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ABSTRACT

Anthropogenic fibers, gathering synthetic fibers, artificial fibers and natural fibers are ubiquitous in the natural environment. Tremendous concentrations of anthropogenic fibers were previously measured in the tropical Saigon River (Vietnam), i.e. a river impacted by textile and apparel industries. In the present study, we want to examine the role of contrasted seasonal variation (e.g., dry and rainy seasons), via the rainfall and monthly water discharges, and of water's physico-chemical conditions on the concentrations of anthropogenic fibers in the surface water. The one year and half monthly survey evidenced that concentrations of anthropogenic fibers varied from 22 to 251 items L^{-1} and their variations were not related to rainfall, water discharge or abiotic factors. However, their color and length distribution varied monthly suggesting variations in sources and sinks. Based on the 2017 survey, we estimated an annual emission of anthropogenic fibers from the river to the downstream coastal zone of 115e164 $\times 10^{12}$ items yr^{-1}.

1. Introduction

Plastic pollution in the aquatic environment is a worldwide issue that affect both the marine and the freshwater environments. Plastic in the aquatic environment are categorized according to their size. Macroplastic refers to plastic items larger than 5 mm while microplastic to items comprised between 1 mm and 5 mm length size (Barnes et al., 2009; Gigault et al., 2018; Hartmann et al., 2019; Frias and Nash, 2019). Microplastic are composed of fragments, fibers, pellets and microbeads originated from both primary and secondary manufacturing.

Among microplastic, fibers are the most prevalent ones observed in the natural environment (Browne et al., 2011) and micropollution fibers are more and more of concern. Anthropogenic fibers, as we defined in Lahens et al. (2018) refer to the synthetic fibers from petrochemical origin (i.e. polyester, polyamide, polypropylene, etc.), to the artificial fibers from artificial cellulose or silk (i.e. viscose, rayon) and to the natural fibers (i.e. cotton, wool), all used in textile and apparel industries. The synthetic fibers are released to the aquatic environment mainly by the use of synthetic polymers in textile and garment industry (e.g. 98 million tons of polyester fibers in 2018, Textile Exchange, 2018), by nets and other materials like geotextile. Synthetic fibers and artificial fibers are found in all aquatic compartments: lake, river, estuary, sea an ocean, atmospheric fallout (see reviews of Cesa et al., 2019; Gago et al., 2018; Blettler et al., 2018) and can be transferred through freshwater and marine foodwebs and have implications to human health (see review Carbery et al., 2018; Blettler et al., 2018). Their concentrations in seawater (e.g. ND - 450 items m^{-3}; Gago et al., 2018) are in the same range as in most riverine waters (e.g. 5e398 items m^{-3}; Dris et al., 2018 and reference within) but their dominant polymer's type differ between environment. Polypropylene (PP) fibers were found the most common in the marine environment (Gago et al., 2018) while polyethylene terephthalate PET (Dris et al., 2018) and polyester (Lahens et al., 2018) were the

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dominant one in rivers, pointing out the different sources of fibers to the environment. These features evidenced then the need to better understand the sources, the fate and dynamic of synthetic fibers from river to sea.

Despite the possibility that the South East Asian countries are among the ones emitting the most plastic to the ocean (Jambeck et al., 2015), the majority of plastic assessment's studies in freshwater environments were conducted in Europe, North America and more recently in China (see review Blettler et al., 2018), pointing out a clear lack of data in South East Asia. Vietnam is the third top garment exporters in the world after China and Bangladesh (International Trade Administration, 2016). There are about 6000 textile and apparel manufacturing companies, employing 2.5 million workers, which 60% of them are located in the Southern part of the country (International Trade Administration, 2016). In the Saigon River and its canals, crossing the megacity Ho Chi Minh City (HCMC; 8.4 million inhabitants (GSO, 2017)) in Southern Vietnam, tremendous concentrations of anthropogenic fibers were measured (e.g.172e519 items L^{-1} Lahens et al., 2018) in the dense and urbanized part of the River. Their synthetic origin, with 70% of them being made of polyester, evidenced that textile and apparel industry are the main sources of fibers in this River and that, associated to poor wastewater treatment, it impacts the quality of the River (Lahens et al., 2018). In line with the previous study, the main objective of the present study is to characterize the temporal variation at an annual scale of the anthropogenic fibers in the surface water of the Saigon River, a tropical river-estuarine environment characterized by two contrasted seasons (e.g. rainy and dry) and by tidal influence. We hypothesized that the contrasted seasons via the rainfall, the change of water discharge and the intrusion of the salinity front will strongly influence the concentrations of anthropogenic fibers in the river. We examined the impact of (i) the season via the rainfall, (ii) the monthly water discharges and (iii) the water's physico chemical conditions on the seasonal dynamic of fibers. We also aim to quantify the emission of fibers by the Saigon River to the coastal zone. Accordingly, we set up a monthly monitoring survey during eighteen months in the surface water of the Saigon River at a sampling site located in the dense urban zone.

2. Material and methods

2.1. The Saigon River Estuary system

The Saigon River Estuary system (250 km long; 4717 km^2), located in Southern Vietnam, originates from South Eastern Cambodia, forms the Dau Tieng Reservoir (120e270 km^2; 470-1680 million m^3), flows through the economic capital city of HCMC, confluences with the Dong Nai River (470 km long) and then flows into the Can Gio mangrove and the South China Sea (Fig. 1). The Saigon River is under a tropical monsoon climate with a rainy season lasting from May to November and a dry season from December to April (Nguyen et al., 2019a,b). The River is affected by asymmetric semidiurnal tides (e.g. tides up to 3 m) that can reach up to 30 km downstream the Dau Tieng reservoir. The saline intrusion is recorded around the Saigon Dong Nai confluence during the rainy season and upstream HCMC during the dry season. The saltwater intrusion upstream HCMC is controlled by the water management at the Dau Tieng Reservoir in order to limit its intrusion for irrigation purposes and water pumping for domestic use. The Saigon River water discharge distribution is controlled by precipitation seasonality and artificially by the reservoir during the dry season to limit the salt intrusion and during the rainy season when the reservoir water level is too high. Accordingly, the mean net inter-annual discharge calculated over the 2012e2016 period was of 50 ± 20 $m^3 s^{-1}$, despite high positive and negative instantaneous water discharge (i.e. more than 1000 $m^3 s^{-1}$; Camenen et al., 2017) with the lowest monthly discharges recorded in January 16 ± 42 $m^3 s^{-1}$ and the highest in October 118 ± 80 $m^3 s^{-1}$ (Nguyen et al., 2019a). Because of the tide dynamic and the intense navigation traffic, the Saigon River is a highly turbulent system with a well homogenized water column regarding temperature, salinity, TSS, pH, Chl-a, with a punctual and local stratification regarding dissolved oxygen concentrations (Nguyen et al., 2019b). HCMC is a dynamic megacity (8.4 million inhabitants) with a dense urban zone in the City Centre fluctuating from 10,000 to 40,000 inhabitants km^{-2}. The sampling site, Bach Dang, is located close to those dense urban zone and close to the main urban canals (e.g. Nhieu Loc Thi Nghe, Tau Hu, Kenh Te; Lahens et al., 2018). This specific site was already characterized by high human pressure on the water quality regarding microplastic (Lahens et al., 2018), macroplastic (van Emmerik et al., 2018; 2019), eutrophication (Nguyen et al., 2019a,b) and trace metal contamination (Strady et al., 2017). At a larger scale, the urban, industrial and demographic growth of HCMC coupled to poor industrial and domestic wastewater treatment facilities impact the quality of the Saigon River Estuary system (Vo, 2007; Strady et al., 2017; Thanh-Nho et al., 2018; Lahens et al., 2018; Babut et al., 2019; Nguyen et al., 2019a,b). The Saigon River catchment basin drains most of the untreated wastewater from dense urban districts and industrial zones from HCMC and Binh Duong Provinces, which include textile, apparel, plastic and packaging production industries as main group of industry.

