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Mountains to the sea: River study of plastic and non-plastic microfiber pollution in the northeast USA

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ABSTRACT

Aquatic environments are sinks for anthropogenic contamination, whether chemical or solid pollutants. Microfibers shed from clothing and other textiles contribute to this problem. These can be plastic or non-plastic origin. Our aim was to investigate the presence and distribution of both types of anthropogenic microfibers along the length of the Hudson River, USA. Surface grab samples were collected and filtered through a 0.45 μm filter paper. Abundance of fibers was determined after subtraction of potential contamination. 233 microfibers were recorded in 142 samples, averaging 0.98 microfibers L^{-1}. Subsequent micro-FTIR showed half of the fibers were plastic while the other half were non-plastic, but of anthropogenic origin. There was no relationship between fiber abundance, wastewater treatment plant location or population density. Extrapolating from this data, and using available hydrographic data, 34.4% of the Hudson River's watershed drainage area contributes an average 300 million anthropogenic microfibers into the Atlantic Ocean per day.

1. Introduction

Within every marine ecosystem and every level of the marine food web; from plankton to predators, there is plastic (Thompson et al., 2004; Law et al., 2010). It has been estimated that approximately eight million metric tons (4.8–12.7) of plastic enters our ocean every year (Jambeck et al., 2015). The longer plastic stays in the marine environment, the more likely it is to break into smaller and smaller pieces due to chemical and mechanical degradation (Browne et al., 2011; Cole et al., 2011). The sources of this pollutant are diverse and include loss from waste management streams, fishing operations, illegal dumping, run-off and natural disasters (Dris et al., 2016).

Pieces of plastic under 5 mm are known as microplastic (Arthur et al., 2009). In the northeast Atlantic, microplastic was found in 94% of all surface samples (Lusher et al., 2014) and a worldwide study found 92% of all surface tows contain microplastics, estimating a global marine surface load of 4.85×10^{12} pieces of microplastic 0.33–4.75 mm in size (Eriksen et al., 2014).

Microplastics can be classified into five different categories due to their shape: Fragments, defined as parts of larger plastics broken into smaller shapes giving jagged edges; Foam, expanded polystyrene, Films, a continuous thin piece of material such as derived from plastic bags or wrappers, Pellets, defined as spherical plastics which are derived from personal care items and pre-production plastics; and Fibers, defined as a threadlike piece of plastic with a length between 100 μm and 5 mm and a width at least 1.5 orders of magnitude shorter (Baldwin et al., 2016; Barrows et al., 2017).

The most abundant type of microplastic found in the environment are fibers. These can come from clothes (Browne et al., 2011, Napper and Thompson, 2016, Pirc et al., 2016) or a direct pathway from clothing to water courses via the atmosphere (Dris et al., 2016; Carr, 2017). In water samples taken in the North East Atlantic, 94% of the samples were found to contain microplastic fibers (Lusher et al., 2014). Naidoo et al. (2015) showed that microfibers were found in between 38 and 66% of estuaries around South Africa. Results on the concentration in these fibers are influenced by the type of sample method with net samples under estimating compared to whole water samples (Barrows et al., 2017), in river samples a range of values from 0.007 (Faure et al., 2015) to 0.00089 (Mani et al., 2015) fibers per liter have been reported (Table 1). Murray and Cowie (2011) found that 62% of the Norway

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Table 1
Abundance of microplastic reported in studies from river environments. "NS" indicates that microfibers were not specified as a counted subset of the microplastics the samples.

