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环境科学
ENVIRONMENTAL SCIENCE

ISSN 0250-3301 CODEN HCKHDV
HUANJING KEXUE

■ 主办 中国科学院生态环境研究中心
■ 出版 科学出版社

2020
Vol.41 No.11
第41卷 第11期

环境科学
(HUANJING KEXUE)
ENVIRONMENTAL SCIENCE
第41卷　第11期
2020年11月15日

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环 境 科 学
Environmental Science

第41卷第11期 2020年11月
Vol.41, No.11 Nov., 2020

长江流域淡水生态系统内分泌干扰物、药物和个人护理品的风险排序

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摘要：作为新兴污染物，内分泌干扰物、药物和个人护理品因其排放对水环境安全产生的风险而引起了广泛关注. 本文以长江流域为例，以 69 种内分泌干扰物、药物和个人护理品的环境暴露数据和生态毒性数据为基础，计算它们的生态风险并进行高低排序，以识别最优先控制的污染物. 结果表明，内分泌干扰物和个人护理品对水生生态系统的风险较高，如雌酮（estrone）、雌三醇（estriol）、17β-雌二醇（17β-estradiol）、双酚 S（bisphenol S）、阿特拉津（atrazine）、三氯卡班（triclocarban）和三氯生（triclosan）；而药物的风险低 500 倍或更多. 相较而言，药物中风险较高的属抗生素类. 湘江和洪湖及其周边河流内多种污染物的浓度呈现出最高值，是长江流域污染最重的区域，其次是太湖、洞庭湖和长江三角洲地区. 与藻类和虫类相比，鱼类是对内分泌干扰物、药物和个人护理品最敏感的物种，尤其对 17α-乙炔雌二醇（17α-ethynylestradiol）和 17β-雌二醇. 本文的研究结果可对我国化学品的监测和管理提供数据支撑.

关键词：长江流域；内分泌干扰物（EDCs）；药物；个人护理品；风险排序

中图分类号：X52；X820.4 **文献标识码**：A **文章编号**：0250-3301（2020）11-4981-08 **DOI**：10.13227/j.hjkx.202003210

Risk Ranking of Endocrine Disrupting Compounds, Pharmaceuticals, and Personal Care Products in the Aquatic Environment of the Yangtze River Basin

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Abstract: Endocrine disrupting compounds（EDCs）, pharmaceuticals, and personal care products（PPCPs）have been of great concern as emerging contaminants of aquatic environments. In this study, the risks of EDCs and PPCPs in the Yangtze River Basin were ranked, based on their environmental exposure datasets and ecotoxicity datasets. The prioritized chemicals were then identified. The results found that EDCs and personal care products were deemed to represent higher risks to aquatic organisms, for example, estrone, estriol, 17β-estradiol, bisphenol S, atrazine, triclocarban, and triclosan, while the risks of pharmaceuticals were 500-fold lower. Among the pharmaceuticals, antibiotics posed relatively higher risks. The Xiangjiang River and Honghu Lake with its surrounding rivers were hotspots where more chemicals were found with the highest concentrations, followed by Taihu Lake, Dongting Lake and the Yangtze River Delta. When comparing with algae and worms, fish were the most sensitive taxa to 17β-estradiol and 17α-ethynylestradiol. The results of this work provide sound guidance for the future monitoring and management of chemicals in China.

Key words: Yangtze River Basin; endocrine disrupting compounds（EDCs）; pharmaceuticals; personal care products; risk ranking

近些年来，内分泌干扰物（endocrine disrupting compounds, EDCs）、药物和个人护理品（pharmaceuticals and personal care products, PPCPs）作为新兴污染物受到了众多环保工作者的广泛关注[1~8]. 药物主要用于预防或治疗人畜疾病，包括抗生素、止痛药和血脂调节剂等，其中抗生素因其广泛应用而受到特别关注[4,7,8]. 在治疗期间和治疗之后，动物和人类排泄代谢部分或完整的药物，而这些药物最终直接或间接地排放到环境中[8]. 个人护理品（如消毒剂、香水、洗发水和防晒霜等）常被用于改善人们的生活质量[7]. 内分泌干扰物是一类即使在浓度极低的情况下，依然会影响动物和人类的生殖、发育过程或干扰其内分泌系统的化学物质[5,9]；它们通常来自于人畜的排泄物（如合成类固醇激素的药物和合成雄激素）或人造产品（如塑料制品）[10].