2.2. Sampling

2.2.1. Monthly sampling

From July 2016 to January 2018, at a monthly frequency, riverine bulk surface water was collected in duplicate during the end of the low tide (i.e. to get the riverine and continental tidal signal) (Figure Supplementary Material 1) using a bucket and a volume of 300 ml was immediately stored in a 500 mL glass bottle, according to the protocol of Lahens et al. (2018). This low volume results from a compromise between the high concentrations of anthropogenic fibers in this river, the turbidity of the water, the local cost of the consumables and the time of observation by stereoscope. The samples were taken from a boat in the middle of the stream of the Saigon River, at the sampling site Bach Dang (Fig. 1). Conductivity, pH, oxygen and temperature were measured using a multiparameter probe WTW® while total suspended solids (TSS) were determined by filtration on GF-F filters (Strady et al., 2017). In this river-estuarine system, conductivity and TSS are a proxy of water body specifically saline intrusion (Strady et al., 2017), temperature of seasons while low oxygen and low pH are a proxy of anthropogenic pressure and bad water quality (Nguyen et al., 2019a,b).

2.2.2. Additional punctual sampling in industrial zone

Two additional bulk surface water samplings were performed in December 2018 at one-week interval in the Thi Tinh River and its affluent, the Sunrise River, both crossing the industrial zone of My Phuoc and confluence with the Saigon River. The My Phuoc Industrial Zone present plastic and textile industry. The sampling methodology was the same as for monthly sampling.

2.3. Treatment and analysis

Bulk riverine water samples were treated based on the protocol of Mintenig et al. (2014) which is composed of three successive reagents addition to the sample (i) 1 g of Sodium Dodecyl Sulfate (SDS, Merck®) at 50 °C for 24 h; (ii) 1 mL of biozym SE (protease and

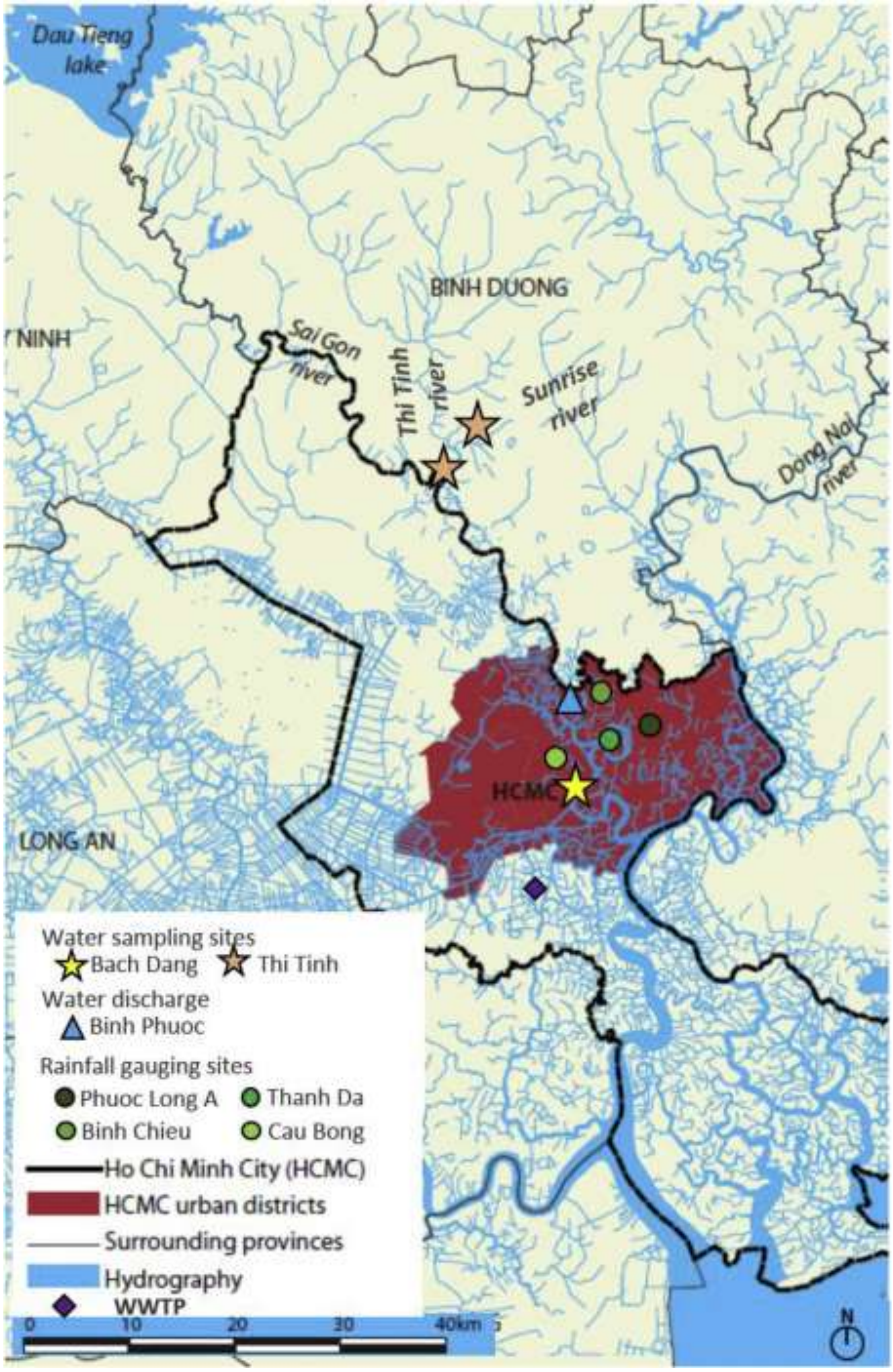

Fig. 1. Map and sampling sites.

