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RESEARCH ARTICLE

Emerging contaminants in Brazilian aquatic environment: identifying targets of potential concern based on occurrence and ecological risk

Marisa de Jesus Silva Chaves[1] · Sergiane Caldas Barbosa[1] · Ednei Gilberto Primel[1]

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Abstract

Although studies have shown the presence of Contaminants of Emerging Concern (CECs) in the Brazilian environment in recent decades, several biological effects on the aquatic ecosystem are unknown. Brazil is the fifth largest country in extension in the world, and its wide territory presents geographic regions with diverse demographic and economic characteristics. In order to identify targets of potential concern based on occurrence and ecological risk, available data from previous studies were examined to conduct environmental risk analysis and provide a ranking of CECs in Brazilian aquatic environment based on environmental concentration measured in the last 10 years. The results indicate that 17α-ethynylestradiol, 17ß-estradiol, acetaminophen, Bisphenol A, caffeine, diclofenac, ibuprofen, methylparaben, sulfamethoxazole and triclosan are the CECs that represent the greatest threats to the Brazilian environment. Therefore, these contaminants should be considered as a priority in future monitoring studies. Besides, identification of target monitoring compounds can facilitate the selection of pollutant candidates in future legislations.

Keywords PPCPs · Environmental occurrence · Surface water · Risk assessment · Priority contaminants · Pollution

Introduction

Contaminants of Emerging Concern (CECs) are biologically active and potentially toxic molecules of recent or prolonged use in which its isolated and combined effects to the aquatic ecosystem are still unknown (Deere et al. 2020). CECs include pesticides, fragrances, plasticizers, hormones, flame retardants, nanoparticles, siloxanes, among others (López-Pacheco et al. 2019); however, the main group of CECs are pharmaceutical and personal care products (PPCPs) such as antibiotics, anti-inflammatory, central nervous system stimulators, ß-blockers, lipid regulators, anticonvulsant, X-ray contrast media, insect repellents, antimicrobials, preservatives and sunscreen UV filters (Kovalakova et al. 2020; Liu et al. 2020b).

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✉ Ednei Gilberto Primel
eprimelfurg@gmail.com

[1] Post-Graduate Program in Technological and Environmental Chemistry, Escola de Química e Alimentos, Laboratório de Análise de Compostos Orgânicos e Metais (LACOM), Universidade Federal do Rio Grande, Av Itália, km 8, Rio Grande, RS 96201-900, Brazil

Research carried out in the last 10 years had detected the presence of CECs in Brazilian aquatic environments. Arsand et al. (2020) studied the occurrence of 40 antibiotics of different classes in surface water from Dilúvio River during a 2-year period and its association with the presence of antibiotic resistance genes. Roveri et al. (2020) screened and quantified 23 pharmaceutical compounds (including illicit drugs), at two sampling points near the diffusers of the Guarujá submarine outfall, State of São Paulo, Brazil, where caffeine, diclofenac, valsartan, benzoylecgonine and cocaine were the main compounds detected. Santos et al. (2020) monitored pharmaceutical compounds during 1 year in four Brazilian water sources, aiming to understand the factors that influence their occurrence and removal in conventional drinking water treatment plants (DWTPs) and to assess the environmental and human health risks. Starling et al. (2019) published the first review about occurrence, control and fate of CECs in environmental compartments in Brazil, in which data gathered indicated that caffeine, acetaminophen, atenolol, ibuprofen, cephalexin and bisphenol A occur in μg L^{-1} range in streams near urban areas. However, most of the published studies have not carried out an environmental risk assessment; therefore, the risks caused in aquatic organisms are still unknown.

Brazil is the fifth largest country in extension and the sixth most populous in the world, with an area of 8,515,767 km^2 and about 211 million inhabitants. It is divided into five geographic regions, which present considerable differences in relation to economic, demographic and sanitation characteristics. The southeast region houses the largest industrial park in the country and more than a third of the Brazilian population, about 89 million inhabitants. While in the other regions, dwell about 57, 30, 18 and 17 million inhabitants in northeast, south, north and midwest, respectively (IBGE 2020). According to the latest Statistical Yearbook of the Pharmaceutical Market published in Brazil, there are 1794 different active pharmaceutical ingredients registered, totaling 6587 pharmaceutical presentations on sale. Among the most commercialized pharmaceuticals products are acetaminophen, atenolol, ibuprofen and sodium diclofenac in association with caffeine (BRASIL, 2018).

The environmental occurrence patterns of pharmaceuticals could be estimated establishing a relationship between human drug use and its presence in the aquatic environment. However, available data is still inadequate to establish the country-specific data for pharmaceutical consumption due to the uncertainty related to the consumption estimates and related to those pharmaceuticals sold as unregulated "over the counter drugs". Besides, the consumption patterns of pharmaceuticals can be influenced by socioeconomic conditions, seasonal changes and on the basis of location/region, affecting the establishment of the relation of PPCP consumption patterns with environmental occurrence (Patel et al. 2019).

Determination of CECs in the environment increased in the last decade due to advancement of analytical chemistry and sample preparation techniques that allowed the quantification of concentrations between μg and ng L^{-1} (López-Pacheco et al. 2019). However, in addition to occurrence studies, a more careful view must be given to the environmental risks caused by CECs to aquatic organisms. Chemicals with low detection frequency but with high ecological risk should be carefully analyzed. More approaches are needed to provide a rigorous scientific basis for identifying the environmentally hazardous compounds. Therefore, the aim of this study was to conduct a detailed review of CECs (pharmaceuticals and personal care products, illicit drugs, plasticizers and hormones) in Brazilian surface water and to perform environmental risk assessment (ERA) using concentrations reported in the last 10 years (2010 to 2020), generating technical support for risk management of CECs in Brazil.

Material and methods

Review and data collection

Occurrence and quantification data of CECs were obtained from previous studies performed in the Brazilian aquatic ecosystem. Peer-reviewed publications published between 2010 and 2020 using the keywords "emerging contaminants", "PPCPs", "surface water" and "Brazil" were reviewed. These studies reported data on 73 CECs, including pharmaceuticals, hormones, plasticizers and personal care products (PCPs) detected in surface waters.

Ecotoxicity data of chemicals for algae, crustaceans and fish were obtained from the ECOTOX database of United States Environmental Protection Agency (USEPA) and previous studies. Effect concentration 50 (EC50) and lethal concentration 50 (LC50) were selected as endpoints for each species for growth, reproduction or lethality. The lowest EC50 or LC50 was selected when there were more than one value reported for the same endpoint. Toxicity data for at least three trophic levels for each chemical was used.

Environmental risk assessment

Environmental Risk Assessment (ERA) of CECs in Brazilian aquatic environment was conducted according to the Technical Guidance Document on risk assessment from European Commission (Eur, E. C 2003) for ecological multiple level using the Risk Quotient (RQ) (Eq. 1).

$$RQ = \frac{MEC}{PNEC} \quad (1)$$

In Eq. 1, MEC is the maximum environmental concentration measured on surface water samples (ng L^{-1}), and PNEC is the predicted no-effect concentration to aquatic organism (ng L^{-1}). Ecotoxicological data are presented in Supplementary Material—Table S1, in addition to being available on the US EPA ECOTOX database (2020) (https://comptox.epa.gov/dashboard/). In determining of PNEC values for each chemical and species, an appropriated assessment factor (AF) was used to account for any uncertainty associated with the available data. AFs were selected according to Technical Guidance Document from the European Commission (AF 10, 50, 100 or 1000, depending on the toxicity values used) (Eur, E. C 2003). Environmental risk was divided into four classes: $RQ < 0.01$, insignificant risk, $RQ \leq 0.1$, low risk and no adverse effects are expected, $0.1 \leq RQ \leq 1.0$, moderate risk, therefore possible adverse effects should be taken into consideration and $RQ \geq 1.0$, high risk, thus it is probable that adverse effects may occur (Sharma et al. 2019).

Prioritization of CECs in Brazilian aquatic environments

Based on the frequency of detection of CECs in Brazilian surface water, concentrations and the environmental risk involved, chemicals were selected to compose the priority ranking of CECs in Brazil, considering studies from the last decade. Those with frequency of detection ≥ 50% were selected, in addition to those with moderate to high environmental risk. Chemicals with high environmental risk reflect the impact of urbanization and industrialization on the environment. Less populated and less socioeconomically developed regions (e.g. Brazilian North, 18,195,973 population) showed a smaller number of studies; however, lower concentrations are observed for most of the CECs detected when compared to large urban centers (e.g. Brazilian Southeast, 89,452,960 population). Therefore, despite there are few studies in Brazil when compared to other countries (China and Spain), this study helps in identification of priority compounds.

Results and discussion

Distribution and frequency of detection of CECs in Brazilian surface water

Studies on the CEC occurrence, mainly PPCPs, in surface water in Brazil have become more frequent in the last decade. Caldas et al. (2013), Thomas et al. (2014), Campanha et al. (2015), Pereira et al. (2016), López-Doval et al. (2017), Barros et al. (2018), Sousa et al. (2018), Reis et al. (2019), Roveri et al. (2020), among others, studied PPCPs in Brazilian waters, including compounds from anti-inflammatories, anticonvulsant, ß-blockers, plasticizers, hormones, bactericides, preservative and solar UV-sunscreen classes. Locatelli et al. (2011), Jank et al. (2014), Monteiro et al. (2018) and Arsand et al. (2020) showed the presence of antibiotics of different classes in waters from Atibaia, Dilúvio and Guandu Rivers, respectively. While Montagner et al. (2014), Galinaro et al. (2015), Silva et al. (2015), Santos et al. (2016) and Ide et al. (2017) screened PCPs in water bodies from Southeast Brazil.

Among thirty-five peer-reviewed publications about occurrence of CECs in Brazilian surface water, twenty were carried out in the southeast region (in São Paulo, Rio de Janeiro and Minas Gerais States), twelve in the south region (in Rio Grande do Sul and Paraná States), one in North (Amazonas State), one in Midwest (Mato Grosso do Sul State) and one in Northeast (Maranhão State). Table 1 shows the CECs found in each study, concentration levels, its maximum environmental concentration measured (MEC) and frequencies of detection (F_d). From all reviewed studies, 73 CECs were identified, of which nine drugs (losartan, metformin, nimesulide, ibuprofen, atenolol, acetaminophen, diclofenac, caffeine and albendazole) make up the ranking of the 20 most commercialized pharmaceutical substances in Brazil (BRASIL, 2018). São Paulo was the state with the highest number of different CECs detected, 41 in total.

Caffeine deserves attention, since it was found in 41% of the reviewed papers, including studies in all Brazilian regions, reaching concentrations from 7 to 129,585 ng L^{-1} and mean concentrations from 80 to 14,955 ng L^{-1}. Caffeine mean concentrations in some studies were higher than concentrations reported in Uruguay (200 ng L^{-1}) (Griffero et al. 2019) and India (743 ng L^{-1}) (Sharma et al. 2019) and lower than that found in Ecuador (248,686 ng L^{-1}) (Voloshenko-Rossin et al. 2015). Caffeine is an emerging contaminant consumed by the population in coffee, tea, drinks and medicines, considered an indicator of human contamination that has been widely detected in aquatic systems worldwide (Dafouz et al. 2018). Rigueto et al. (2020) showed that the removal of caffeine in WWTPs using different treatment methods occurs from 46 to 98%; therefore, high concentrations of this compound in surface waters may indicate untreated sewage disposal.