目前 EDCs 和 PPCPs 在世界范围内被广泛使用，并且极易排放到环境中. 这些物质大多数易溶于水，因此 EDCs 和 PPCPs 在世界各地的淡水环境中被普遍检出[1,11~13]. 而且，这些物质中的大多数具有持久性有机污染物的特点，即持久性、毒性和生物富集性. 因此，EDCs 和 PPCPs 对生态系统健康的不良影响引起了广泛关注.

由于我国的快速发展和人口激增，我国成为 EDCs 和 PPCPs 的最大生产国和消费国. 据估算，2011 年我国的药品消费量约为 200 万 t，其中抗生

收稿日期：2020-03-21；**修订日期**：2020-05-09

基金项目：山西省高等学校科技创新项目（2019L0017）；山西省高等学校“服务产业创新学科群建设计划”项目（20181401）；国家自然科学基金项目（41771548）

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素的消费量超过了 18 万 t,人均消费量远远超过美国[14,15],这间接导致了抗生素在水环境中的普遍检出. 另外,其他种类的药物、个人护理品和内分泌干扰物也在水环境中普遍存在. 鉴于众多种类的化学物质被检出,那么,分析每种化学物质的相对风险,并确定需要优先控制的污染物已显得非常必要. 长江流域是我国的第一大流域,流域面积约占中国陆地总面积的 1/5,水资源总量超过全国河流径流量的 1/3,人口和经济总量均超过全国的 40%[16,17]. 因此,本文以长江流域为研究区,以文献搜集到的 EDCs 和 PPCPs 的环境暴露浓度和生态毒性浓度为数据基础,计算每种污染物的生态风险并确定优先控制的污染物,分析长江流域的热点污染区域,识别最敏感的生物群,以期为化学品的风险管理提供数据基础.

1 材料与方法

1.1 污染物筛选及环境暴露数据收集

污染物的选择由其可获得性和环境暴露数据的质量决定. 中文文献来自中国知网、维普和万方数据库,同时包括硕士毕业论文和博士毕业论文. 英文文献来自于 Web of Science 和 Google Scholar 两个数据库. 首先,以“内分泌干扰物 & 水/河/湖 & 中国”、“药物 & 水/河/湖 & 中国”、“抗生素 & 水/河/湖 & 中国”和“个人护理品 & 水/河/湖 & 中国”为主题关键词进行文献搜索. 之后筛选出属于英文 SCI 期刊和中文核心期刊(包括所有硕士和博士毕业论文)且采样位置位于长江流域的文献进行统计. 本文只统计采样时间在 2014 年 1 月至 2019 年 9 月的文献. 若文献里的浓度数据模糊、采样时间不符、地理信息不匹配或不清等,则予以删除. 对于检索到的数据,若文献里明确说明数据有异常值,则删除异常值,否则保留全部数据. 对于任何一种污染物而言,纳入研究的物质必须至少包含 3 个采样点的数据. 此外,本文不考虑排污河和水库的浓度数据. 当污染物的暴露浓度低于检出限(LOD)时,其浓度用 LOD/$\sqrt{2}$表示[14,18,19].

1.2 生态毒理数据收集和筛选

污染物的生态毒理数据主要在美国环保署(USEPA)网站的 ECOTOX 数据库里下载得到,同时包括了从文献中检索到的毒性数据. 这里的毒性数据库包括了大多数物种(如藻类、鱼类、植物和软体动物等)的效应浓度. 首先,从数据库里中提取出环境介质为淡水的毒性数据. 其次,本文同时考虑了毒性数据的致死和亚致死效应浓度. 对任一物种,EC_{50} (effect concentration 50)和 LC_{50} (lethal concentration 50)是最优先选择的评价终点,其次为 EC_{xx} 和 LC_{xx} (如 EC_{20}、EC_{10} 和 LC_{20} 等),最后为最低效应浓度(LOEC)[14,18,19]. 对任一物种,若同一评价终点下有多个值,那么选取最低值. 随后,只有中国的本土物种和标准测试物种数据被保留. 最后,对于任何一种污染物而言,纳入研究的物质必须至少包含 3 条毒性数据.