amylase, Spinnrad®) and 1 mL of biozym F (lipase, Spinnrad®) at 40 °C for 48 h; (iii) 15 mL of hydrogen peroxide (H_2O_2 30%, Merck®) at 40 °C for 48 h. During each step, the bottle was closed and maintained in a laboratory oven. Then, the samples were filtered through a glass fiber filters (GF/A, 1.6 mm porosity) using a glassware filtration unit with a cover to prevent airborne contamination. Blank tests using 1 L of purified water (Elga®) were performed using the same protocol and evidenced fiber's concentrations of 7e12 items L^{-1}. The length of those fibers being different and longer than the one of the samples (median 152 mm; min 39 mm, max: 2211 mm), we believe that the contamination is linked to purified water and specifically its production which requires a first manual distillation step. We consider that the contamination doesn't affect the samples as no purified water is used during the treatment, except the rinsing of the filtration device using 10e20 mL of purified water maximum. Therefore, the fiber's concentrations in the samples were not corrected from the blank values.

2.4. Sample observation

The filters were observed using the stereomicroscope Leica

S6D® with HD camera. Morphology of fibers was measured, i.e length and diameter, using the LAS software® and their color were recorded. The minimum length size of anthropogenic fibers observation was set up at 40 mm, as it is difficult for lower size to ensure visually their synthetic origin, while the maximum one was of 5 mm. However, the precision of the Leica S6D allows to measure the diameter of the fibers at a minimal limit of 2 mm. We defined as anthropogenic fibers elongated fibers being equally thick, not taper towards the ends, having a three-dimensional bending, having no visible cellular or organic structures and being homogeneously colored (red, blue, green, grey, black). We excluded straight fibers and transparent or whitish fibers in order to exclude biological or organic origin (Nore´n, 2007).

2.5. Rainfall and water discharges data

Daily rainfall data for 2016e2017 at four stations located near the Saigon River (Phuoc Long; Binh Chieu; Thanh Da; Cau Bong) were measured from the Department of Natural Resources and Environment of HCMC (DONRE) and gathered monthly (Table 1). Water discharges data for 2016e2017 were measured by the Centre of Environmental Monitoring (CEM) from DONRE at the sampling location Binh Phuoc. The monthly water discharges were calculated as presented previously by Nguyen et al. (2019a) (Table 1). We note that current velocity data and wind data are not available for this system.

3. Results

Over the year and half monthly sampling, a total of 1055 anthropogenic fibers were observed and measured. The fiber's concentrations vary through the year, with a minimum of concentrations of 22 items L^{-1} observed in July 2017 and a maximum of 251 items L^{-1} observed in August 2016 (Fig. 2). The difference between the two duplicates ranged from 2% to 65% with a mean and a median of 25%, showing that anthropogenic fiber's concentrations

Table 1
Monthly raw data of minimum and maximum concentrations of anthropogenic fibers, abiotic conditions (temperature, pH dissolved oxygen, conductivity, TSS; Bach Dang, rainfall (4 gauging sites) and water discharge (Binh Phuc).

Date	Fibre's concentra	Tempera ture pH	o2	conductivi ty	TSS
	item L^{-1}	°C			

t i c r v a t e r d i s c h a r g e

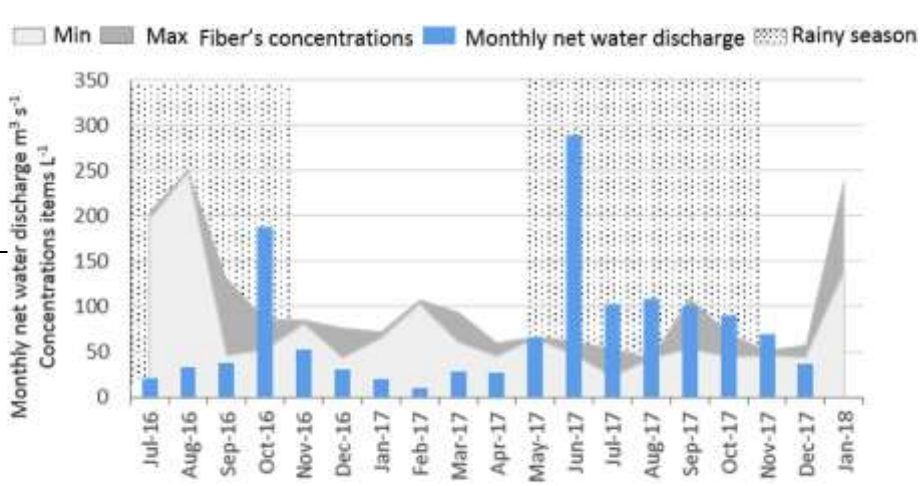

Fig. 2. Monthly net water discharge estimated at Binh Phuoc by DONRE and monthly minimum and maximum concentrations of anthropogenic fibers sampled in the Saigon River at Bach Dang site from July 2016 to January 2018. Dashed area represents the rainy season period.