Evaluating by class, from 73 CECs detected in the reviewed studies, 25% belong to the antibiotics class, and 21% were NSAIDs (Figure 1). Among antibiotics, sulfamethoxazole and trimethoprim presented frequencies of detection of 18% and 15%, respectively (Table 2). Sulfamethoxazole was quantified in concentrations from 0.6 to 572 ng L^{-1} reaching mean concentrations from 1 to 458 ng L^{-1}. Some studies in Brazil quantified concentrations higher than that found in China (26 ng L^{-1}) (Li et al. 2018) and in India (8.5 ng L^{-1}) (Sharma et al. 2019) and other, lower than reported in Kenya (1214 ng L^{-1}) (Kairigo et al. 2020) and in Mexico (173–1143 ng L^{-1}) (Rivera-Jaimes et al. 2018). Trimethoprim, commonly used in combination with sulfamethoxazole, was determined in concentrations from 1 to 484 ng L^{-1} and mean concentrations ranging from 3 to 85 ng L^{-1}, which is lower than found in Colombia (210–3580 ng L^{-1}) (Bedoya-Ríos et al. 2018).

In NSAID class, diclofenac (41%), acetaminophen (32%), ibuprofen (24%) and naproxen (15%) were the most detected (Table 2). Similar to caffeine, diclofenac also deserves attention since it was detected in 41% of studies, and it has been reported in several countries, having been included in the list of priority substances in the EU Water Framework Directive (Eur, E. C 2013). Diclofenac was quantified in concentrations from 4 to 2626 ng L^{-1} and mean concentrations from 20 to 1161 ng L^{-1}. The highest mean concentrations quantified in Brazilian studies are higher than those found in China (67 ng L^{-1}) (Dai et al. 2015) and lower than those quantified in South Africa (600–8174 ng L^{-1}) (Agunbiade and Moodley 2016). In Brazil, diclofenac, together with nimesulide, ibuprofen and acetaminophen, is the most commercialized NSAID. In 2018, between 25 and 50 million presentations of diclofenac and nimesulide were sold, while for ibuprofen and acetaminophen, between 50 and 100 million presentations were sold (BRASIL, 2018).

Acetaminophen presented concentrations from 1.2 to 30,421 ng L^{-1} reaching mean concentrations from 1.3 to 6860 ng L^{-1}, while ibuprofen, from 3 to 2710 and mean concentrations from 33 to 1472 ng L^{-1}. Mean concentrations in some studies are higher than those reported in Ganges River,

Table 1 Sampling location, detected chemicals, range of concentration in ng L^{-1} (mean concentration), frequency of detection, F_d in % (sample number, n) and maximum measured environmental concentration in ng L^{-1} (MEC) in Brazilian surface water

Location (sampling year)	Chemicals	Concentration (ng L^{-1}) min–max (mean)	F_d (n)	MEC	Reference
Atibaia River, SP, Southeast Brazil	Amoxicillin	< 0.5–1284 (264)	70 (10)	1284	(Locatelli et al. 2011)
	Cefalexin	< 0.6–2422 (440)	70 (10)	2422	
	Ciprofloxacin	< 0.4–119 (31)	70 (10)	119	
	Norfloxacin	< 0.4–51 (11)	60 (10)	51	
	Sulfamethoxazole	< 0.6–106 (28)	50 (10)	106	
	Tetracycline	< 2.5–11 (4)	30 (10)	11	
	Trimethoprim	< 0.6–484 (85)	70 (10)	484	
Atibaia River, SP, Southeast Brazil (2006–2007)	17α-ethynylestradiol	501–4390 (1957)	11 (26)	4390	(Montagner and Jardim 2011)
	17ß-estradiol	106–6808 (2516)	27 (26)	6808	
	Acetaminophen	280–13,440 (6860)	8 (26)	13,440	
	Acetylsalicylic acid	476–20,960 (8619)	19 (26)	20,960	
	Bisphenol-A	204–13,016 (4226)	54 (26)	13,016	
	Caffeine	74–127,092 (10,152)	92 (26)	127,092	
	Dibutylphthalate	1300–33,100 (4167)	92 (26)	33,100	
	Diclofenac	96–115 (106)	6 (26)	115	
Rio das Velhas River, MG, Southeast Brazil (2009)	17α-ethynylestradiol	6–64	14 (56)	64	(Moreira et al. 2011)
	17β-estradiol	63 (63)	2 (56)	63	
	Bisphenol A	9–168 (39)	100 (56)	168	
	Diethylphthalate	5–410	100 (56)	410	
	Nonylphenol	26–1435	100 (56)	1435	
Corsan Reservatory RS, South Brazil (2011–2012)	Haloperidol	100	--	100	(Silveira et al. 2013)
	Methylparaben	7600–29,800	--	29,800	
	Nimesulide	50	--	50	
Arroio Carvão, RS, South Brazil (2010–2011)	Diclofenac	<8	30 (10)	-	(Caldas et al. 2013)
	Mebendazole	14 (14)	10 (10)	14	
	Nimesulide	12 (12)	10 (10)	12	
	Propylparaben	128 (128)	10 (10)	128	
Arroio Diluvio, RS, South Brazil (2011)	Azithromycin	24–40 (32)	50 (8)	40	(Jank et al. 2014)
	Ciprofloxacin	16–66 (38)	75 (8)	66	
	Norfloxacin	30–64 (41)	75 (8)	64	
	Sulfamethoxazole	376–572 (458)	75 (8)	572	
	Trimethoprim	27–94 (62)	75 (8)	94	
São Paulo, Southeast Brazil (2010–2011)	Caffeine	< 20–42,000 (4229)	63 (71)	42,000	(Montagner et al. 2014)
	Triclosan	< 0.7–66 (20)	63 (71)	66	
Jundiaí River, SP, Southeast Brazil (2011–2012)	Atenolol	15–413 (190)	100 (28)	413	(Sousa et al. 2014)
	Caffeine	994–19,330 (6551)	100 (28)	19,330	
	Carbamazepine	6–659 (131)	100 (28)	659	
	Diclofenac	37–328 (109)	96 (28)	328	
	Estrone	5–8 (6)	25 (28)	8	
	Ibuprofen	3–208 (74)	100 (28)	208	
	Naproxen	5–99 (29)	93 (28)	99	
	Propanolol	4–53 (23)	86 (28)	53	
	Triclosan	5–323 (69)	75 (28)	323	
Rio Negro, AM, North Brazil (2011)	Amitriptyline	20–22 (21)	12 (16)	22	(Thomas et al. 2014)
	Benzoylecgonine	366–3582 (1421)	56 (16)	3582	
	Carbamazepine	14–652 (207)	62 (16)	652	
	Citalopram	48–79 (61)	31 (16)	79	
	Cocaine	677–5896 (1985)	50 (16)	5896	
	Diclofenac	63–785 (313)	44 (16)	785	
	Metoprolol	5–28 (15)	37 (16)	28	
	Propranolol	26 (26)	6 (16)	26	
	Sertraline	36–164 (78)	50 (16)	164	
Monjolinho River, SP, Southeast Brazil (2011–2013)	17ß-estradiol	0.3–15 (1.8)	21 (21)	15	(Campanha et al. 2015)
	Acetaminophen	38–30,421 (3702)	77 (21)	30,421	
	Atenolol	32–8199 (1182)	78 (21)	8199	
	Caffeine	20–129,585 (14,955)	93 (21)	129,585	
	Carbamazepine	2–215 (72)	74 (21)	215	
	Diclofenac	22–386 (93)	60 (21)	386	
	Estrone	< 0.1–15 (7)	30 (21)	15	

Table 1 (continued)

Location (sampling year)	Chemicals	Concentration (ng L^{-1}) min–max (mean)	F_d (n)	MEC	Reference
	Ibuprofen	< 2–744 (185)	60 (21)	744	
	Naproxen	3–655 (104)	60 (21)	655	
	Propranolol	1–77 (16)	77 (21)	77	
	Triclosan	< 0.8–281 (35)	80 (21)	281	
Mogi Guaçu River, SP, Southeast Brazil	Butylparaben	9–20 (15)	50 (14)	20	(Galinaro et al. 2015)
	Ethylparaben	2–30 (6)	78 (14)	30	
	Methylparaben	2–27 (8)	50 (14)	27	
	Propylparaben	1–52 (13)	86 (14)	52	
São Paulo, Southeast Brazil (2012–2014)	Benzophenone-3	18–44 (27)	60 (30)	44	(Silva et al. 2015)
	EHMC	50–755 (329)	37 (30)	755	
	Octocrylene	188–208 (198)	13 (30)	208	
Piracicaba River, SP, Southeast Brazil (2011–2012)	17β-estradiol	41–87 (56)	6 (98)	87	(Torres et al. 2015)
	17α-ethinylestradiol	26–150 (77)	10 (98)	150	
	Estrone	6–14 (10.5)	4 (98)	14	
	Estriol	44–46 (45)	2 (98)	46	
Pavuna, Fundo, Camorim and Grande Rivers, RJ, Southeast Brazil (2015)	Acetaminophen	90–140 (118)	80 (5)	140	(Lopes et al. 2016)
	Salicylic acid	1650–4810 (3550)	80 (5)	4810	
	Bisphenol-A	1370–39,860 (15,890)	100 (5)	39,860	
	Diclofenac	220 (220)	20 (5)	220	
Santos Bay, SP, Southeast Brazil (2014)	Acetaminophen	17–35 (23)	100 (10)	35	(Pereira et al. 2016)
	Atenolol	< 7	20 (10)	-	
	Benzoylecgonine	5–21 (12)	100 (10)	21	
	Caffeine	84–649 (272)	100 (10)	649	
	Cocaine	13–537 (144)	100 (10)	537	
	Diclofenac	< 7.4–19 (19)	100 (10)	19	
	Ibuprofen	326–2094 (1472)	100 (10)	2094	
	Losartan	12–32 (20)	90 (10)	32	
	Valsartan	11–75 (28)	100 (10)	75	
Upper Iguassu Watershed, PR, South Brazil (2011–2012)	Butylparaben	< 6–268	71 (80)	268	(Santos et al. 2016)
	Ethylparaben	<4–1485	18 (80)	1485	
	Methylparaben	< 5–2875	86 (80)	2875	
	Propylparaben	< 5–486	84 (80)	486	
	Triclosan	<1–415	86 (80)	415	
Iguaçu River, PR, South Brazil	Caffeine	< 27–27,000	58 (64)	27,000	(Ide et al. 2017)
	Salicylic acid	< 112–5000	22 (64)	5000	
	Acetylsalicylic	<120–930	20 (64)	930	
	acid Naproxen	< 32–340	34 (64)	340	
	Ketoprofen	< 17–620	18 (64)	620	
	Estradiol	< 85–1420	24 (64)	1420	
	Ethinylestradiol	< 161–1480	7 (64)	1480	
	Estrone	< 89–940	2 (64)	940	
	Fenofibrate	< 3–40	25 (64)	40	
	Gemfibrozil	< 3–70	40 (64)	70	
	4-MBC	< 1–50	20 (64)	50	
Guarapiranga Reservoir, SP, Southeast Brazil (2014)	Caffeine	17–4726 (646)	100 (16)	4726	(López-Doval et al. 2017)
	Cocaine	3–12 (5)	44 (16)	12	
	Benzoylecgonine	3–179 (41)	100 (16)	179	
	Bisphenol-A	10–345 (105)	88 (16)	345	
Paraopebas River, MG, Southeast Brazil	Acetaminophen	200–1700 (668)	67 (12)	1700	(Barros et al. 2018)
	Bezafibrate	133 (133)	8 (12)	133	
	Diclofenac	197–2626 (1161)	100 (12)	2626	
	Diltiazem	3–171 (42)	67 (12)	171	
	Fluconazole	9–99 (48)	67 (12)	99	
	Miconazole	5–117 (34)	50 (12)	117	
	Trimethoprim	8–124 (37)	75 (12)	124	
Guandu and Queimados rivers, RJ, Southeast Brazil (2016)	Amoxicillin	38–289 (163)	25 (9)	289	(Monteiro et al. 2018)
	Azithromycin	36 (36)	13 (9)	36	
	Clarithromycin	39 (39)	13 (9)	39	
	Cefalexin	576 (576)	13 (9)	576	
	Sulfamethoxazole	60–105 (83)	25 (9)	105	
Jundiaí River, SP, Southeast Brazil (2012–2013)	Atenolol	107–665 (296)	100 (24)	665	(Sousa et al. 2018)