1.3 风险评价

收集完成污染物的毒性数据集和暴露数据集后,它们反映出的信息便可以分别绘制出来. 对每一种污染物的每一个数据集,需要计算出它们的中值. 那么,毒性数据集和暴露数据集的中值的接近程度可以用一个比例来表示,如公式(1)所示,这个比例被定义为污染物的风险 R[20~23]. 那么,比值越大,表示污染物的风险越大.

$$R = \frac{M_{\mathrm{w}}}{M_{\mathrm{T}}} \tag{1}$$

式中,M_{w} 表示暴露浓度的中值($ng \cdot L^{-1}$),M_{T} 表示毒性数据的中值($ng \cdot L^{-1}$).

此外,这个方法还可用来比较特定污染物对不同生物群体(如藻类和鱼类等)的相对风险,从而识别最敏感的生物群体.

2 数据概况与范围

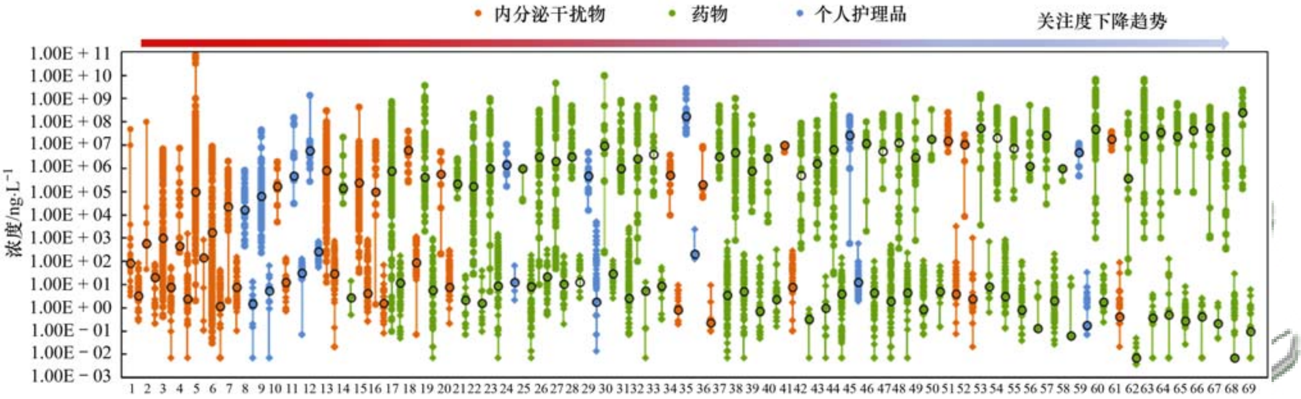
根据上述数据检索规则,本文共综述了 257 篇文献,其中 204 篇由于浓度数据模糊、采样时间不符、地理信息不匹配或不清等原因不予考虑. 最后进行统计的文献中,包括 19 篇中文和 34 篇英文文献. 数据统计完成后发现,有 117 种 EDCs 和 PPCPs 至少被报道了一次; 之后,由于缺乏充分的暴露数据或毒性数据,共有 69 种 EDCs 和 PPCPs 参与风险排序,包括 19 种内分泌干扰物, 41 种药物和 9 种个人护理品. 初步分析发现,大多数的药物为抗生素,包括磺胺类、四环素类、大环内酯类和氟喹诺酮类. 个人护理品中,作为广谱杀菌剂的三氯生(TCS)和三氯卡班(TCC)是报道最多的两种. 此外,酚类 EDCs(如双酚 A 和双酚 S)和甾体类 EDCs(如 17β-雌二醇和 17α-乙炔雌二醇)是最主要的两类内分泌干扰物.