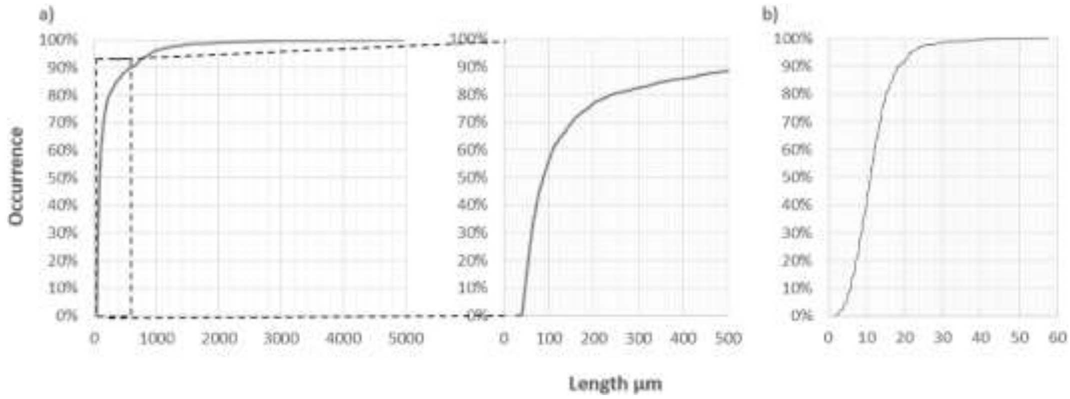

Fig. 3. Size distribution of a) length and b) diameter of anthropogenic fibers in respect to their occurrence sampled in the Saigon River at Bach Dang site from July 2016 to January 2018. For a) the lower detection limit to recognize microplastic was set at 40 mm. For b) the precision of the measurement is of 2 mm.

can be both well-homogenized and not well-homogenized in the surface water (Fig. 2). Their temporal variation do not present particular pattern with dry or rainy season (Fig. 2). The length and diameter size distribution of anthropogenic fibers observed over the year and half sampling in respect to their occurrence (Fig. 3) is showing the clear domination of smaller fibers in the riverine surface water: 50% of their occurrence have a size range of 40e80 mm and 82% a size range of 40e300 mm. Despite that we set up a lower measurement limit of 40 mm, mainly due to the difficulty to accurately identify anthropogenic fibers, we often observed fibers smaller than 40 mm. We note that the fibers have a median diameter of 12 mm, ranging from 2 to 58 mm (Fig. 3). The domination of the smallest fibers size range points out the crucial role of the employed methodology on the determination of fiber's characteristics in the water. Through time, the monthly size length distribution present low variation (Fig. 4) considering an upper limit size of 5000 mm defining a microplastic (e.g. Barnes et al., 2009). The median is always lower than 130 mm length, except an increase up to 320 mm in November 2017. Even if the smaller fiber's size are dominating, longer fibers were measured monthly: the maximum length were comprised between 621 mm in December 2016 until 4935 mm in August 2016, with most of them being longer than 1000 mm. Globally, over the sampling period, the total color's repartition of fibers present two dominant colors, blue (38%) and red (33%), followed by grey (18%), black (7%) and green (3%) (Fig. 5).

Seasonally, blue color dominates over red, grey, black and green (respectively 44%, 29%, 19%, 4%, 3%) during the rainy season while red dominates over blue, black, grey and green during the dry season (respectively 38%, 29%, 18%, 13%, 3%). The color repartition fluctuates monthly (Fig. 5): blue fibers ranged from 11% to 69% of total fibers (April 2017 and September 2016, respectively), red ones from 6% to 51% (December 2017 & August 2017 and April 2017, respectively), grey ones from 0 to 31% (January 2017 and December 2017, respectively) and black ones from 0 to 26% (maximum in March 2017).

4. Discussion

4.1. Variation of anthropogenic fiber's concentrations and size

The range of anthropogenic fiber's concentrations measured during this survey is lower than previously observed by Lahens et al. (2018) at the same sampling site in April 2016 (172e519 items L^{-1}) but much higher than concentrations reported in most rivers like in the Seine River (0.005e0.398 items L^{-1}; Dris et al., 2018), the Yangtze River (1.9 items L^{-1}; Wang et al., 2017), the Hanjiang River (2.3 items L^{-1}; Wang et al., 2017; the Antua River (0.02e0.071 items L^{-1}; Rodrigues et al., 2018) for fibers or even all microplastic (fibers, fragments and pellets) recorded in the Pearl River (0.379e7924 items L^{-1}; Lin et al., 2018), the Jiaojiang River

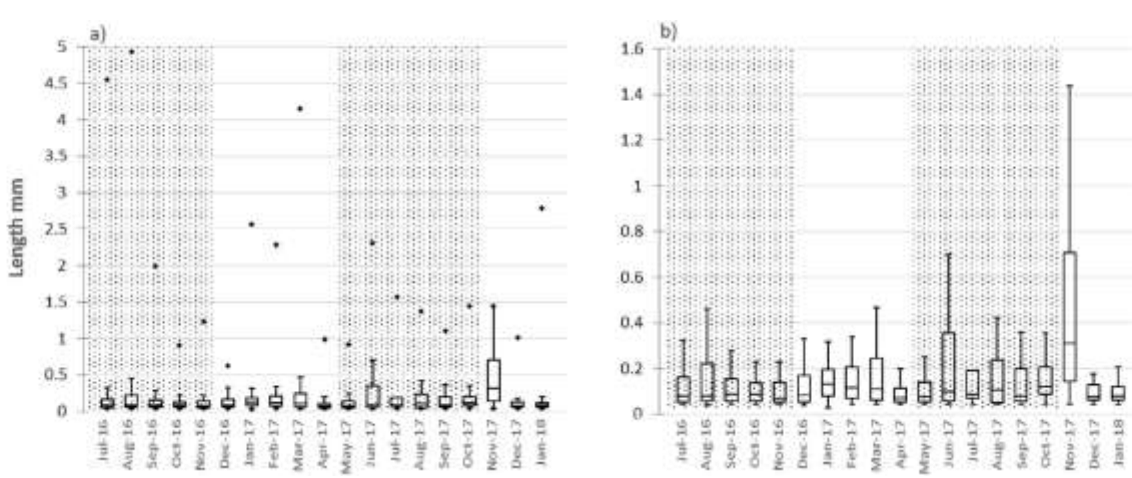

Fig. 4. Monthly boxplot of length of anthropogenic fibers sampled in the Saigon River at Bach Dang site from July 2016 to January 2018. A) boxplot: median, quartiles, min max; b) zoom on boxplot excluding min and max. Dashed area represents the rainy season period.