Table 1 (continued)

Location (sampling year)	Chemicals	Concentration (ng L^{-1}) min–max (mean)	F_d (n)	MEC	Reference
	Caffeine	1156–24,961 (8125)	100 (24)	24,961	
	Carbamazepine	15–659 (129)	87 (24)	659	
	Diclofenac	26–364 (143)	100 (24)	364	
	Estrone	5–29 (10)	63 (24)	29	
	Ibuprofen	24–373 (152)	100 (24)	373	
	Naproxen	7–145 (59)	100 (24)	145	
	Propranolol	5–48 (20)	100 (24)	48	
	Triclosan	5–61 (18)	100 (24)	61	
Rio Grande do Sul, South Brazil	Acetaminophen	104–4200 (1329)	67	4200	(Souza et al. 2018)
	Bisphenol A	73–665 (248)	67	665	
Dourados and Brilhante Rivers, MS, Midwest Brazil (2016)	17α-ethynylestradiol	39 (39)	5 (18)	39	(Sposito et al. 2018)
	Bisphenol A	10–49 (20)	83 (18)	49	
	Caffeine	< 20–1040 (118)	100 (18)	1040	
	Estriol	11–12 (11)	11 (18)	12	
	Triclosan	9 (9)	5 (18)	9	
Rio Grande do Sul, South Brazil	Glibenclamide	50–120 (91)	29 (48)	120	(Caldas et al. 2019)
	Methylparaben	15–840 (262)	100 (48)	840	
	Nimesulide	70–730 (238)	43 (48)	730	
	Propylparaben	90–190 (115)	29 (48)	190	
Santos Bay, SP, Southeast Brazil (2016–2017)	Benzoylecgonine	< 8–28 (14)	96 (24)	28	(Fontes et al. 2019)
	Caffeine	< 12–169 (80)	63 (24)	169	
Atibaia River, SP, Southeast Brazil (2006–2015)	4-n-nonylphenol	1–2018 (429)	2 (205)	2018	(Montagner et al. 2019)
	4-n-octylphenol	2–1029 (266)	2 (205)	1029	
	17-α ethynylestradiol	4–4390 (777)	4 (221)	4390	
	17ß-estradiol	2–6806 (969)	9 (221)	6806	
	Acetaminophen	280–13,440 (6860)	6 (34)	13,440	
	Acetylsalicylic acid	476–20,960 (5978)	18 (34)	20,960	
	Benzoylecgonine	10–1019 (133)	84 (51)	1019	
	Bisphenol A	2–13,016 (513)	67 (217)	13,016	
	Caffeine	19–127,000 (4823)	97 (203)	127,000	
	Ciprofloxacin	0.6–12 (7)	85 (13)	12	
	Cocaine	2–62 (10)	53 (51)	62	
	Dibutylphthalate	1300–33,100	94 (36)	33,100	
	Diclofenac	96–115 (106)	6 (34)	115	
	Dioctylphthalate	465–674 (570)	100 (2)	674	
	Estriol	1–1398 (38)	31 (187)	1398	
	Estrone	0.8–39 (5)	28 (221)	39	
	Norfloxacin	0.7–4 (2)	31 (13)	4	
	Sulfamethoxazole	0.6–2 (1)	46 (13)	2	
	Triclosan	2–289 (24)	67 (257)	289	
	Trimethoprim	1–7 (3)	100 (13)	7	
Vacacaí and Vacacaí Mirim watershed, RS, South Brazil	Acetaminophen	120–9900 (1488)	90 (20)	9900	(Pivetta and Gastaldini 2019)
	Diclofenac	< 150	5 (20)	-	
	Ibuprofen	200–2710 (891)	95 (20)	2710	
Lobo reservoir, SP, Southeast Brazil	Acetaminophen	n.d.–130 (30)	86 (9)	130	(Pompei et al. 2019)
	Benzophenone-3	320–2100 (1140)	100 (9)	2100	
	Diclofenac	n. d.–50 (20)	71 (9)	50	
	Ibuprofen	n. d.–130 (10)	43 (9)	130	
	Naproxen	n. d.–100 (10)	100 (9)	100	
	Methylparaben	100–1,192,390 (170,870)	86 (9)	1,192,390	
Minas Gerais, Southeast Brazil (2016–2017)	Atorvastatin	< 104–1020 (559)	46 (84)	1020	(Reis et al. 2019)
	Betamethasone	< 73–11,960 (5897)	32 (84)	11,960	
	Caffeine	1385 (1385)	1 (84)	1385	
	Clarithromycin	168–199 (184)	2 (84)	199	
	Danofloxacin	23–272 (83)	14 (84)	272	
	Enoxacin	240–386 (310)	11 (84)	386	
	Enrofloxacin	13–71 (44)	11 (84)	71	
	Fenofibrate	119–1388 (599)	4 (84)	1388	
	Fluconazole	< 73–1413 (840)	55 (84)	1413	
	Gemfibrozil	< 73–948 (448)	24 (84)	948	
	Ibuprofen	302–333 (318)	2 (84)	333	

Table 1 (continued)

Location (sampling year)	Chemicals	Concentration (ng L^{-1}) min–max (mean)	F_d (n)	MEC	Reference
	Ketoprofen	< 73–1020 (524)	26 (84)	1020	
	Loratadine	56–486 (299)	10 (84)	486	
	Metformin	49–203 (140)	7 (84)	203	
	Norfloxacin	< 73–285 (160)	27 (84)	285	
	Phenazone	< 1.5–33 (8)	5 (84)	33	
	Phenylbutazone	76–275 (176)	3 (84)	275	
	Prednisone	< 73–8105 (2906)	58 (84)	8105	
Dilúvio River, RS, South Brazil (2016–2018)	Azithromycin	< 10–158 (65)	100 (48)	158	(Arsand et al. 2020)
	Cephalexin	< 10–179 (75)	100 (48)	179	
	Ciprofloxacin	< 10–344 (172)	100 (48)	344	
	Clindamycin	< 5–134 (74)	100 (48)	134	
	Norfloxacin	29–292 (89)	100 (48)	292	
	Sulfadiazine	< 5–120 (57)	100 (48)	120	
	Sulfamethoxazole	34–184 (60)	100 (48)	184	
	Trimethoprim	20–84 (33)	100 (48)	84	
Anil and Bacanga Rives, MA, Northeast Brasil (2018–2019)	Acetaminophen	< 200–1716 (1011)	54 (26)	1716	(Chaves et al. 2020)
	Albendazole	< 4–22 (12)	43 (26)	22	
	Caffeine	7–13,798 (2489)	92 (26)	13,798	
	Carbamazepine	7–83 (36)	71 (26)	83	
	Diclofenac	103–463 (299)	46 (26)	463	
	Ibuprofen	< 100–320 (202)	57 (26)	320	
	Mebendazole	< 4–18 (9)	38 (26)	18	
	Methylparaben	37–660 (153)	92 (26)	660	
	Sulfamethoxazole	< 20–120 (58)	50 (26)	120	
Piratininga and Itaipu Lagoons, RJ, Southeast Brazil (2017)	Ibuprofen	28–38 (33)	50 (20)	38	(Cunha et al. 2020)
	Naproxen	16–23 (19)	50 (20)	23	
	17α-ethinyloestradiol	54 (54)	25 (20)	54	
	4-nonylphenol	5–16 (9)	75 (20)	16	
	4-octylphenol	17–29 (23)	50 (20)	29	
	Bisphenol-A	251–368 (310)	50 (20)	368	
	Estrone	12 (12)	25 (20)	12	
	17ß-estradiol	8–24 (15)	75 (20)	24	
	Estriol	3 (3)	25 (20)	3	
Upper Tibagi River, PR, South Brazil (2015–206)	Butylparaben	< 23–133 (59)	100 (44)	133	(Reichert et al. 2020)
	Ethylparaben	< 10–145 (65)	100 (44)	145	
	Gemfibrozil	<18–2591 (337)	100 (44)	2591	
	Methylparaben	< 48–265 (107)	100 (44)	266	
	Propylparaben	< 3.2–487 (52)	100 (44)	487	
	Triclosan	50–789 (253)	100 (44)	798	
Guarujá, SP, Southeast Brazil (2018)	Acetaminophen	1.2–1.4 (1.3)	25 (8)	1.4	(Roveri et al. 2020)
	Atenolol	0.1–0.3 (0.15)	50 (8)	0.3	
	Benzoylecgonine	0.3–2 (0.7)	75 (8)	2	
	Caffeine	42–141 (80)	75 (8)	141	
	Carbamazepine	< 0.01–0.1 (0.1)	13 (8)	0.1	
	Cocaíne	0.3–0.6 (0.4)	75 (8)	0.6	
	Diclofenac	4–86 (44)	75 (8)	86	
	Losartan	0.7–3 (2)	25 (8)	3	
	Orphenadrine	0.6–3 (2)	50 (8)	3	
	Valsartan	5–14 (10)	75 (8)	14	
South and Southeast Brazil (2016–2017)	Atorvastatin	300–1150 (400)	10 (20)	1150	(Santos et al. 2020)
	Betamethasone	34–3200 (645)	50 (20)	3200	
	Fluconazole	35–4200 (760)	60 (20)	4200	
	Metformin	36–130 (83)	10 (20)	130	
	Prednisone	34–3600 (1008)	60 (20)	3600	

India (2 and 23 ng L^{-1}) (Sharma et al. 2019) and Jiulong River, China (2 and 69 ng L^{-1}) (Lin et al. 2016). South American countries have reported high concentrations of these compounds. In Mexico, concentrations from 354 to 14,900 (1634) ng L^{-1} of acetaminophen, from 284 to 2835 (520) ng L^{-1} for ibuprofen and from 258 to 2470 (740) ng L^{-1}

Table 2 Frequencies of detection (Fd %) of individual emerging contaminants in Brazilian aquatic environment, considering thirty-five studies available on literature

Chemical	Fd (%)
Caffeine	41
Diclofenac	41
Acetaminophen	32
Ethylparaben	29
Ibuprofen	24
Triclosan	24
Bisphenol A	21
17α-ethynylestradiol	18
17ß-estradiol	18
Atenolol	15
Benzoylecgonine	18
Cocaine	18
Carbamazepine	18
Estrone	18
Methylparaben	18
Sulfamethoxazole	18
Naproxen	15
Propylparaben	15
Trimethoprim	15

for diclofenac were detected (Rivera-Jaimes et al. 2018). In Colombia, Pemberthy et al. (2020) quantified 460 ng L^{-1} for ibuprofen and 310 ng L^{-1} for diclofenac in Gulf Urabá. Brazil is among the ten largest consumers of medicines in the world. According to Aitken and Kleinrock (2015), over 50% of the world population will consume in 2020 more than 1 dose per person per day of medicines, up from one third of the world in 2005, driven by India, China, Brazil and Indonesia.