3 结果与讨论

3.1 淡水环境中污染物的风险排序

基于污染物对所有生物种的风险,本文得到了 69 种污染物的相对风险排序结果(图 1). 从图 1 中可看出,整体上,内分泌干扰物(橘色)和个人护理品(蓝色)表现出较高风险,而药物(绿色)呈现出较低风险. 风险最高的 10 种物质依次是雌酮(E1)、雌

三醇(E3)、17β-雌二醇(βE2)、双酚 S(BPS)、阿特拉津(ATZ)、17α-乙炔雌二醇(EE2)、对-特辛基苯酚(4-t-OP)、三氯卡班(TCC)、三氯生(TCS)和双酚AF(BPAF),即以内分泌干扰物和个人护理品为主.相比之下,苯甲酮-2(BP-2,排名 59)和对-羟基苯甲酸乙酯(EtP,排名 61)对生物体的风险较低.与雌酮的风险相比,药物的风险低 500 倍或更多(图 2).药物中,风险较高的是抗生素类,如洛美沙星(LOM)、磺胺甲噁唑(SMX)、红霉素(ETM)、强力霉素(DOX)、四环素(TC)和罗红霉素(RTM)等,以及氟西汀(FLX);然而,氯霉素(CHP)、吉非贝齐(GFB)、美托洛尔(MTP)、吲哚美辛(IMC)、磺胺噻唑(STZ)、萘普生(NAP)、对-乙酰氨基酚(ACE)和苯扎贝特(BZB)等污染物处于较低风险. Li 等[24]的评价结果认为,在众多药物中,双氯芬酸(DIC)、红霉素、青霉素、阿奇霉素和阿莫西林等抗生素类药物是中国淡水环境风险最高的物质;与之相比,本文发现,在长江流域,上述内分泌干扰物和个人护理品的风险总体上高于双氯芬酸、红霉素和阿莫西林等药物的风险.此外,观察图 1 中毒性数据集的较小值和暴露数据集的较大值,发现多种污染物的暴露数据和毒性数据表现出较大比例的重叠分布,如雌酮、17β-雌二醇、双酚 S、阿特拉津、17α-乙炔雌二醇和对-特辛基苯酚等,表明多种水生生物处于危险状态.



1. estrone (E1), 2. estriol (E3), 3. 17β-estradiol (βE2), 4. bisphenol S (BPS), 5. atrazine (ATZ), 6. 17α-ethynylestradiol (EE2), 7. 4-tert-octylphenol (4-t-OP), 8. triclocarban (TCC), 9. triclosan (TCS), 10. bisphenol AF (BPAF), 11. benzophenone-4 (BP-4), 12. benzophenone (BP), 13. bisphenol A (BPA), 14. lomefloxacin (LOM), 15. 4-nonylphenol (4-NP), 16. testosterone (TES), 17. sulfamethoxazole (SMX), 18. 4-tert-butylphenol (4-TBP), 19. erythromycin (ETM), 20. 4-octylphenol (4-OP), 21. doxycycline (DOX), 22. fluoxetine (FLX), 23. tetracycline (TC), 24. phantolide (PHE), 25. roxithromycin (RTM), 26. ibuprofen (IBU), 27. caffeine (CAF), 28. sulfadimidine (SMD), 29. benzophenone-3 (BP-3), 30. diazepam (DZM), 31. oxytetracycline (OTC), 32. clofibric acid (CA), 33. lincomycin (LCM), 34. diethylstilbestrol (DES), 35. p-hydroxybenzoic acid (PHBA), 36. butyl paraben (BuP), 37. sulfamethazine (SMZ), 38. ofloxacin (OFL), 39. norfloxacin (NOR), 40. mefenamic acid (MA), 41. 4-butylphenol (4-BP), 42. diphenhydramine (DHM), 43. phenazone (PHO), 44. carbamazepine (CBZ), 45. diethyltoluamide (DEET), 46. climbazole (CLM), 47. sulfadiazine (SDZ), 48. diclofenac (DIC), 49. ciprofloxacin (CIP), 50. florfenicol (FFC), 51. methyl paraben (MeP), 52. propyl paraben (PrP), 53. amoxicillin (AMX), 54. chlortetracycline (CTC), 55. enrofloxacin (ENR), 56. thiamphenicol (TAP), 57. trimethoprim (TMP), 58. tylosin tartrate (TS), 59. benzophenone-2 (BP-2), 60. paracetamol (PRC), 61. ethyl paraben (EtP), 62. bezafibrate (BZB), 63. acetaminophen (ACE), 64. naproxen (NAP), 65. sulfathiazole (STZ), 66. indomethacin (IMC), 67. metoprolol (MTP), 68. gemfibrozil (GFB), 69. chloramphenicol (CHP); 每种污染物的左边列和圆形图例表示毒性数据,右边列和菱形图例表示环境暴露数据; 每一个数据集的中值以空心圆表示