Location/ type	Abundance microplastics L^{-1}	Sampling method	% microfibers
Switzerland[a]	0.007	300 μm*	NS
Los Angeles River[b]	0.00606	333–500 μm*	100
San Gabriel River[b]	0.00439	333–500 μm*	100
Coyote Creek[b]	0.00434	333–500 μm*	100
Rhine River[c]	0.00089	300 μm*	NS

* Neuston net.
[a] Faure et al. (2015).
[b] Moore et al. (2011).
[c] Mani et al. (2015).

lobster (*Nephrops norvegicus*) collected from the Clyde Sea Area, Scotland, UK contained microfibers. Watts et al. (2015) showed that the ingestion of fibers by the shore crab (*Carcinus maenas*) reduced the amount of food ingested over a 4-week period, this was not compensated by reduced activity which in the long term could induce a starvation effect. Other studies have shown uptake and biological effects on the Freshwater crustacean *Daphnia magna* (Jemec et al., 2016) and the freshwater amphipod *Hyalalella Azteca* (Au et al., 2015).

Not all anthropogenic microfibers are plastic. Clothing and other textiles are made of both plastics including polypropylene, polyester, polyamide, acrylic, polyethylene and non-plastic processed natural materials such as cotton, wool, silk, bamboo, rayon (viscose/regenerated cellulose) (natural) fibers. These non-plastic fibers used in the manufacture of clothing and other textiles are processed, dyed and often coated. Cotton will degrade in the environment more quickly than plastic microfibers; however the degradation process is prolonged when resin is added (Li et al., 2010). Chemicals associated with this processing include flame retardants, Poly Brominated Diphenyl Ethers (PBDEs) and other known carcinogens (Schreder and La Guardia, 2014) making them both an item of health concern and a focus of this study.

Clothing, no matter its composition, breaks down due to: aging and abrasion from wear, and abrasion in the washing machine (Hartline et al., 2016). This abrasion creates microfibers: if the clothing is synthetic this will produce plastic microfibers; if the clothing is non-synthetic this will produce non-plastic microfibers. Washing machines do not have filters capable of capturing such small items. Therefore, microfibers wash out with household greywater, through wastewater treatment plants (WWTPs) and enter public waterways via sewage outfalls (Browne et al., 2011; Mason et al., 2016), or via leech fields in septic systems. When quantifying microfibers in the environment they should be described as anthropogenic microfibers before testing the material to see if they are plastic microfibers or non-plastic microfibers.

Across 17 studied wastewater treatment plants (WWTP), there was an average of 4 million pieces of microplastic, 59% of which was plastic microfiber, leaving each facility per day through the effluent alone (Mason et al., 2016).

Other studies have measured the number of microfibers discharged from WWTPs to range from 0.004 fibers L^{-1} to 160 fibers L^{-1} (HELCOM, 2014; Gasperi et al., 2015), indicating that wash water via WWTP outfall pipes contributes significantly to aquatic microfiber pollution. Effluent is not the only microfiber carrier from WWTPs. Denser fibers such as nylon, polyester, and acrylic can settle out of the wastewater and get caught in the sludge, which is usually repurposed as fertilizer, sending fibers into the environment and waterways via runoff (Habib et al., 1998; Zubris and Richards, 2005). Levels of microfiber pollution are expected to fluctuate seasonally, as household laundry increases as much as 700% in colder months. (Browne et al., 2011).

River systems play a critical role in carrying microfibers to the marine environment (Moore et al., 2011; Lechner and Ramler, 2015; Vermaire et al., 2017). Population centers commonly exist adjacent to bodies of water such as lakes and rivers. WWTPs take advantage of nearby water bodies to receive their effluent. Some microfibers settle into banks and riverbeds, while suspended microfibers are available to be carried downstream to the ocean (Faure et al., 2015; Klein et al., 2015; Mani et al., 2015). Surface monitoring in Switzerland measured an average of 0.007 microplastics L^{-1} (Faure et al., 2015) and in the Rhine River 0.00089 microplastics L^{-1} (Mani et al., 2015). While looking at these numbers, it is important to note that both river studies used 300 μm mesh to filter the water. Subsequent studies have indicated mesh in the 300 μm range is not a fine enough to fully measure the extent of the microplastic/microfiber pollution problem (Kang et al., 2015; Barrows et al., 2017) making the data above a conservative estimate. Investigating river systems and watersheds offers the potential opportunity to learn about specific inputs of microfiber pollution via the presence of WWTPs and population size. Whereas, in contrast, ocean samples reflect the current magnitude of the problem, consisting of microfibers circulating locally and globally, possibly for many years, even decades.