Preservatives, hormones, plasticizers, UV-sunscreen and ß-blockers are 6%, each, from 73 ECs detected in this study (Figure 1). In the preservative group, ethylparaben (29%), methylparaben (18%) and propylparaben (15%) presented the highest frequencies of detection. Ethylparaben was detected in concentrations from 2 to 29,800 ng L^{-1}, while methyl and propylparaben were reported in mean concentrations from 8 to 170,870 ng L^{-1} and from 13 to 243 ng L^{-1}, respectively. Methyl and propylparaben were quantified in some studies in concentrations higher than those reported in Jiulong River, China (21 and 16 ng L^{-1}) (Sun et al. 2016) and Pakistan (6 and 3 ng L^{-1}) (Ashfaq et al. 2019).

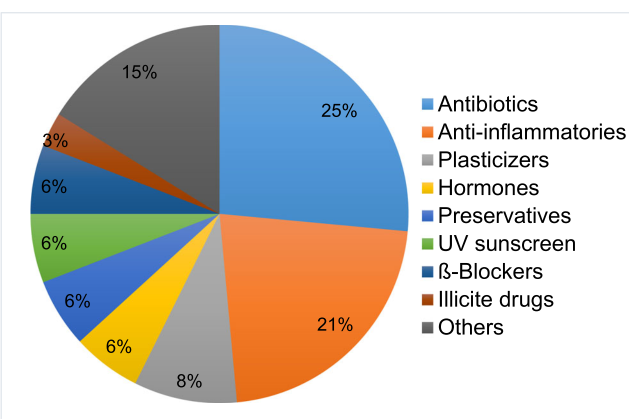

Fig. 1 Frequencies of detection of therapeutic classes in Brazilian aquatic environment, considering thirty-five studies available on literature

Hormones (17α-ethynylestradiol, 17ß-estradiol, estrone and estriol) were detected mainly in the southeast region. 17ß-estradiol concentrations ranged from 0.3 to 6808 ng L^{-1} and 17α-ethynylestradiol from 6 to 4390 ng L^{-1} with mean concentrations from 1.8 to 2515 and from 15 to 1957 ng L^{-1} of 17ß-estradiol and 17α-ethynylestradiol, respectively. Some studies reported 17ß-estradiol and 17α-ethynylestradiol concentrations lower than those reported in Uruguay (2350 and 11,600 ng L^{-1}, respectively) (Griffero et al. 2019), while other, higher than those quantified in Malaysia (31 and 8 ng L^{-1}) (Ismail et al. 2019). Estrone occurred in 18% of the studies, in concentrations ranging from < 0.1 (Monjolinho River) to 940 ng L^{-1} (Iguaçu River) (Campanha et al. 2015; Ide et al. 2017), while estriol was quantified in concentrations from 1 to 1398 ng L^{-1} in Atibaia River (Montagner et al. 2019). In developed countries, as in the USA and Spain, relatively low concentrations are reported for hormones. Deere et al. (2020) reported 54, 89 and 726 ng L^{-1} for 17α-ethynylestradiol, 17ß-estradiol and estrone, respectively, in Minnesota. While Gorga et al. (2015) found up to 2, 8, 7 and 6 ng L^{-1} for 17α-ethynylestradiol, 17ß-estradiol, estrone and estriol in Iberian rivers. The presence of hormones in Brazilian surface waters is mainly related to the use of oral and injectable contraceptives by Brazilian women. About 65% of women aged 15 to 49 reported using a modern contraceptive method (Farias et al. 2016). Steroid estrogens gained scientific attention in the last decades due their potential to cause undesirable ecological effects at very low concentrations (0.1–0.5 ng L^{-1}), being considered as prospective endocrine disruptors (Ilyas and Van Hullebusch 2020).

On plasticizers group, bisphenol-A, dibutylphthalate, diethylphthalate and dioctylphthalate were detected. Bisphenol-A was quantified in 21% of studies, in concentrations from 2 to 39,860 ng L^{-1} and mean concentrations from 20 to 15,890 ng L^{-1}. This chemical has exhibited genotoxicity, reproductive toxicity, endocrine disrupting effects, cytotoxicity and neurotoxicity in these concentration levels (Liu et al. 2020a). Global bisphenol-A production had exceeded 4.6 million tons in 2012 and is expected to grow at an annual rate of 4.6% from 2013 to 2019. These data highlight the concern with the presence of this compound in the environment, since it has proven adverse effects to living beings and it has been detected in many biological matrices including human amniotic fluid, blood, breast milk, placenta, sweat and urine (Wang et al. 2021).

On pharmaceutical ß-blockers group, atenolol, metoprolol and propranolol were detected. Atenolol presented frequency of detection of 15%, being found in the southeast region in concentration level from 0.1 to 8199 ng L^{-1}. This compound has not been detected in other Brazilian regions. This is one of the most used ß-blocker to control blood pressure in Brazil, being marketed between 50 and 100 million presentations in 2018 (BRASIL, 2018).

On illicit drugs group, only cocaine and its metabolite benzoylecgonine were studied. These compounds were detected in 18% of the reviewed studies, in concentrations ranging from 0.3 to 5896 ng L^{-1} for cocaine and from 0.3 to 3586 ng L^{-1} for benzoylecgonine in the north region (Thomas et al. 2014). In the southeast region, concentrations from 13 to 537 ng L^{-1} for cocaine (Pereira et al. 2016) and from 3 to 179 ng L^{-1} for benzoylecgonine (López-Doval et al. 2017) were quantified. North American countries have shown the presence of these compounds in its surface water; Deere et al. (2020) quantified up to 259 ng L^{-1} for cocaine and 61 ng L^{-1} for benzoylecgonine in the USA, while Comtois-Marotte et al. (2017) found up to 4 ng L^{-1} for cocaine and up to 10 ng L^{-1} for benzoylecgonine, in Canada. Fontes et al. (2019) showed that cocaine and their metabolites are widespread in aquatic ecosystems in levels able to trigger sub-lethal effects to non-target organisms, besides to concentrate in seafood, presenting risks to human health and the environment.

Carbamazepine, an anticonvulsant drug, was detected in Brazilian surface water with concentrations from 0.1 to 659 ng L^{-1} and mean concentration up to 207,131 and 36 ng L^{-1} in North, Southeast and Northeast regions. Some Brazilian studies reported carbamazepine concentrations lower than those found in other Latin American countries (195,943 ng L^{-1} in Ecuador and 4300 ng L^{-1} in Colombia) and other, higher than European countries (37 ng L^{-1} in Italy, 29 ng L^{-1} in Spain and 25 ng L^{-1} in German) (Carmona et al. 2017; Kötke et al. 2019; Feo et al. 2020). Studies suggest that rivers from developed countries contain less PPCPs than developing countries, primarily attributable to better medical regulations rather than availability of wastewater treatment facilities (Kumar et al. 2019).

Other chemical detected in Brazilian surface waters was triclosan, an antimicrobial agent widely used in personal care products such as soaps, skin creams, toothpaste and deodorants. In Brazil, the National Health Surveillance Agency (ANVISA) allows concentration of up to 0.3% of triclosan in personal care products as a preservative (BRASIL 2012). Triclosan was reported in 24% of the reviewed studies in concentrations from 2 to 789 ng L^{-1}, reaching mean concentration up to 253 ng L^{-1} in Upper Tibagi River (Reichert et al. 2020) and 69 ng L^{-1} in Jundiaí River (Sousa et al. 2014). These concentrations are higher than those quantified in Nigeria (59 ng L^{-1}) (Inam et al. 2015) and in China (22 ng L^{-1}) (Sun et al. 2016) and lower than those found in Colombia (295 ng L^{-1}) (Pemberthy et al. 2020) and in the USA (1830 ng L^{-1}) (Deere et al. 2020).

Therefore, evaluating the concentrations of CECs quantified in Brazilian surface waters, a high level is observed for some compounds when compared to developed countries such as the USA and European countries. However, when comparing the levels found in Brazil with other South American countries, lower concentrations are observed for most compounds. Caffeine, diclofenac, acetaminophen, ethylparaben, ibuprofen, triclosan and bisphenol-A deserve attention, since among the ECs reviewed in this study, they had the highest frequencies of detection.

Ecological risk of CECs in Brazilian surface water

Using the MEC values reported in studies carried out in the last decade in Brazil, an environmental risk assessment multiple-level ecological was performed. In Figure 2, risk quotients (RQ) for chemicals found in each Brazilian region are presented. Southeast seemed to be the region most impacted by CECs in Brazil; however, few studies have been conducted in the North, Northeast and Midwest regions, and it is not possible to have a complete outline of the real situation of ECs in the country. Analyzing the three trophic levels, daphnia was the most sensitive organism being subject to high risk mainly for acetaminophen (950), caffeine (431), 17ß-estradiol (340), ibuprofen (309), dibutylphthalate (292), diclofenac (262) and methylparaben (106). Therefore, it is probable that adverse effects may occur to aquatic biota exposed. In addition to these ones, 17α-ethynylestradiol (42), diethylphthalate (14), sertraline (2.5), triclosan (2) and bisphenol-A (2) presented high environmental risk in the southeast region.

High environmental risk resulting from high concentrations of CECs quantified in the southeast region may be related to the greater socioeconomic development of this region. The large industrial centers in Brazil are concentrated in the southeast of the country, with emphasis on the São Paulo State, which is home to large chemical and pharmaceutical industries. In addition, the southeast region stands out for containing the cities with the highest demographic densities in the country, which also contributes to environmental contamination by CECs, due to generating a greater volume of domestic sewage when compared to less populous cities.

Considering the vast geographical area of Brazil, the differences in the population density and the wide variation in the climate conditions that influences the pattern of the PPCP consumption, the discussion was done considering the spatial distribution. However, considering the highest RQ found in the Brazilian regions, a comparison with other studies around the world was carried out after.