图 1　基于配对的毒性数据和环境暴露数据的 69 种污染物的风险排序

Fig. 1　Risk ranking of 69 chemicals using paired datasets of all the collected ecotoxicity data and measured freshwater concentrations

雌酮对长江流域的生物体表现出最大风险,风险值 R 为 0.040,其次为雌三醇($R=0.034$)和 17β-雌二醇($R=0.0079$),见图 2.长江流域的河(湖)水中,雌酮的暴露浓度的中值为 3.00 ng·L^{-1}.雌酮的最低效应浓度(也即最敏感)为 3.30 ng·L^{-1},为幼年虹鳟鱼(*Oncorhynchus mykiss*)的 LOEC 值[25];对斑马鱼(*Danio rerio*)而言,暴露 18 d 的 EC$_{50}$ 值低至 78.00 ng·L^{-1}[26].雌酮和雌三醇是常见且流行的类固醇化合物,被广泛用为口服避孕药和人类、牲畜疾病的治疗药物,因此常作为人和牲畜的排泄物进入环境[27].正是由于它们的广泛使用,它们在世界各地的地表水中的检出率超出 70%,浓度范围从 ng·L^{-1}至μg·L^{-1}不等[5].长江流域作为我国第一大流域,人口总量超过全国的 40%[16, 17],养殖业发达,导致雌酮和雌三醇的暴露浓度范围分别为 ND ~ 84.00 ng·L^{-1}和 ND ~ 82.00 ng·L^{-1}.此外,内分泌干扰物和个人护理品被广泛用于人类的各种消费品中,随着长江流域城市化和现代化水平的快速发展,产生了大量含有内分泌干扰物和个人护理品的生活污水、工业废水和养殖废水,而这些物质在废水处理

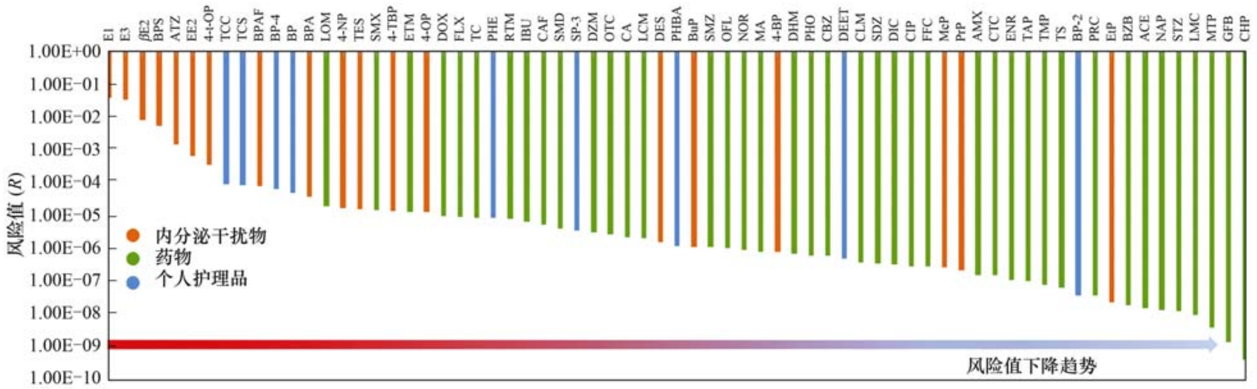


图 2 基于污染物暴露数据和毒性数据中值的风险值排序结果

Fig. 2 Risk ranking of the chemicals by plotting the ratios of the median environmental concentrations and median effect concentrations

过程中并不能被完全去除,因此这些物质可能经污水处理厂排放、养殖废水排放和地表径流等方式进入长江水域,从而造成内分泌干扰物和个人护理品在长江流域的高暴露水平[28].加之它们的效应浓度较低,因此内分泌干扰物和个人护理品呈现出较高风险.