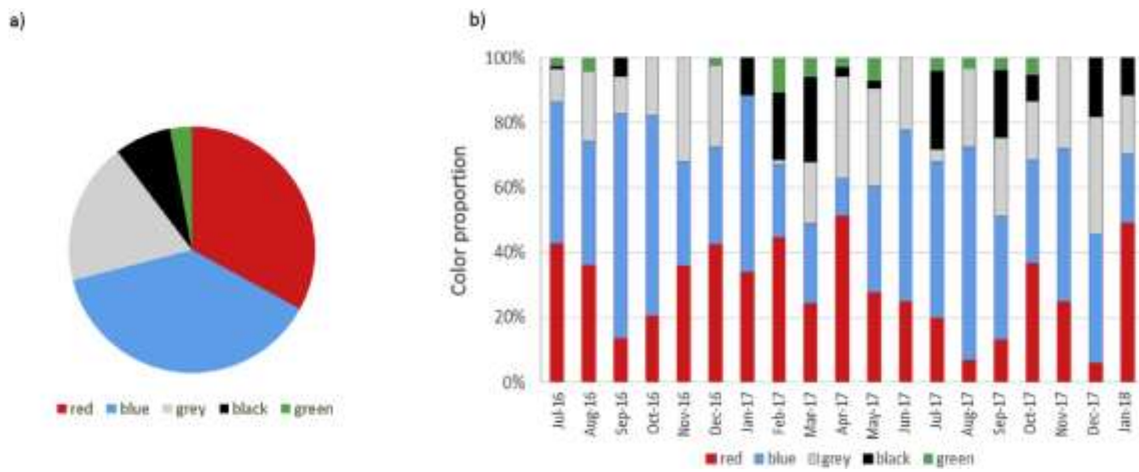

Fig. 5. a) Global and b) monthly color distribution of anthropogenic fibers sampled in the Saigon River at Bach Dang site from July 2016 to January 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(0.1e4.1 items L^{-1}; Zhao et al., 2015). The color domination observed is similar than in the Yangtze River and the Hanjiang River (Wang et al., 2017) and in surface seawater of most oceans where blue fibers are dominating (Gago et al., 2018). The different methodologies used in the above studied and the types of microplastic targeted induced a bias in the estimation of the concentrations and distribution size of fibers. The choice of (i) using mesh size net (e.g., 80 or 300 mm mesh size net (Dris et al., 2018; Faure et al., 2015)) or sampling bulk water (e.g. Lahens et al., 2018), of (ii) setting up a lower limit size to count microplastic (e.g., 50 mm: Lahens et al., 2018; Wang et al., 2017; 100 mm: Miller et al., 2017) and of (iii) defining the targeted microplastic (synthetic or anthropogenic fibers) induced thus a bias in the estimation of the concentrations and in their comparison from site to site.

4.2. Sources of anthropogenic fibers in the Saigon River

The anthropogenic fibers sampled in the Saigon River previously by Lahens et al. (2018) were composed by a large majority (e.g. 92%) of synthetic fibers, namely 70% of polyester. This high proportion of synthetic fibers, quite specific to this environment, reflects the impacts of wastewater and possible influence of textile and apparel industry developed in the surroundings of HCMC. Therefore, the sources of anthropogenic fibers in the Saigon River can be from: (i) domestic wastewater, (ii) industrial wastewaters and (iii) atmospheric fallout. In HCMC, during 2016e2017 period, only 5% of the released domestic wastewaters were treated (426,000 over 8,400,000 inhabitants; Nguyen et al., 2019a) while the industrial ones were estimated to be 50% (Vo, 2007). Knowing that a washing machine can conduct up to 728,000 fibers from a 6 kg wash load (Napper and Thompson, 2016), that 60% of Vietnamese textile and garment industry is located near HCMC (International Trade Administration, 2016) and that the wastewater treatment plants rely on basic chemical treatment only (e.g. sedimentation and oxygenation), both treated and untreated wastewaters can be thus a source of anthropogenic fibers to the Saigon River. In developed countries mainly, the primary sedimentation step of current WWTP retains the major part of microplastic and fibers in wastewaters (see in review Cesa et al., 2019). In advanced tertiary level wastewater treatment plant, the retention can be even up to 99% after all treatment steps (Talvitie et al., 2017). But in HCMC, it remains difficult to estimate the impact of domestic and industrial wastewater release on fiber's concentrations in the Saigon River, as the removal of anthropogenic fibers by Vietnamese waste water treatment plant is not yet quantified. Therefore, at a first step, we sampled bulk water in the Sunrise River and the Thi Tinh River, both crossing the My Phuoc Industrial Zone (Binh Duong Province). We note that the Thi Tinh River is an affluent of the Saigon River already characterized by important industrial pollution, especially the textile industry regarding its elevated chromium's concentrations (Strady et al., 2017). In the Thi Tinh River (60 m width) and the Sunrise River (45 m width), the concentrations of fibers in the surface water fluctuated from 30 to 242 and from 30 to 166 items L^{-1}, respectively. They are in the same order of magnitude as in the Saigon River (300 m width, up to 20 m depth), located 66 km downstream of the Sunrise and Thi Tinh River's confluence. Their length distribution are also similar (first quartile: 49 and 48 mm; median: 59 and 65 mm; third quartile 104 and 91 mm respectively in the Sunrise and Thi Tinh River). Those findings evidenced that both the plastic industrial activities in the industrial zone impact the quality of the River regarding anthropogenic fibers and that no dilution effect is observed from the Thi Tinh River to downstream the Saigon River in HCMC central districts. We assumed that important additional inputs must exist along the river toward HCMC to maintain such elevated concentrations despite water dilution and distance. Concerning the internal variability of these domestic and industrial wastewater sources, in term of quality (i.e. color) and also of quantity (i.e. concentrations), their assessment remains to be addressed. At an annual or seasonal scale, we can assume that the sources are constant and that the daily qualitative and quantitative variability of anthropogenic fibers released by washing machine or by industrial wastewaters is negligible. But, the color repartition varied monthly, evidencing that the sources of anthropogenic fibers in term of quality are not constant at a monthly scale, they have internal variation, which can for example rely on the demand relative to textile and garment production. Concerning the variability of the source's quantity, even if the measured concentrations evidenced monthly variation in the Saigon, Thi Tinh and Sunrise Rivers, it is difficult to evaluate if the quantity measured in the river depends on the quantity emitted by the source and/or by the factors which might control the fate and transport of anthropogenic fibers in the river (e.g. river discharge, current velocity, precipitations).

Atmospheric fallouts are a source of microplastic in the environment, especially of synthetic fibers (Dris et al., 2016; Cai et al., 2018). In the Paris Metropole (France), Dris et al. (2016) estimated

Table 2
Pearson matrix correlation. Values in bold are different from 0 to a level of significance alpha ¼ 0.05 (Q refers to net monthly water discharges).