In the south region, acetaminophen, 17ß-estradiol, 17α-ethynylestradiol, caffeine, estrone and triclosan presented high environmental risk (RQ > 1.0), while methylparaben,

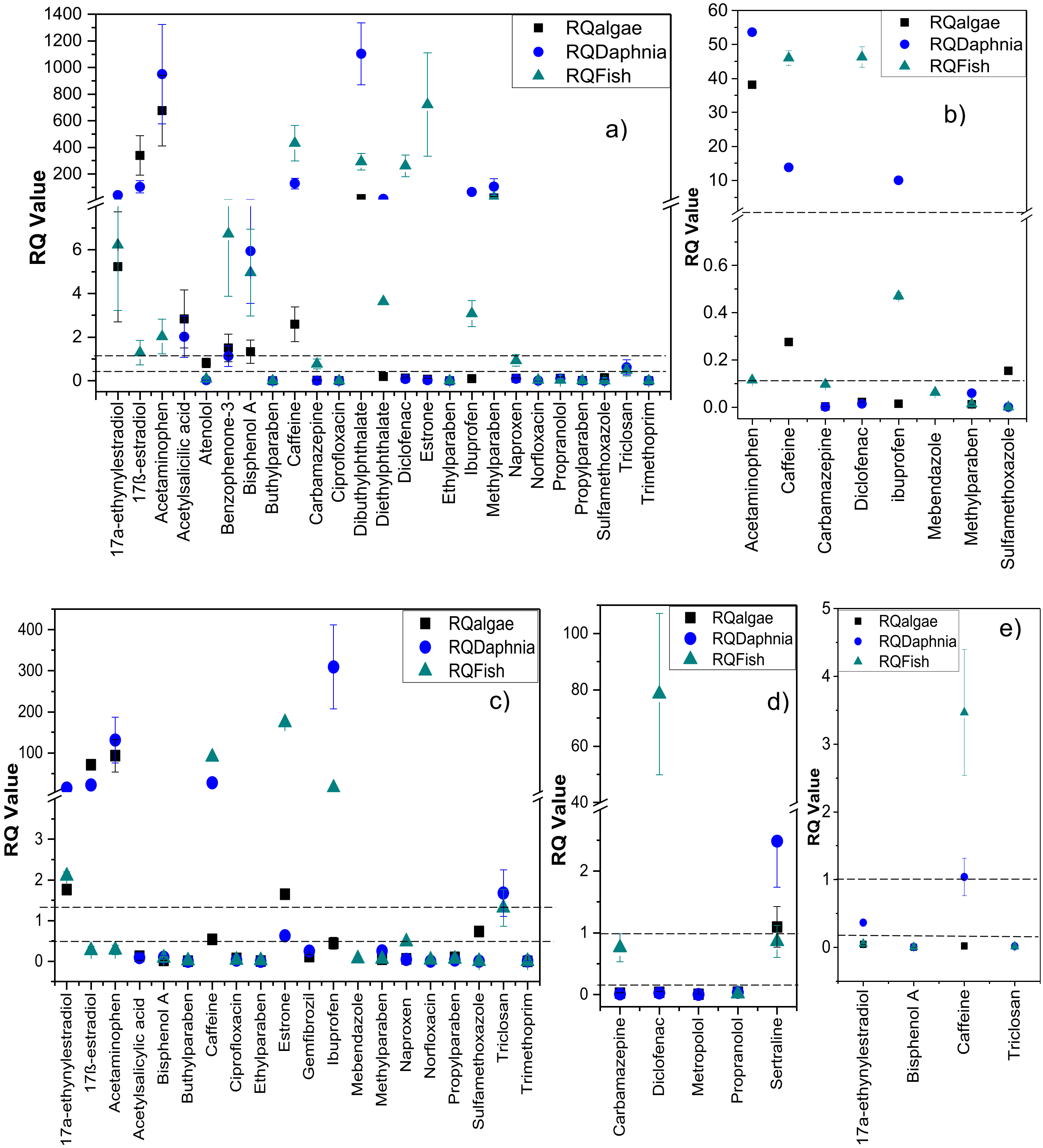

Fig. 2 Risk Quotients (RQ) for maximum concentration measured in surface water from Brazilian southeast (**a**), northeast (**b**), south (**c**), north (**d**) and midwest (**e**). The dashed lines represent the separation of the levels of environmental risk. Values below the dashed lines represent low risk, between the lines, moderate risk and above, high environmental risk

gemfibrozil and sulfamethoxazole present moderate risk (0.1 < RQ < 1). Other chemicals (acetylsalicylic acid, bisphenol A, butylparaben, ciprofloxacin, ethylparaben, norfloxacin, propylparaben and trimethoprim) showed low or insignificant risk in the region. In the North Brazil, high risk was estimated to diclofenac and sertraline, moderate risk to carbamazepine and insignificant risk to metoprolol and propranolol. In the northeast region, high risk was calculated to acetaminophen (algae and Daphnia), caffeine (Daphnia and fish), diclofenac (fish) and ibuprofen (Daphnia). Sulfamethoxazole showed moderate risk for algae, while carbamazepine, mebendazole and methylparaben, low risk for the three trophic levels. In the midwest region, high risk was found only to caffeine (Daphnia and fish), while moderate risk was detected to 17α-ethynylestradiol (Daphnia). Triclosan present low risk and bisfenol A, insignificant risk.

Similarly to the RQs found in Brazil, low or medium RQ in surface waters was found for atenolol and naproxen in Pakistan (Ashfaq et al. 2019), carbamazepine, metoprolol, norfloxacin and trimethoprim in China (Zheng et al. 2020), ciprofloxacin in India (Singh and Suthar 2021), mebendazole in China (Chen et al. 2021) and India (Singh and Suthar 2021), propranolol in Sri Lanka (Guruge et al. 2019) and trimethoprim in Vietnam (Ngo et al. 2020).

Related to the four parabens investigated (ethylparaben, methylparaben, propylparaben and butylparaben), only methylparaben have shown high risk in Brazil. In the surface water of the Yangtze River in China, the same preservatives were investigated and minimal or low risk was found (Liu et al. 2015).

17ß-estradiol and 17α-ethynylestradiol showed high risk in this study. In surface water samples obtained from sampling points in Mexico, the RQs of 17ß-estradiol ranged from 0.07 to 0.94 and of 17α-ethynylestradiol from 0.21 to 2.56, presenting medium to high risk (Calderón-Moreno et al. 2019). In China, medium to high risk was also found for these compounds (Zhong et al. 2021). Estrone showed medium to high risk in this study. Similar results were found in surface waters from China (Zhong et al. 2021).

Acetaminophen showed high RQ in Brazil and in China (Zheng et al. 2020) but showed medium RQ in Pakistan (Ashfaq et al. 2019) and low RQ in India (Singh and Suthar 2021). Ibuprofen has been shown to have different RQ according to the studies. Similarly, to this study, high RQ was found in Pakistan (Ashfaq et al. 2019) and Sri Lanka (Guruge et al. 2019), but in China and India, low RQ was found (Zheng et al. 2020; Singh and Suthar 2021). Diclofenac showed high RQ in Brazil and China (Zheng et al. 2020) and low to medium in Vietnam, Pakistan and Sri Lanka (Ashfaq et al. 2019; Guruge et al. 2019; Ngo et al. 2020).

Similarly to the high RQ found in this study, high risk was also found for bisphenol A in surface waters from Mexico (Calderón-Moreno et al. 2019), and for caffeine in China (Zheng et al. 2020) and Pakistan (Ashfaq et al. 2019). Dibuthylphthalate and diethylphthalate were detected in Brazilian surface waters in concentrations that represent high risk (RQ > 1.0). In a study carried out in Uganda, high RQ was found for dibuthylphthalate and low risk for diethylphthalate (Nantaba et al. 2021). Benzophenone-3 showed high risk in Brazil, but in surface waters from Romania, low risk was found (Chiriac et al. 2021) and medium risk in surface waters from Shanghai, China (Wu et al. 2017).

Gemfibrozil presented high RQ in this study and low in Pakistan (Ashfaq et al. 2019) and Sri Lanka (Guruge et al. 2019) surface waters. Sertraline had shown high RQ in some studies in Brazilian waters, and in Turkey surface waters low RQ was calculated (Guzel et al. 2019). For sulfamethoxazole, low to medium RQ was found in this study and in China (Zheng et al. 2020) and Pakistan (Ashfaq et al. 2019), but in surface waters from Greece (Nannou et al. 2015), Vietnam (Ngo et al. 2020) and Sri Lanka (Guruge et al. 2019) high RQ was found.

Triclosan showed high RQ in this study, and in Greece (Nannou et al. 2015), Indian (Singh and Suthar 2021) and Uganda (Nantaba et al. 2021) surface waters; however, in China (Zheng et al. 2020) and Sri Lanka (Guruge et al. 2019), low or medium RQ was found.

This estimation of RQs was made for each compound separately, but it must be taken into consideration the fact that in the aquatic environment PPCPs never occur individually and the mixture of various pharmaceuticals may lead to different toxicity risks on aquatic organisms. However, the estimations made in this study are based on the RQ of a single pharmaceutical (Kosma et al. 2014; Nannou et al. 2015).

How could be observed, the risk assessment for PPCPs can vary around the world, and among regions from the same country, since it depends on the quantified concentrations, which vary according to the PPCP usage, sanitary conditions, removal efficiency in wastewater treatment plants and environmental conditions.

Prioritization of CECs in Brazilian aquatic environments

In Brazil, there is no national environmental legislation to regulate CECs in the environment or even in drinking water. The monitoring initiatives come from academics and environmental agencies, such as the São Paulo State Environmental Company (CETESB) (Aragão et al. 2020). Because of this, it is important to create a list of priority contaminants in the country, which in addition to taking into account data on the consumption of pharmaceutical and personal care products, occurrence data and the environmental risks involved must be considered. Norman Network and the European Watch-List are two important examples of prioritization of CECs in the environment. Norman Network seeks to promote the exchange of information on emerging environmental substances from different countries (Norman 2019), while the European Watch-List is used by European Union with the goal of obtaining monitoring data for pollutants for which available data to assess their risks are still insufficient to allow conclusions on their effects (Eur, E. C 2013).

Based on occurrence data and environmental risk, it was possible to highlight the most concerning CECs in Brazilian aquatic environment. CECs with moderate or high ecological risk were classified as environmentally hazardous compounds and therefore should receive more attention and further studies on occurrence, persistence and toxicity should be performed. About 25% of the reviewed CECs are antibiotics and other 21% are anti-inflammatories drugs, with emphasis on diclofenac, acetaminophen and ibuprofen that presented frequency of detection of 41%, 32% and 24%, respectively, presenting high risk to aquatic biota. These compounds may result in negative effects on wild bivalves after long-term exposures and even on organisms from higher trophic level due to food-chain transfer (Almeida et al. 2020). Therefore, considering the risk associated with the occurrence of these compounds in Brazilian aquatic ecosystems, they can be considered of concern and included in the list of priority contaminants.