The consequence of microfiber pollution, both plastic and non-plastic to human health is not yet known. However, the negative effect microfibers have on marine life warrants a better understanding of, its sources, and ultimately, preventative and restorative solutions. The overarching purpose of this study is to advance understanding of the presence and concentration of anthropogenic microfibers in an entire watershed, specifically one with diverse population and terrain. The specific study aim is to investigate the presence and distribution of plastic and non-plastic microfibers in the Hudson River, from the headwaters to the sea.

2. Materials and methods

The study area encompasses the Hudson River, New York State, USA; from the headwaters, Lake Tear of the clouds (44.17°N, −73.96°W) to the Atlantic Ocean, Ambrose Light (40.74°N, −73.96°W). The Hudson River basin covers 21,565 km^2.

2.1. Collecting water samples

Abundance of microfibers was determined via the grab sample protocol set out in Barrows et al. (2017). This method was developed and used to ensure uniformity of samples over a variety of sampling platforms (boat, dock, beach, rocks) and reduce contamination. Simply, approximately 3 L of water from the top 8 to 18 cm of the water surface was collected via a triple-rinsed metal bucket and 1 L decanted into a triple-rinsed glass jar of the same volume. Samples of water were collected every 4.3 km (3 miles) over the length of the entire Hudson River. Upper Hudson samples were accessed via car and foot, except for four taken from a whitewater raft (samples 11–14). Lower Hudson samples were accessed from *American Promise*, an 18.3 m sailing research vessel, except for 2 samples (49 and 50) taken via a 3.7 m inflatable dinghy. Sample locations were predetermined with exact sample sites selected by safe access (Upper Hudson) and safe holding position (Lower Hudson). The full list of sample locations can be viewed in SI.1.

2.2. Processing samples

All samples were vacuum filtered through a Whatman 47 mm diameter, 0.45 μm gridded filter paper (Whatman ME 25/21). Flasks and sample bottles stayed capped when not being actively used. The filtrate water was placed in a Fisher 1 L squeeze bottle for rinsing the sample jar and flask during filtration. Once complete, the filters were stored in triple-rinsed (with tap water) metal petri dishes. White cotton lab coats were worn for all processing and laboratory analysis.

2.3. Determining microfiber concentration

Filters were examined at 45 × magnification under a stereo microscope. Anthropogenic microfibers were first identified visually based on guidelines outlined in previous studies (Hidalgo-Ruz et al., 2012; De Witte et al., 2014): no cellular or organic structures visible and equal thickness throughout the piece in question. Anthropogenic microfiber pieces were categorized by color (blue, red, black, transparent, other color), shape (fiber, round, other shape), and length (100 μm–1.5 mm, 1.6–3.2 mm, 3.3–9.6 mm) (Barrows et al., 2017). Plastics down to 0.45 μm could be captured using this field and lab methodology but we use fiber length 100 μm and greater because it is the length that we can confidently visually identify/categorize down to using a 40 × magnification microscope.

2.4. Reducing and measuring contamination

All equipment was triple rinsed and covered before and between sample processing to minimize contamination. At each sampling site the sample collector triple-rinsed their hands and forearms and had bare wrists (free of watches and bracelets). We conducted air and water blanks during sample processing and counting to control for contamination.

2.5. Contamination controls

For the six days aboard the *American Promise* a minimum of three air blanks were run each day at the sampling processing locations (filtration bench, counting table and on a bench midway between the two former) (n = 18). An air blank consisted of a Whatman 47 mm diameter, 0.45 μm gridded filter placed on an open triple-rinsed metal petri dish, these blanks where open for the duration of the water filtering or counting activity.

An additional set of air blanks (n = 5) were run for four individual samples and for the filtration duration of eight field samples (sample 54–62). These blanks were exposed simultaneously to the air as the field sample was exposed (during sample decantation into flask and during final rinse of bottle and flask) and covered while field sample was covered.

