http://www.slwr.gov.cn/szy2011/201701/P020170110494972943464.pdf>, 2016.
- [49] 马冠生. 我国成人及儿童青少年饮水量调查 [A]. 见: 达能营养中心第十五届学术年会论文集 [C]. 重庆: 达能营养中心, 2012. 108-114.
- [50] 成兴源. 城市污水处理厂出水用于绿化灌溉时全氟辛酸健康风险评价 [D]. 兰州: 兰州交通大学, 2013.



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