On the antibiotics group, only sulfamethoxazole presented moderate risk for algae. This is one of the most consumed antibiotics by the Brazilian population and, similar to caffeine, has been considered a marker of anthropogenic contamination being ubiquitous in water bodies worldwide (Thiebault 2020).

Caffeine was the most detected chemical in the Brazilian surface water presenting low to high environmental risk. Moreover, it is an anthropogenic marker, helping to identify places where effluents are discarded without treatment and that probably are contaminated with other CECs present in wastewater. Therefore, this compound must be also considered a priority in environmental monitoring studies.

In addition these, 17α-ethynylestradiol, 17ß estradiol, bisphenol A, methylparaben and triclosan presented high frequencies of detection and concentration that caused high risk to algae, crustaceans and fish. These CECs are reported in several environmental matrices worldwide and have the potential for endocrine disruption.

Therefore, taking into account the occurrence data and the estimated environmental risks, Figure 3 shows the CECs of most concern in each Brazilian region, highlighting that risk quotient takes into account the maximum environmental concentration found, being an indicative of the environmental risk. Considering a general ranking, the most concerning CECs in Brazil are diclofenac, acetaminophen, caffeine, methylparaben, sulfamethoxazole, bisphenol A, ibuprofen, 17α-ethynylestradiol, 17ß-estradiol and triclosan. Monitoring studies for these compounds should be carried out in order to generate data to assist decision-making and the creation of environmental legislation in the future.

In the European Union, they have a surface water Watch List (WL) under the Water Framework Directive (WFD) which is a mechanism for obtaining data on potential water pollutants for the purpose of determining the risk they pose. This list is updated every 2 years. From the compounds ranked to be studied in Brazil as a priority, diclofenac was included in the first WL (2015), 17α-ethynylestradiol and 17ß-estradiol in the first (2015) and second (2018) WL and sulfamethoxazole was recently added in the third WL (2020). These substances are considered in these lists because they are considered substances that may pose a significant risk, at Union level, to or via the aquatic environment, but for which monitoring data are insufficient to come to a conclusion on the actual risk posed (Eur 2020).

In this study, it was possible to notice that the prioritizing pharmaceuticals in Brazilian urban rivers impacted by domestic effluents is directly related to medicine consumption. From twenty most commercialized pharmaceutical substances in Brazil, nine (45%) were among the most detected compounds in Brazilian surface waters. Therefore, the relationship between regional usage of pharmaceuticals and levels quantified in different regions presents a challenge to prioritization in a country with several socioeconomic characteristics, like Brazil.

Uncertainties and limitations

This study was carried out based on measured concentrations and ecotoxicity data from literature. For some chemicals, that ecotoxicity data are not available (benzoylecgonine, citalopram, cocaine, nimesulide, among others), it was not possible to carry out risk analysis. Therefore, results of priority ranking of CECs in Brazil may change or remain unchanged if there are other updated measured and ecotoxicity data.

Compounds detected with low frequency (<10%), as amitriptyline, azithromycin, avobenzone, benzylparaben, erythromycin, glibenclamide, losartan, valsartan, among others, were not taken into consideration in the risk assessment, but they also may present risk to the aquatic biota. In addition, few studies were found in the north (Thomas et al. 2014), northeast (Chaves et al. 2020) and midwest (Sposito et al. 2018), and some chemicals (e.g. 17ß-estradiol, 17α-ethynylestradiol, estrone, naproxen and sertraline) were reported in more than one sampling locations, but from the same region, being insufficient to represent the complete ranking of CECs in the country.

Conclusions

Monitoring data of CECs in Brazil is still limited; most studies had occurred mainly in the south and southeast regions. However, based on current knowledge, it was possible to build a priority ranking of CECs by frequency of occurrence and environmental risk levels. The reviewed CECs were mainly distributed in highly urbanized and industrialized regions, including the São Paulo State. The water bodies from the southeast region are the most studied, consequently have a greater amount of different chemicals reported and seemed to be the hot-spot region where several chemicals were ranked with high risk. Levels of CECs in Brazilian aquatic

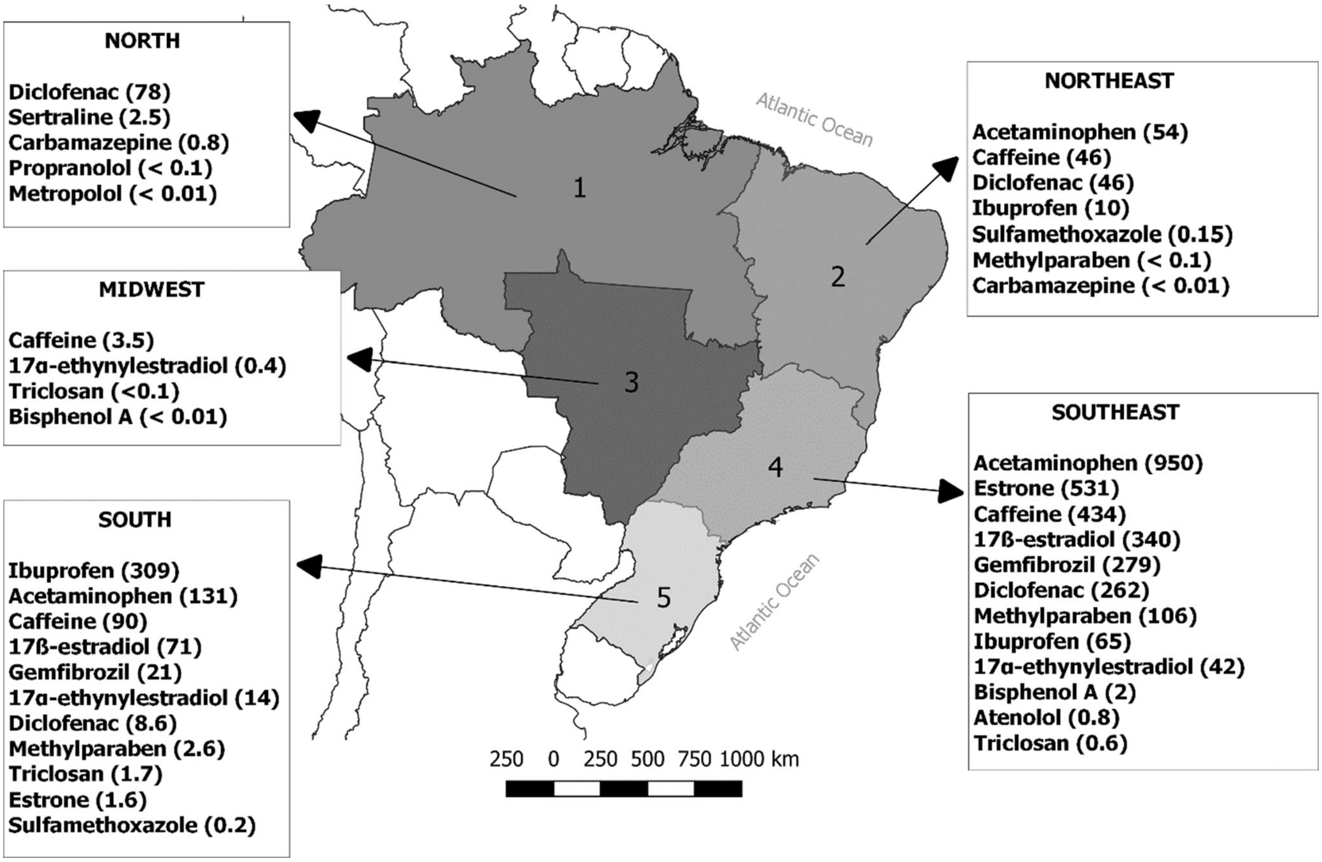

Fig. 3 CECs of greatest concern in Brazilian surface waters, considering occurrence and ecological risk. In parentheses is presented the maximum risk quotient found for each chemical

environment were usually higher than in other emerging countries (China, India, South Africa and Pakistan) and lower than South American countries.

Analyzing the environmental risks caused by CECs in Brazilian surface water, it was observed that pharmaceuticals presented higher risks to aquatic organisms compared to PCPs. Crustaceans (Daphnia) were the most sensitive organism for risk assessment of CECs. Ranked CECs with the highest risk were anti-inflammatories drugs (acetaminophen, diclofenac and ibuprofen), caffeine, steroid estrogens (17ß-estradiol and 17α-ethynylestradiol) and preservative (methylparaben). These results indicate a great threat to Brazilian aquatic ecosystem. Therefore, risk management actions must be carried out to promote safety to aquatic biota and protection of the environment.

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References

Agunbiade FO, Moodley B (2016) Occurrence and distribution pattern of acidic pharmaceuticals in surface water, wastewater, and sediment of the Msunduzi River, Kwazulu-Natal, South Africa. Environ. Toxicol. Chem. 35:36–46

Aitken M, Kleinrock M (2015) Global medicines use in 2020: outlook and implications. USA: Parsippany, New Jersey

Almeida Â, Solé M, Soares AM, Freitas R (2020) Anti-inflammatory drugs in the marine environment: Bioconcentration, metabolism and sub-lethal effects in marine bivalves. Environ. Pollut. 263: 114442

Aragão RBDA, Semensatto D, Calixto LA, Labuto G (2020) Pharmaceutical market, environmental public policies and water quality: the case of the São Paulo Metropolitan Region. Brazil. Reports in Public Health 36:e00192319

Arsand JB, Hoff RB, Jank L, Bussamara R, Dallegrave A, Bento FM, Kmetzsch L, Falção DA, Peralba MDCR, De Araujo Gomes A (2020) Presence of antibiotic resistance genes and its association with antibiotic occurrence in Dilúvio River in southern Brazil. Sci. Total Environ. 738:139781

Ashfaq M, Li Y, Rehman MSU, Zubair M, Mustafa G, Nazar MF, Yu C-P, Sun Q (2019) Occurrence, spatial variation and risk assessment of pharmaceuticals and personal care products in urban wastewater, canal surface water, and their sediments: a case study of Lahore, Pakistan. Sci. Total Environ. 688:653–663

Barros ALC, Schmidt FF, De Aquino SF, Afonso RJDCF (2018) Determination of nine pharmaceutical active compounds in surface waters from Paraopeba River Basin in Brazil by LTPE-HPLC-ESI-MS/MS. Environ. Sci. Pollut. Res. 25:19962–19974

Bedoya-Ríos DF, Lara-Borrero JA, Duque-Pardo V, Madera-Parra CA, Jimenez EM, Toro AF (2018) Study of the occurrence and ecosystem danger of selected endocrine disruptors in the urban water cycle of the city of Bogotá, Colombia. J Environ Sci Health A 53:317–325

Brasil, Agência Nacional de Vigilancia Sanitária - ANVISA. Anuário Estatístico do Mercado Farmacêutico (2018) Disponível em: http://portal.anvisa.gov.br/documents/374947/3413536/Anu%C3%A1rio+Estat%C3%ADstico+do+Mercado+Farmac%C3%AAutico+-+2017/3179a522-1af4-4b4c-8014-cc25a90fb5a7

Brasil, A. N. D. V. S. RDC N. 29, June 1, 2012 (RDC N. 29 de 1 de junho de 2012). DOU, (2012), pp. 4.