表 1 EDCs 和 PPCPs 的最高浓度分析1) /ng·L^{-1}

Table 1 Rivers/lakes with the highest reported concentrations of EDCs and PPCPs/ng·L^{-1}

排名	物质	最高浓度	相应位置	排名	物质	最高浓度	相应位置
1	E1	83.52	洪湖[32]	36	BuP	9.50	湘江[49]
2	E3	81.60	三峡库区[10]	37	SMZ	715.30	洪湖周边河流[45]
3	βE2	58.94	洪湖[32]	38	OFL	203.70	洪湖周边河流[45]
4	BPS	1 569.00	太湖[33]	39	NOR	142.00	东荆河[41]
5	ATZ	496.00	京杭运河[34]	40	MA	324.03	长江三角洲[46]
6	EE2	43.93	洪湖[32]	41	4-BP	282.40	太湖[42]
7	4-t-OP	156.10	湘江[9]	42	DHM	0.89	汉江[35]
8	TCC	12.66	汉江[35]	43	PHO	22.50	东洞庭湖[44]
9	TCS	65.60	长江中游[36]	44	CBZ	145.95	长江三角洲[46]
10	BPAF	140.00	太湖[37]	45	DEET	574.75	长江三角洲[46]
11	BP-4	131.00	黄浦江[38]	46	CLM	100.00	湘江[47]
12	BP	712.59	苏州河[38]	47	SDZ	499.50	洪湖周边河流[45]
13	BPA	771.50	湘江[9]	48	DIC	230.05	东洞庭湖[44]
14	LOM	14.60	太湖[39]	49	CIP	106.20	洪湖周边河流[45]
15	4-NP	858.00	长江(南京段)[40]	50	FFC	63.50	太湖[39]
16	TES	70.40	湘江[9]	51	MeP	3 173.90	湘江[49]
17	SMX	173.46	三峡库区[41]	52	PrP	1 040.40	湘江[49]
18	4-TBP	1 121.00	长江(南京段)[40]	53	AMX	710.00	湘江[47]
19	ETM	982.00	东荆河[41]	54	CTC	876.20	洪湖周边河流[45]
20	4-OP	305.10	太湖[42]	55	ENR	96.55	鄱阳湖[43]
21	DOX	23.93	鄱阳湖[43]	56	TAP	12.00	湘江[47]
22	FLX	40.20	东洞庭湖[44]	57	TMP	209.69	三峡库区[50]
23	TC	1454.80	洪湖周边河流[45]	58	TS	19.50	三峡库区[51]
24	PHE	66.41	长江三角洲[46]	59	BP-2	34.70	黄浦江[38]
25	RTM	190.00	湘江[47]	60	PRC	65.50	汉江[35]
26	IBU	320.00	湘江[47]	61	EtP	87.00	湘江[49]
27	CAF	174.40	东洞庭湖[44]	62	BZB	0.05	洞庭湖[52]
28	SMD	172.40	洪湖[45]	63	ACE	3.88	洞庭湖[52]
29	BP-3	5 013.07	黄浦江[38]	64	NAP	125.71	长江三角洲[46]
30	DZM	104.92	长江三角洲[46]	65	STZ	8.18	太湖[39]
31	OTC	2 796.60	洪湖周边河流[45]	66	IMC	2.70	湘江[47]
32	CA	13.00	太湖[48]	67	MTP	1.60	东洞庭湖[44]
33	LCM	53.80	太湖[39]	68	GFB	30.50	洞庭湖[52]
34	DES	9.60	湘江[9]	69	CHP	6.10	湘江[47]
35	PHBA	2 380.00	长江中游[36]				