	Min	max	$Rainfall_{phuoc\ long}$	$Rainfall_{Binh\ chieu}$	$Rainfall_{Thanh\ Da}$	$Rainfall_{Cau\ Bong}$	Q_{month}	T	pH	O_2	conductivity	TSS
min	1	0.862	−0.069	0.051	−0.090	−0.137	−0.316	0.307	−0.176	−0.037	0.104	0.050
max	0.862	1	0.046	0.189	0.092	0.106	−0.339	0.165	−0.228	−0.014	0.077	0.213
$Rainfall_{phuoc\ long}$	−0.069	0.046	1	0.785	0.895	0.860	0.717	0.223	−0.099	−0.134	−0.365	0.030
$Rainfall_{Binh\ chieu}$	0.051	0.189	0.785	1	0.830	0.856	0.471	0.295	−0.163	−0.088	−0.348	−0.012
$Rainfall_{Thanh\ Da}$	−0.090	0.092	0.895	0.830	1	0.907	0.580	0.207	−0.047	−0.186	−0.424	0.017
$Rainfall_{Cau\ Bong}$	−0.137	0.106	0.860	0.856	0.907	1	0.433	0.108	−0.309	−0.078	−0.480	0.080
Q_{month}	−0.316	−0.339	0.717	0.471	0.580	0.433	1	0.154	0.174	−0.080	−0.389	−0.283
T	0.307	0.165	0.223	0.295	0.207	0.108	0.154	1	0.030	−0.036	0.109	0.042
pH	−0.176	0.228	0.099	−0.163	0.047	−0.309	0.174	0.030	1	0.380	0.463	−0.134
O_2	−0.037	−0.014	−0.134	−0.088	−0.186	−0.078	−0.080	−0.036	0.380	1	0.468	−0.339
conductivity	0.104	0.077	−0.365	−0.348	−0.424	−0.480	−0.389	0.109	0.463	0.468	1	−0.030
TSS	0.050	0.213	0.030	−0.012	0.017	0.080	−0.283	0.042	−0.134	−0.339	−0.030	1

Values in bold are different from 0 to a level of significance alpha ¼ 0.05

an annual atmospheric input of 3e10 ton synthetic fibers. Highest fiber's inputs were recorded during rainfall events rather than during dry period, and in urban areas rather than in sub-urban zone (Dris et al., 2016). The smallest fibers (i.e., 200e600 mm length) were the most abundant (Dris et al., 2016) and most of the fibers observed in Dongguan City's fallout evidenced degradation marks indicating past mechanical erosion and/or chemical weathering (Cai et al., 2018). Given the importance of annual rainfall in HCMC compared to Paris City (rainfall of 1600 mm and 637 mm, respectively), the atmospheric fallout can be considered as a source of fibers to the environment in this system, via direct precipitation in the River or indirectly via runoff of the surrounding watershed. However, their effect on the river as direct accumulation or dilution (if their concentrations in the rainfall and their fluxes at the watershed level are much lower than in the river) required to be estimated and compared to the other sources that are domestic wastewater and industrial wastewaters.

4.3. *Anthropogenic fiber's seasonal patterns*

The Saigon River is under a tropical regime with a dry season lasting from December to April and a rainy season from May to November which accumulate up to 1600 mm of rainfall. Even if the water discharge of the Saigon River is controlled by the upstream reservoir and is strongly affected by tides with important instantaneous upward discharge (Camenen et al., 2017; Nguyen et al., 2019a), the resulting water discharge over a tidal cycle and at a monthly scale reflects this contrasted seasonal regime (Table 1, Fig. 2). Accordingly, anthropogenic fiber's concentrations are expecting to be affected by this seasonality as we considered the main sources stable through time.

Globally, in the Saigon River, no correlation between anthropogenic fiber's concentrations and monthly rainfall can be seen during our sampling period suggesting an absence of seasonal pattern (Pearson correlation $p > 0.05$; Table 2; Fig. 6). Elevated fiber's concentrations were observed at the beginning of the 2016 rainy season (July and August; 248e251 items L^{-1}) but the concentrations dropped a month later (September 2016; 46e131 items L^{-1}) in the same time than rainfall increased (Fig. 6). During the 2017's rainy season (May to November, Fig. 6), fiber's concentrations remained low and constant, with a median of 53 items L^{-1} over the seven months. During the first dry season (November 2016 to April 2017) fiber's concentrations were constant with a median of 75 items L^{-1} while higher concentrations (139e241 items L^{-1} Fig. 6) were measured during the beginning of the second dry season, especially in January 2018. We note that the presence or

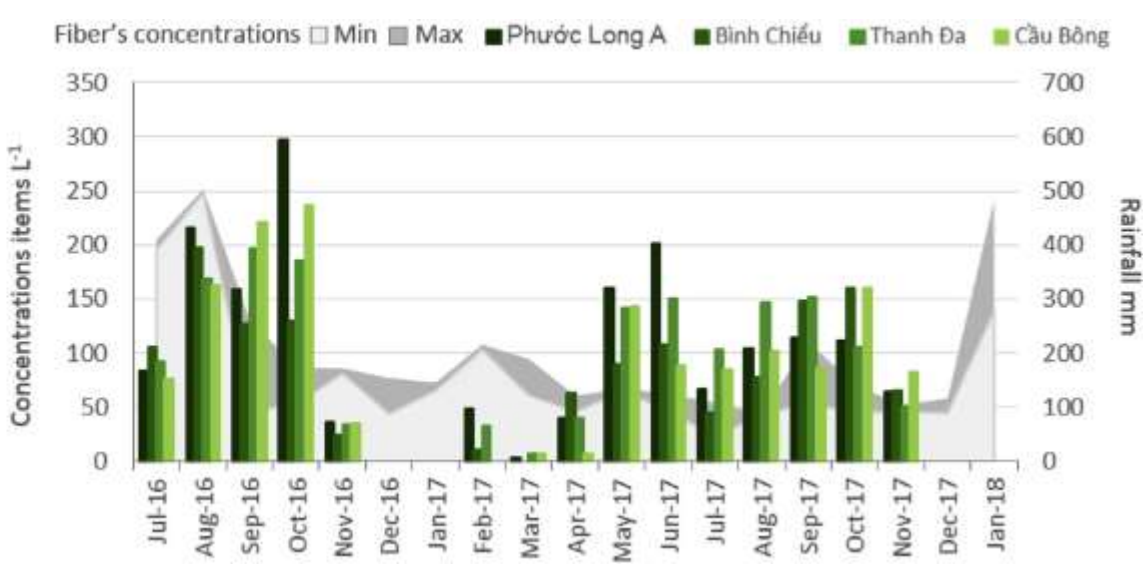

Fig. 6. Monthly rainfall measured at four gauging station by DONRE and monthly minimum and maximum concentrations of anthropogenic fibers sampled in the Saigon River at Bach Dang site from July 2016 to January 2018.

absence of rain events one to three days before the sampling did not present correlation with the concentrations of anthropogenic fibers in the Saigon River (DONRE data, not public). In the same way, an absence of correlation was observed between anthropogenic fiber's concentrations and monthly water discharge, temperature, pH, oxygen level, conductivity, and TSS concentrations in the surface water over the one year and half sampling (Pearson correlation $p > 0.05$; Table 2). Thus, the temporal dynamic of anthropogenic fibers in the Saigon River is correlated neither to abiotic factors such as the physico-chemical conditions of the water body (T, pH, O_2, conductivity or TSS concentrations; Table 1) nor to the tropical conditions characterized here by monthly water discharge and/or monthly rainfall.