Caldas SS, Bolzan CM, Guilherme JR, Silveira MAK, Escarrone ALV, Primel EG (2013) Determination of pharmaceuticals, personal care products, and pesticides in surface and treated waters: method development and survey. Environ. Sci. Polluti. Res. 20:5855–5863

Caldas SS, Arias JLO, Rombaldi C, Mello LL, Cerqueira MB, Martins AF, Primel EG (2019) Occurrence of pesticides and PPCPs in surface and drinking water in Southern Brazil: data on 4-year monitoring. J. Braz. Chem. Soc. 30:71–80

Calderón-Moreno GM, Vergara-Sánchez J, Saldarriaga-Noreña H, García-Betancourt ML, Domínguez-Patiño ML, Moeller-Chávez GE, Ronderos-Lara JG, Arias-Montoya MI, Montoya-Balbas IJ, Murillo-Tovar MA (2019) Occurrence and risk assessment of steroidal hormones and phenolic endocrine disrupting compounds in surface water in Cuautla River, Mexico. Water 11:2628

Campanha MB, Awan AT, De Sousa DN, Grosseli GM, Mozeto AA, Fadini PS (2015) A 3-year study on occurrence of emerging contaminants in an urban stream of São Paulo State of Southeast Brazil. Environ. Sci. Polluti. Res. 22:7936–7947

Carmona E, Andreu V, Picó Y (2017) Multi-residue determination of 47 organic compounds in water, soil, sediment and fish—Turia River as case study. J. Pharm. Biomed. 146:117–125

Chaves MJS, Barbosa SC, Malinowski MDM, Volpato D, Castro ÍB, Franco TCRS, Primel EG (2020) Pharmaceuticals and personal care products in a Brazilian wetland of international importance: occurrence and environmental risk assessment. Sci. Total Environ. 734: 139374

Chen S, Gan Z, Li Z, Li Y, Ma X, Chen M, Qu B, Ding S, Su S (2021) Occurrence and risk assessment of anthelmintics in Tuojiang River in Sichuan. China. Ecotox Environ Safe 220:112360

Chiriac FL, Paun I, Pirvu F, Iancu V, Galaon T (2021) Distribution, removal efficiencies and environmental risk assessment of benzophenone and salicylate UV filters in WWTPs and surface waters from Romania. New J. Chem 45:2478–2487

Comtois-Marotte S, Chappuis T, Duy SV, Gilbert N, Lajeunesse A, Taktek S, Desrosiers M, Veilleux É, Sauvé S (2017) Analysis of emerging contaminants in water and solid samples using high resolution mass spectrometry with a Q Exactive orbital ion trap and estrogenic activity with YES-assay. Chemosphere 166:400–411

Cunha, D. L.,Muylaert, S.,Nascimento, M. T.,Felix, L. C.,Gomes, G., Bila, D. M., Fonseca, E. M. Occurrence of emerging contaminants and analysis of oestrogenic activity in the water and sediments from two coastal lagoons in south-eastern Brazil. Mar. Freshwater Res., 72 (2020), pp. A-O.

Dafouz R, Cáceres N, Rodríguez-Gil JL, Mastroianni N, De Alda ML, Barceló D, De Miguel ÁG, Valcárcel Y (2018) Does the presence of caffeine in the marine environment represent an environmental risk? A regional and global study. Sci. Total Environ 615:632–642

Dai G, Wang B, Huang J, Dong R, Deng S, Yu G (2015) Occurrence and source apportionment of pharmaceuticals and personal care products in the Beiyun River of Beijing. China. Chemosphere 119:1033–1039

Deere JR, Moore S, Ferrey M, Jankowski MD, Primus A, Convertino M, Servadio JL, Phelps NB, Hamilton MC, Chenaux-Ibrahim Y (2020) Occurrence of contaminants of emerging concern in aquatic ecosystems utilized by Minnesota tribal communities. Sci. Total Environ. 724:138057

Eur EC (2020) Commission Implementing Decision (EU) 2020/1161 of 4 August 2020 Establishing a watch list of substances for union-wide monitoring in the field of water policy pursuant to directive 2008/105/EC of the European Parliament and of the council. Off. J. Eur. Union. 257:32–35

Eur, E. C.-. Technical Guidance Document on Risk Assessment in support of Commission Directive 93/67/EEC on Risk Assessment for new notified substances. Ispra (IT): European Commission Joint Research Centre. EUR, 20418 (2003), pp.

Eur, E. C. Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. Off. J. Eur. Union, 226 (2013), pp. 1-17.

Farias MR, Leite SN, Tavares NUL, Oliveira MA, Arrais PSD, Bertoldi AD, Pizzol TDSD, Luiza VL, Ramos LR, Mengue SS (2016) Use of and access to oral and injectable contraceptives in Brazil. Revista de Saúde Pública 50:14s

Feo ML, Bagnati R, Passoni A, Riva F, Manta DS, Sprovieri M, Traina A, Zuccato E, Castiglioni S (2020) Pharmaceuticals and other contaminants in waters and sediments from Augusta Bay (southern Italy). Sci. Total Environ. 739:139827

Fontes MK, De Campos BG, Cortez FS, Pusceddu FH, Moreno BB, Maranho LA, Lebre DT, Guimarães LL, Pereira CDS (2019) Seasonal monitoring of cocaine and benzoylecgonine in a subtropical coastal zone (Santos Bay, Brazil). Mar. Pollut. Bull. 149:110545

Galinaro CA, Pereira FM, Vieira EM (2015) Determination of parabens in surface water from Mogi Guaçu River (São Paulo, Brazil) using dispersive liquid-liquid microextraction based on low density solvent and LC-DAD. J. Braz. Chem. Soc. 26:2205–2213

Gorga M, Insa S, Petrovic M, Barceló D (2015) Occurrence and spatial distribution of EDCs and related compounds in waters and sediments of Iberian rivers. Sci. Total Environ 503:69–86

Griffero L, Alcántara-Durán J, Alonso C, Rodríguez-Gallego L, Moreno-González D, García-Reyes JF, Molina-Díaz A, Pérez-Parada A (2019) Basin-scale monitoring and risk assessment of emerging contaminants in South American Atlantic coastal lagoons. Sci. Total Environ 697:134058

Guruge KS, Goswami P, Tanoue R, Nomiyama K, Wijesekara R, Dharmaratne TS (2019) First nationwide investigation and environmental risk assessment of 72 pharmaceuticals and personal care products from Sri Lankan surface waterways. Sci Total Environ 690:683–695

Guzel, E. Y.,Cevik, F., Daglioglu, N. Determination of pharmaceutical active compounds in Ceyhan River, Turkey: seasonal, spatial variations and environmental risk assessment. Hum Ecol Risk Assess, 25 (2019), pp. 1980-1995.

Ibge, B. I. B. D. G. E. E.-. Projeção da população do Brasil e das Unidades da Federação. (2020). Disponível em: https://www.ibge.gov.br/apps/populacao/projecao/.

Ide AH, Osawa RA, Marcante LO, Da Costa Pereira J, De Azevedo JCR (2017) Occurrence of pharmaceutical products, female sex hormones and caffeine in a subtropical region in Brazil. CLEAN–Soil, Air, Water 45:1700334

Ilyas H, Van Hullebusch ED (2020) A review on the occurrence, fate and removal of steroidal hormones during treatment with different types of constructed wetlands. J. Environ. Chem. Eng. 8:103793

Inam E, Offiong N-A, Kang S, Yang P, Essien J (2015) Assessment of the occurrence and risks of emerging organic pollutants (EOPs) in Ikpa River Basin freshwater ecosystem, Niger Delta-Nigeria. Bull. Environ. Contam. Toxicol. 95:624–631

Ismail NAH, Wee SY, Kamarulzaman NH, Aris AZ (2019) Quantification of multi-classes of endocrine-disrupting compounds in estuarine water. Environ. Pollut 249:1019–1028

Jank L, Hoff RB, Costa FJD, Pizzolato TM (2014) Simultaneous determination of eight antibiotics from distinct classes in surface and wastewater samples by solid-phase extraction and high-performance liquid chromatography–electrospray ionisation mass spectrometry. Int. J. Environ. Anal. Chem. 94:1013–1037

Kairigo P, Ngumba E, Sundberg L-R, Gachanja A, Tuhkanen T (2020) Occurrence of antibiotics and risk of antibiotic resistance evolution in selected Kenyan wastewaters, surface waters and sediments. Sci. Total Environ. 720:137580

Kosma CI, Lambropoulou DA, Albanis TA (2014) Investigation of PPCPs in wastewater treatment plants in Greece: occurrence, removal and environmental risk assessment. Sci Total Environ 466:421–438

Kötke D, Gandrass J, Xie Z, Ebinghaus R (2019) Prioritised pharmaceuticals in German estuaries and coastal waters: Occurrence and environmental risk assessment. Environ. Pollut 255:113161

Kovalakova P, Cizmas L, Mcdonald TJ, Marsalek B, Feng M (2020) Sharma. V. K. Occurrence and toxicity of antibiotics in the aquatic environment: a review. Chemosphere 251:126351

Kumar M, Ram B, Honda R, Poopipattana C, Canh VD, Chaminda T, Furumai H (2019) Concurrence of antibiotic resistant bacteria (ARB), viruses, pharmaceuticals and personal care products (PPCPs) in ambient waters of Guwahati, India: urban vulnerability and resilience perspective. Sci. Total Environ. 693:133640

Li S, Shi W, Li H, Xu N, Zhang R, Chen X, Sun W, Wen D, He S, Pan J (2018) Antibiotics in water and sediments of rivers and coastal area of Zhuhai City, Pearl River estuary, south China. Sci. Total Environ. 636:1009–1019

Lin T, Yu S, Chen W (2016) Occurrence, removal and risk assessment of pharmaceutical and personal care products (PPCPs) in an advanced drinking water treatment plant (ADWTP) around Taihu Lake in China. Chemosphere 152:1–9

Liu W-R, Zhao J-L, Liu Y-S, Chen Z-F, Yang Y-Y, Zhang Q-Q, Ying G-G (2015) Biocides in the Yangtze River of China: spatiotemporal distribution, mass load and risk assessment. Environ Pollut 200:53–63

Liu J, Zhang L, Lu G, Jiang R, Yan Z, Li Y (2020a) Occurrence, toxicity and ecological risk of Bisphenol A analogues in aquatic environment—a review. Ecotox. Environ. Safe. 208:111481

Liu N, Jin X, Feng C, Wang Z, Wu F, Johnson AC, Xiao H, Hollert H, Giesy JP (2020b) Ecological risk assessment of fifty pharmaceuticals and personal care products (PPCPs) in Chinese surface waters: a proposed multiple-level system. Environ. Int. 136:105454

Locatelli MAF, Sodré FF, Jardim WF (2011) Determination of antibiotics in Brazilian surface waters using liquid chromatography–electrospray tandem mass spectrometry. Arch. Environ. Contam. Toxicol 60:385–393