1)表中污染物的排名和图 1 的一致

环境科学

在风险较高的药物中，氟西汀为临床广泛应用的抗抑郁药物，其环境浓度范围为 ND ~ 40.20 ng·L^{-1}，中值为 1.60 ng·L^{-1}；其效应浓度的中值为 169.81 μg·L^{-1}. 洛美沙星、磺胺甲噁唑、红霉素、强力霉素、四环素和罗红霉素都是常用的抗生素. 在长江流域，洛美沙星、磺胺甲噁唑、红霉素、强力霉素、四环素和罗红霉素的环境浓度范围分别为 0.50 ~ 14.60、ND ~ 173.46、ND ~ 982.00、ND ~ 23.93、ND ~ 1454.80 和 ND ~ 190.00 ng·L^{-1}，中值分别为 2.85、11.80、5.80、2.20、8.89 和 8.10 ng·L^{-1}. 它们效应浓度的中值分别为 141.50、775.00、430.00、215.50、1 000.00和1 000.00 ng·L^{-1}. 文献报道的洛美沙星的效应浓度的最低值为 30.00 μg·L^{-1}，为暴露 7 d 的浮萍（*Lemna gibba*）的 LOEC 值，该浓度会影响浮萍的繁殖[29]. 磺胺甲噁唑的效应浓度的最低值为 3.36 μg·L^{-1}，为暴露 7 d 的浮萍的 EC$_{50}$值. 事实上，磺胺类、氟喹诺酮类和大环内酯类的抗生素在中国的消费量约占抗生素总消费量的 12%、15% 和 20%[14,30,31]. 然而，现有的研究结果发现抗生素对水生生物体是相对安全的，而且本文没有考虑生物体对抗生素的抗药性.

3.2　热点污染区域分析

每种污染物的最高浓度及其相应位置见表 1. 从中可知，湘江是长江流域污染最重的河流，其中 15 种污染物的最高浓度均位于此，包括对-特辛基苯酚[9]、双酚 A（BPA）[9]、睾酮（TES）[9]、罗红霉素[47]、布洛芬（IBU）[47]、己烯雌酚（DES）[49]、对-羟基苯甲酸丁酯（BuP）[49]、氯咪巴唑（CLM）[47]、对-羟基苯甲酸甲酯（MeP）[49]、对-羟基苯甲酸丙酯（PrP）[49]、阿莫西林（AMX）[47]、甲砜霉素（TAP）[47]、对-羟基苯甲酸乙酯（EtP）[49]、吲哚美辛[47]和氯霉素[47]. 污染热点区域其次是洪湖及其周边河流[32,45]、太湖[33,37,39,42,48]、洞庭湖[44,52]和长江三角洲地区[46]. 另外，从污染物的风险高低顺序可看出，洪湖及其周边河流、太湖和湘江的多种污染物处于较高风险（表 1）.

湘江是长江流域的一个主要支流，长约 856 km，流域人口大于 4 千万，被誉为湖南省的“母亲河”，是湖南省的重要经济纽带[9,47]. 湘江流域包含着许多养殖区、工业区、耕作区、医院和药品生产企业[47]. 近些年来，随着人口增长、经济发展和快速的城市化过程，湘江流域的水污染现象日益突出. 有研究表明，工业加工助剂是对-特辛基苯酚和双酚 A 的主要来源[9]；此外，污水处理厂污水的低处理效率和生活污水的直接排放也是上述污染物的主要来源[47,49].