4.4. Fate of anthropogenic fibers in the water column

Anthropogenic fibers are composed of fibers of various densities, ranging from 0.91 g cm^{-3} (i.e. polyethylene) to 1.38 g cm^{-3} (i.e. polyester) meaning that they have both the theoretical ability to remain buoyant and to sink in the surface water. Under freshwater laboratory experiments, the fibers' settling velocity varied from 0.01 to 0.06 m s^{-1} for a density varying between 1008 and 1307 kg m^{-3} (Waldschläger and Schüttrumpf, 2019), which is quite elevated compared to the settling velocity of suspended particulate matter (from clays to flocs) varying from 0.01 mm s to 1 up to several centimetres per second (Lick, 1994). The general shape of particles (e.g., spherical, cylindrical, elongated) (Khatmullina and Isachenko, 2017) and more precisely the spatial orientation of the sinking fibers (Bagaev et al., 2017) were shown to be important parameters controlling the sinking velocity of particles and fibers in the water column. From field data, laboratory experiments and numerical testing, Bagaev et al. (2017) evidenced that a vertical oriented fiber sinks 3–4 times faster than a horizontal oriented one. They also demonstrated that turbulence or currents at the water column's surface retain light fibers in suspension and prevent them to sink while in water layers characterized by less turbulence and currents, fibers preserve their free-fall sinking regime. Interestingly, the sinking depends on the diameter of the fibers, the larger the higher velocity (Waldschläger and Schüttrumpf, 2019) and is independent of the material, e.g. and so the density, of the fibers as both heavy but small fibers were entrained in the surface layer by turbulence mixing (Reisser et al., 2015) and as light fibers sank due to biofouling. In the Saigon River, 50% of the anthropogenic fibers observed ranged between 40 and 80 μm length, and even 73% of them have smaller length than the one studied by Bagaev et al. (2017) (i.e. minimal length of 170 μm). We can thus hypothesize that the turbulence induced by water current, tides, wind and/or intense navigation keep the fibers in the turbulence mixing layer (i.e. the surface water). The low proportion of longest fibers in the surface water (>500 μm) may reflect the fact that they are more likely to sink in the water column (Fig. 2). In perspective, we recommend to address a sampling strategy considering different tidal amplitude and so contrasted surface current velocity to identify the effect of surface current velocity on anthropogenic fiber concentrations.

4.5. Fibers annual emission

The annual emission of anthropogenic fibers from the Saigon River to the South China Sea was estimated using the monthly minimum and maximum fiber's concentrations measured at Bach Dang and the monthly water discharge measured once a month at Binh Phuoc by CEM, a few kilometers upstream our sampling site. In 2017, the flux ranged from 115 to 164 trillion items yr^{-1}. Several assumptions underline this estimation. At first, we assumed that the water discharge at Bach Dang is the same as at Binh Phuoc, as no water discharge measurements are made at Bach Dang by the CEM. Second, as water discharge are measured only once a month by the CEM, we assumed that the river discharge is constant over the whole month. We remind that the water discharge data correspond to the residual discharge which is the net positive water flow of the river from land to the sea (Nguyen et al., 2019a). Third, we assumed that the concentrations of anthropogenic fibers at low tide is constant over a month. Fourth, we neglected input and output of anthropogenic fibers into/from the surface water from the sampling site at Bach Dang until the coastal zone and we assumed no anthropogenic fiber sinking in the water column. This estimation is the first yearly emission of synthetic fibers toward the ocean.

5. Conclusions

The dynamic of anthropogenic fibers in the surface waters of this tropical river-estuarine environment was independent of the seasonal variability of rainfall, water discharges, saline intrusion and others abiotic factors (e.g. TSS concentrations, pH, O_2) of the river. We suggested that their fate might rely mostly on both their sinking properties in the water column under contrasted estuarine water current velocities and on the sources. Efforts should be continued on those topics to better characterize the role of transition environment from land to sea, like estuaries and mangroves, in the fate and transport of fibers to the sea. In perspective, the sources of anthropogenic fibers in the Saigon River system should be more clearly identified and quantified, in order to mitigate their release and suggest adapted policies.

Declaration of competing interest

We declare that we don't have any conflicts of interest with no one considering this study.

CRediT authorship contribution statement

Emilie Strady: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing. Thuy-Chung Kieu-Le: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing. Johnny Gasperi: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. Bruno Tassin: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

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References

Babut, M., Mourier, B., Desmet, M., Simonnet-Laprade, C., Labadie, P., Budzinski, H., De Alencastro, L.F., Tu, A.T., Strady, E., Gratiot, N., 2019. Where has the pollution