Lopes VSA, Riente RR, Da Silva AA, Torquilho DF, Da Silva Carreira R, Da Costa Marques MR (2016) Development of a solid-phase extraction system modified for preconcentration of emerging contaminants in large sample volumes from rivers of the lagoon system in the city of Rio de Janeiro, Brazil. Mar. Pollut. Bull. 110:572–577

López-Doval JC, Montagner CC, De Alburquerque AF, Moschini-Carlos V, Umbuzeiro G, Pompêo M (2017) Nutrients, emerging pollutants and pesticides in a tropical urban reservoir: spatial distributions and risk assessment. Sci. Total Environ 575:1307–1324

López-Pacheco IY, Silva-Núñez A, Salinas-Salazar C, Arévalo-Gallegos A, Lizarazo-Holguin LA, Barceló D, Iqbal HM, Parra-Saldívar R (2019) Anthropogenic contaminants of high concern: existence in water resources and their adverse effects. Sci. Total Environ 690: 1068–1088

Montagner CC, Jardim WF (2011) Spatial and seasonal variations of pharmaceuticals and endocrine disruptors in the Atibaia River, São Paulo State (Brazil). J. Braz. Chem. Soc. 22:1452–1462

Montagner CC, Jardim WF, Von Der Ohe PC, Umbuzeiro GA (2014) Occurrence and potential risk of triclosan in freshwaters of São Paulo, Brazil—the need for regulatory actions. Environ. Sci. Polluti. Res. 21:1850–1858

Montagner CC, Sodré FF, Acayaba RD, Vidal C, Campestrini I, Locatelli MA, Pescara IC, Albuquerque AF, Umbuzeiro GA, Jardim WF (2019) Ten years-snapshot of the occurrence of emerging contaminants in drinking, surface and ground waters and wastewaters from São Paulo State. Brazil. J. Braz. Chem. Soc. 30:614–632

Monteiro MA, Spisso BF, Ferreira RG, Pereira MU, Grutes JV, De Andradec BR, D'avila LA (2018) Development and validation of liquid chromatography-tandem mass spectrometry methods for determination of beta-lactams, macrolides, fluoroquinolones, sulfonamides and tetracyclines in surface and drinking water from Rio de Janeiro, Brazil. J. Braz. Chem. Soc 29:801–813

Moreira M, Aquino S, Coutrim M, Silva J, Afonso R (2011) Determination of endocrine-disrupting compounds in waters from Rio das Velhas, Brazil, by liquid chromatography/high resolution mass spectrometry (ESI-LC-IT-TOF/MS). Environ. Technol. 32: 1409–1417

Nannou CI, Kosma CI, Albanis TA (2015) Occurrence of pharmaceuticals in surface waters: analytical method development and environmental risk assessment. Inter J Environ Anal Chem 95:1242–1262

Nantaba F, Palm W-U, Wasswa J, Bouwman H, Kylin H, Kümmerer K (2021) Temporal dynamics and ecotoxicological risk assessment of personal care products, phthalate ester plasticizers, and organophosphorus flame retardants in water from Lake Victoria, Uganda. Chemosphere 262:127716

Ngo TH, Van D-A, Le Tran H, Nakada N, Tanaka H, Huynh TH (2020) Occurrence of pharmaceutical and personal care products in Cau River, Vietnam. Environ. Sci. Pollut. Res. Int. 28:12082–12091

Norman, N. NORMAN Suspect List Exchange. (2019).

Patel M, Kumar R, Kishor K, Mlsna T, Pittman CU Jr, Mohan D (2019) Pharmaceuticals of emerging concern in aquatic systems: chemistry, occurrence, effects, and removal methods. Chem. Rev. 119:3510–3673

Pemberthy D, Padilla Y, Echeverri A, Peñuela GA (2020) Monitoring pharmaceuticals and personal care products in water and fish from the Gulf of Urabá, Colombia. Heliyon 6:e04215

Pereira CDS, Maranho LA, Cortez FS, Pusceddu FH, Santos AR, Ribeiro DA, Cesar A, Guimarães LL (2016) Occurrence of pharmaceuticals and cocaine in a Brazilian coastal zone. Sci. Total Environ. 548: 148–154

Pivetta GG, Gastaldini MDCC (2019) Presence of emerging contaminants in urban water bodies in southern Brazil. J. Water Health 17: 329–337

Pompei CME, Campos LC, Da Silva BF, Fogo JC, Vieira EM (2019) Occurrence of PPCPs in a Brazilian water reservoir and their removal efficiency by ecological filtration. Chemosphere 226:210–219

Reichert G, Mizukawa A, Antonelli J, Goulart FDAB, Filippe TC, De Azevedo JCR (2020) Determination of parabens, triclosan, and lipid regulators in a subtropical urban river: effects of urban occupation. Water Air Soil Pollut 231:1–11

Reis EO, Foureaux AFS, Rodrigues JS, Moreira VR, Lebron YA, Santos LV, Amaral MC, Lange LC (2019) Occurrence, removal and seasonal variation of pharmaceuticals in Brasilian drinking water treatment plants. Environ. Pollut. 250:773–781

Rigueto CVT, Nazari MT, De Souza CF, Cadore JS, Brião VB, Piccin JS (2020) Alternative techniques for caffeine removal from wastewater: an overview of opportunities and challenges. J. Water Proc. Engineering 35:101231

Rivera-Jaimes JA, Postigo C, Melgoza-Alemán RM, Aceña J, Barceló D, De Alda ML (2018) Study of pharmaceuticals in surface and wastewater from Cuernavaca, Morelos, Mexico: occurrence and environmental risk assessment. Sci. Total Environ 613:1263–1274

Roveri, V.,Guimarães, L. L.,Toma, W., Correia, A. T. (2020) Occurrence and risk assessment of pharmaceuticals and cocaine around the coastal submarine sewage outfall in Guarujá, São Paulo State, Brazil. Environ. Sci. Pollut. Res, pp. 1-17

Santos MMD, Brehm FDA, Filippe TC, Knapik HG, Azevedo JCRD (2016) Occurrence and risk assessment of parabens and triclosan in surface waters of southern Brazil: a problem of emerging compounds in an emerging country. RBRH 21:603–617

Santos AV, Couto CF, Lebron YAR, Moreira VR, Foureaux AFS, Reis EO, de Souza Santos LV, De Andrade LH, Amaral MCS, Lange LC (2020) Occurrence and risk assessment of pharmaceutically active compounds in water supply systems in Brazil. Sci. Total Environ. 746:141011

Sharma BM, Bečanová J, Scheringer M, Sharma A, Bharat GK, Whitehead PG, Klánová J, Nizzetto L (2019) Health and ecological risk assessment of emerging contaminants (pharmaceuticals, personal care products, and artificial sweeteners) in surface and groundwater (drinking water) in the Ganges River Basin, India. Sci. Total Environ. 646:1459–1467

Silva CP, Emídio ES, De Marchi MRR (2015) The occurrence of UV filters in natural and drinking water in São Paulo State (Brazil). Environ. Sci. Pollut. Res. 22:19706–19715

Silveira MAK, Caldas SS, Guilherme JR, Costa FP, Guimarães BDS, Cerqueira MB, Soares BM, Primel EG (2013) Quantification of pharmaceuticals and personal care product residues in surface and drinking water samples by SPE and LC-ESI-MS/MS. Journal of the Brazilian Chemical Society 24:1385–1395

Singh V, Suthar S (2021) Occurrence, seasonal variations, and ecological risk of pharmaceuticals and personal care products in River Ganges at two holy cities of India. Chemosphere 268:129331

Sousa DNR, Mozeto AA, Carneiro RL, Fadini PS (2014) Electrical conductivity and emerging contaminant as markers of surface freshwater contamination by wastewater. Sci. Total Environ 484:19–26

Sousa DNR, Mozeto AA, Carneiro RL, Fadini PS (2018) Spatio-temporal evaluation of emerging contaminants and their partitioning along a Brazilian watershed. Environ. Sci. Polluti. Res. 25:4607–4620

Souza M, Rizzetti T, Francesquett J, Prestes O, Zanella R (2018) Bar adsorptive microextraction (BAμE) with a polymeric sorbent for the determination of emerging contaminants in water samples by ultra-high performance liquid chromatography with tandem mass spectrometry. Anal. Methods 10:697–705

Sposito JC, Montagner CC, Casado M, Navarro-Martín L, Solórzano JCJ, Piña B, Grisolia AB (2018) Emerging contaminants in Brazilian rivers: occurrence and effects on gene expression in zebrafish (Danio rerio) embryos. Chemosphere 209:696–704

Starling MCV, Amorim CC, Leão MMD (2019) Occurrence, control and fate of contaminants of emerging concern in environmental compartments in Brazil. J. Hazard. Mater. 372:17–36

Sun Q, Li Y, Li M, Ashfaq M, Lv M, Wang H, Hu A, Yu C-P (2016) PPCPs in Jiulong River estuary (China): spatiotemporal distributions, fate, and their use as chemical markers of wastewater. Chemosphere 150:596–604

Thiebault T (2020) Sulfamethoxazole/Trimethoprim ratio as a new marker in raw wastewaters: a critical review. Sci. Total Environ. 715: 136916

Thomas KV, Da Silva FMA, Langford K, De Souza ADL, Nizzeto L, Waichman A (2014) Screening for selected human pharmaceuticals and cocaine in the urban streams of Manaus, Amazonas, Brazil. J. Am. Water Resour. As 50:302–308

Torres NH, Aguiar MM, Ferreira LFR, Américo JHP, Machado ÂM, Cavalcanti EB, Tornisielo VL (2015) Detection of hormones in surface and drinking water in Brazil by LC-ESI-MS/MS and ecotoxicological assessment with Daphnia magna. Environ. Monitor. Asses. 187:379

Voloshenko-Rossin A, Gasser G, Cohen K, Gun J, Cumbal-Flores L, Parra-Morales W, Sarabia F, Ojeda F, Lev O (2015) Emerging pollutants in the Esmeraldas watershed in Ecuador: discharge and attenuation of emerging organic pollutants along the San Pedro–Guayllabamba–Esmeraldas rivers. Environ. Sci. Proces. Impacts 17:41–53

Wang C, He J, Xu T, Han H, Zhu Z, Meng L, Pang Q, Fan R (2021) Bisphenol A (BPA), BPS and BPB-induced oxidative stress and apoptosis mediated by mitochondria in human neuroblastoma cell lines. Ecotoxicology and Environmental Safety 207:111299

Wu M-H, Xie D-G, Xu G, Sun R, Xia X-Y, Liu W-L, Tang L (2017) Benzophenone-type UV filters in surface waters: an assessment of profiles and ecological risks in Shanghai, China. Ecotox Environ Safe 141:235–241

Zheng Y, Lu G-H, Shao P-W, Piao H-T, Gai N, Rao Z, Zhao Q-S, Yang Y-L (2020) Source tracking and risk assessment of pharmaceutical and personal care products in surface waters of Qingdao, China, with emphasis on influence of animal farming in rural areas. Arch Environ Con Tox 78:579–588

Zhong R, Zou H, Gao J, Wang T, Bu Q, Wang Z-L, Hu M, Wang Z (2021) A critical review on the distribution and ecological risk assessment of steroid hormones in the environment in China. Sci Total Environ 786:147452