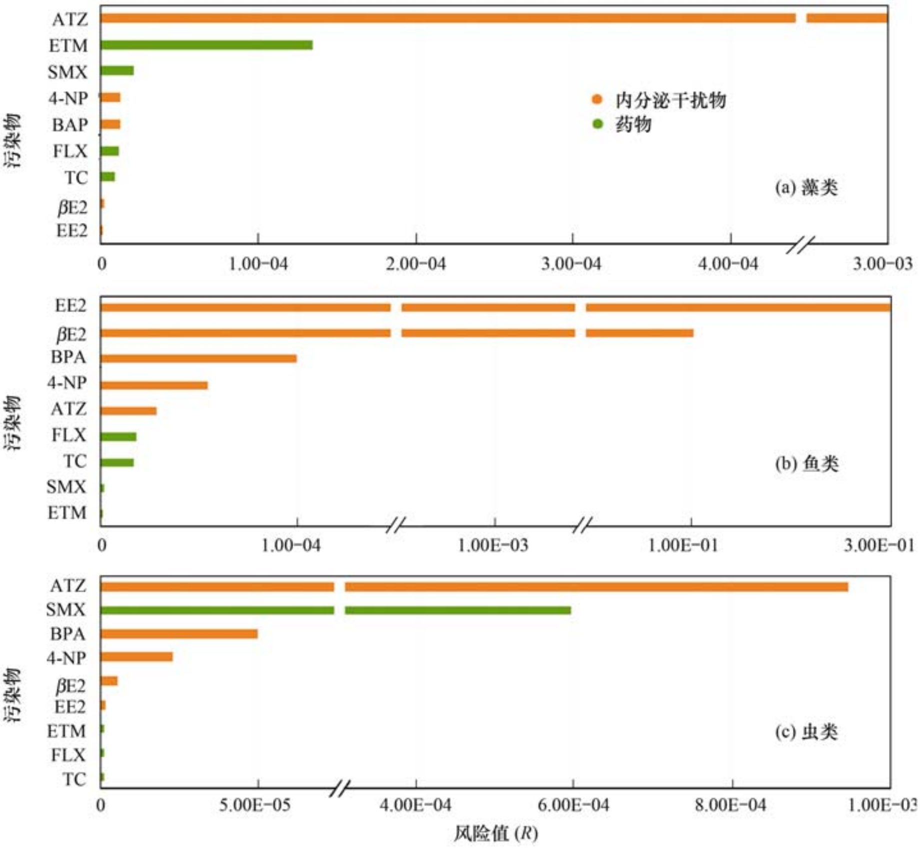


图 3　部分内分泌干扰物和药物对藻类、鱼类和虫类的风险排序

Fig. 3　Risk ratio ranking of some EDCs and pharmaceuticals by algae, fish, and worms

洪湖是长江中游的一个典型浅水湖,水产养殖业是其支柱产业,围网养鱼现象在洪湖周边普遍存在; 而围栏和围网是围网养殖业的主要方式,因此成为内分泌干扰物的主要来源[32]. 另外,洪湖周边的人口密集,畜牧业也非常发达(>8 百万头猪),有大量生活污水和畜牧业污水排入湖内,而内分泌干扰物和抗生素被广泛用于人类生活和水产养殖业、畜牧业中,因此洪湖及其周边河流内的多种内分泌干扰物和抗生素呈现出最高水平[45].

3.3 敏感物种识别

根据图 1 的风险排序结果,本文选择排名前 40 的污染物,并筛选出那些毒性数据包含共同生物群的污染物,来进行敏感物种分析. 这些污染物是阿特拉津、红霉素、磺胺甲噁唑、对-壬基苯酚(4-NP)、双酚 A、氟西汀、四环素、17β-雌二醇和 17α-乙炔雌二醇,之后分别计算出这些污染物对藻类、鱼类和虫类的风险,计算得到的风险排序结果见图 3. 从中可知,内分泌干扰物对藻类、鱼类和虫类的风险都较高. 具体地,阿特拉津对藻类和虫类的风险较高,风险值几乎处于同一量级,但是对鱼类的风险较低(图3). 17α-乙炔雌二醇和 17β-雌二醇(分别排名 1 和 2)对鱼类的风险远远高于其他污染物,但是对藻类(分别排名 8 和 9)和虫类(分别排名 5 和 6)的风险极低. 另一区别是,药物(红霉素和磺胺甲噁唑)对藻类和虫类呈现出较高风险,而对鱼类的风险很低.

从风险值来看,与藻类和虫类相比,鱼类是最敏感的生物,尤其是对 17α-乙炔雌二醇和 17β-雌二醇,风险值分别为 0.27 和 0.10[图 3(b)],约为藻类和虫类的100 000倍. 与这两种污染物相比,其他污染物对鱼类的风险低1 000倍或更多. 藻类是对阿特拉津(一种除草剂)最敏感的物种,而鱼类是最不敏感的. 相比之下,因为较高的效应浓度,虫类是最不敏感的物种.

4 结论

(1)内分泌干扰物和个人护理品的生态风险相对较高,而药物的风险较低; 药物中,风险较高的属抗生素类.

(2)湘江流域是长江流域污染最重的区域,其次是洪湖及其周边河流、太湖、洞庭湖和长江三角洲地区.

(3)与藻类和虫类相比,鱼类是最敏感的物种,尤其对 17α-乙炔雌二醇和 17β-雌二醇,风险值约为藻类和虫类的100 000倍. 相比之下,虫类是最不敏感的物种.

(4)长江流域是我国的第一大流域,对其淡水生态系统的新兴污染物开展风险评估及排序,可为化学品的风险管理提供指导.

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