gone? A survey of organic contaminants in Ho-Chi-Minh City/Saigon River (Vietnam) bed sediments. Chemosphere 217, 261e269.
Bagaev, A., Mizyuk, A., Khatmullina, L., Isachenko, I., Chubarenko, I., 2017. Anthropogenic fibers in the Baltic Sea water column: field data, laboratory and numerical testing of their motion. Sci. Total Environ. 600, 560e571.
Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Biol. Sci. 364, 1985e1998.
Blettler, M.C.M., Abrial, E., Khan, F.R., Sivri, N., Espinola, L.A., 2018. Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps. Water Res. 143, 416e424.
Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175e9179.
Cai, M., He, X., Liu, M., Li, S., Tang, G., Wang, W., Huang, P., Wei, G., Lin, Y., Chen, B., Hu, J., Cen, Z., 2018. Lost but can't be neglected: huge quantities of small microplastics hide in the South China Sea. Sci. Total Environ. 633, 1206e1216.
Camenen, B., Dramais, G., Le Coz, J., Ho, T.-D., Gratiot, N., Piney, S., 2017. Estimation of a water level - discharge rating curve for a river influenced by the tide (Estimation d'une courbe de tarage hauteur-de´nivele´e-de´bit pour une rivie`re influence´e par la mare´e). Houille Blanche 16e21. https://doi.org/10.1051/lhb/2017039.
Carbery, M., O'Connor, W., Thavamani, P., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ. Int. 115, 400e409.
Cesa, F.S., Turra, A., Baruque-Ramos, J., 2019. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116e1129.
Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104, 290e293.
Dris, R., Gasperi, J., Rocher, V., Tassin, B., 2018. Synthetic and non-synthetic anthropogenic fibers in a river under the impact of Paris Megacity: sampling methodological aspects and flux estimations. Sci. Total Environ. 618, 157e164.
Faure, F., Demars, C., Wieser, O., Kunz, M., De Alencastro, L.F., 2015. Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. Environ. Chem. 12, 582e591.
Frias, J.P.G.L., Nash, R., 2019. Microplastics: finding a consensus on the definition. Mar. Pollut. Bull. 138, 145e147.
Gago, J., Carretero, O., Filgueiras, A.V., Vin˜as, L., 2018. Synthetic microfibers in the marine environment: a review on their occurrence in seawater and sediments. Mar. Pollut. Bull. 127, 365e376.
Gigault, J., ter Halle, A., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., Hadri, H.-E., Grassl, B., Reynaud, S., 2018. Current opinion: what is a nanoplastic? Environ. Pollut. 235, 1030e1034.
General Statistics Office of Vietnam (GSO), 2017. Statistical Yearbook of Ho Chi Minh City d2016, Ho Chi Minh City Statistical Office.
Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassello€v, M., Verschoor, A., Daugaard, A.E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N.P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039e1047.
International Trade Administration, 2016. ITA Technical Textiles Top Markets Report. https://www.trade.gov/topmarkets/pdf/Textiles_Vietnam.pdf.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768e771.
Khatmullina, L., Isachenko, I., 2017. Settling velocity of microplastic particles of regular shapes. Mar. Pollut. Bull. 114, 871e880.
Lahens, L., Strady, E., Kieu-Le, T.C., Dris, R., Boukerma, K., Rinnert, E., Gaspe´ri, J., Tassin, B., 2018. Macroplastic and microplastic contamination assessment of a tropical river (Saigon River, Vietnam) transversed by a developing megacity. Environ. Pollut. 236, 661e671.
Lick, W., 1994. Modelling the Transport of Sediment and Hydrophobic Contaminants in Surface Waters. US/Israel Workshop on Monitoring and Modelling Water Quality, May 8e13, 1994. Haifa, Israel.
Lin, L., Zuo, L.Z., Peng, J.P., Cai, L.Q., Fok, L., Yan, Y., Li, H.X., Xu, X.R., 2018. Occurrence and distribution of microplastics in an urban river: a case study in the Pearl River along Guangzhou City, China. Sci. Total Environ. 644, 375e381.
Miller, R.Z., Watts, A.J.R., Winslow, B.O., Galloway, T.S., Barrows, A.P.W., 2017. Mountains to the sea: river study of plastic and non-plastic microfiber pollution in the northeast USA. Mar. Pollut. Bull. 124, 245e251.
Mintenig, S., Int-Veen, I., Lo€der,M., Gerdts, G., 2014. Mikroplastik in ausgew€ahlten Kla€ranlagen des Oldenburgisch - Ostfriesischen Wasserverbandes (OOWV) in Niedersachsen. Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar-und Meeresforschung.
Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibers from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39e45.
Nguyen, T.T.N., Ne´mery, J., Gratiot, N., Strady, E., Tran, Q.V., Nguyen, A.T., Aime´, J., Peyne, A., 2019a. Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon e Dongnai (southern Vietnam). Sci. Total Environ. 653, 370e383.
Nguyen, T.T.N., Nemery, J., Gratiot, N., Garnier, J., Strady, E., Tran, Q.V., Nguyen, A., Nguyen, T., Golliet, C., Aime, J., 2019b. Phosphorus adsorption-desorption processes in the tropical Saigon River estuary (Southern Vietnam) impacted by a megacity. Estuar. Coast Shelf Sci. 227, 106321.
Nore´n, F., 2007. Small Plastic Particles in Coastal Swedish Waters. report N-research, p. 11p.
Reisser, J.W., Slat, B., Noble, K.D., Plessis, K.D., Epp, M., Proietti, M.C., de Sonneville, J., Becker, T., Pattiaratchi, C., 2015. The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic gyre. Biogeosciences 12, 1249e1256.
Rodrigues, M.O., Abrantes, N., Gonçalves, F.J.M., Nogueira, H., Marques, J.C., Gonçalves, A.M.M., 2018. Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antua˜ River, Portugal). Sci. Total Environ. 633, 1549e1559.
Strady, E., Dinh, Q.T., Ne´mery, J., Nguyen, T.N., Gue´dron, S., Nguyen, S.N., Denis, H., Nguyen, P.D., 2017. Spatial variation and risk assessment of trace metals in water and sediment of the Mekong Delta. Chemosphere 179, 367e378.
Talvitie, J., Mikola, A., Seta€la€, O., Heinonen, M., Koistinen, A., 2017. How well is microlitter purified from wastewater? A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. Water Res. 109, 164e172.
Textile Exchange, 2018. Preferred Fiber & Materials Benchmark Insights Report, p. 24. https://textileexchange.org/downloads/2018-preferred-fiber-materials-benchmark-insights-report/.
Thanh-Nho, N., Strady, E., Nhu-Trang, T.T., David, F., Marchand, C., 2018. Trace metals partitioning between particulate and dissolved phases along a tropical mangrove estuary (Can Gio, Vietnam). Chemosphere 196, 311e322.
van Emmerik, T., Kieu-Le, T.C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P.D., Schwarz, A., Slat, B., Tassin, B., 2018. A methodology to characterize riverine macroplastic emission into the ocean. Front. Mar. Sci. 5, 372.
Van Emmerik, T., Strady, E., Kieu-Le, T.C., Gratiot, N., 2019. Seasonality of riverine macroplastics. Sci. Rep. 9, 13549.
Vo, P.L., 2007. Urbanization and water management in Ho Chi Minh city, Vietnam-issues, challenges and perspectives. GeoJ 70, 75e89.
Waldschla€ger, K., Schüttrumpf, H., 2019. Effects of particle properties on the settling and rise velocities of microplastics in freshwater under laboratory conditions. Environ. Sci. Technol. 53, 1958e1966, 2019.
Wang, W., Ndungu, A.W., Li, Z., Wang, J., 2017. Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci. Total Environ. 575, 1369e1374.
Zhao, S., Zhu, L., Li, D., 2015. Microplastic in three urban estuaries, China. Environ. Pollut. 206, 597e604.