Every day that we collected and processed samples, at minimum a tap water and filtrate blank was processed (n = 15). The tap water blank came from the tap that was used to rinse all laboratory glassware, petri dishes and sample jars, this was placed into a triple rinsed sample jar for decantation. The filtrate blank was the field sample water that had passed through the 0.45 μm filter and into the triple-rinsed beaker. The filtrate water was placed in a fisher 1 L squeeze bottle for rinsing down sample jar and flask during filtration. An additional blank was collected from the water that was used to fill the boat tanks and rinse the sample bottles initially (dock water from Kittery, Maine).

For samples not processed aboard the *American Promise* we implemented similar air and water blanks (n = 16, n = 11, respectively). In total, the air blanks (n = 39) were between 0.00 and 0.37 microfibers per day with an average of 0.11 microfibers per L^{-1} per day. Air blank contamination on the processing day for each sample day was subtracted from the microfiber total for each sample. Water blank contamination was negligible (0.01 pieces L^{-1} of tap water and 0.07 pieces L^{-1} of filtrate) and was not subtracted out from plastic totals.

2.6. FT-IR analysis

2.6.1. Onboard FT-IR

Anthropogenic microfibers from the blanks were taken from the filter paper and analyzed on an Agilent carry 630 Fourier transform infrared spectroscopy (FTIR) Spectrometer. Spectra were compared against the internal database. Likely results are displayed as compared to the original spectra and the percentage match is noted. When no database library came up possible results were applied and visually checked. Results of these are seen in SI.2.

FT-IR was used to characterize the commonly occurring transparent/clear fibers occurring in a third of the water blanks and in all but one air blank. The fibers were characterized in nine water blanks with seven samples containing non-synthetic cellulose. Considering this characterization all transparent/clear fibers were subtracted from all of the field samples. FT-IR spectra output can be seen in SI.2.

2.6.2. Micro FT-IR

To determine the non-synthetic proportion of the anthropogenic microfibers in field samples we randomly selected archived samples and pulled one non-transparent fiber from 14 filters. We analyzed each fiber using a micro-FT-IR (a Bruker LUMOS FT-IR operated in reflectance mode) to identify material type. The LUMOS has a spectral range from 7000 to 600 cm^{-1} and uses a VCSEL laser with a wavelength of 850 nm. The instrument is operated using OPUS software. See SI.3 for FT-IR spectra output.

2.7. Statistical analysis

The average particulate contamination in air and water blanks was calculated separately. Between five and seven blanks were taken per day. The calculated air blank average was then subtracted from each field sample processed on the corresponding day. The resulting total was divided by the sample water volume to give a total of microplastic pieces per liter. Water blank contamination was not subtracted from each field sample as the average number of plastics in the 1 L of combined tap and filtrate water that each field sample was exposed to was 0.03 pieces. To test the relationship between how microfiber concentration relates to sample location a general linear model (GLM) was performed in MINITAB 17. Number of microfibers was square root transformed to meet parametric assumptions of normality of residuals and homogeneity of variances.

2.8. Estimating microfiber discharge along the river

To estimate the discharge of microfibers along the river six stations were picked based on available hydrographic data relevant to our study dates. Flow rate was collected from the USGS data base for the sample period and used alongside our estimates of microfiber abundance. River velocity was calculated using the average flow rate (cfs) of June 2016 as reported by the USGS (USGS, 2016) using river stage gauges that collect data, then converted to discharge, every 30 s. This time period represents the time in which the water samples were collected for this study and does not necessarily reflect an annual average or seasonal fluctuations.

To calculate the total flow of microfibers along the Hudson River the average Flow rate (F) was converted from F_m ($m^{-3}\,s^{-1}$) to F_l ($L^{-1}\,s^{-1}$) (Eq. (1)).

$$F_l = F_m \times 1000 \tag{1}$$

where F_m was taken as the average Flow rate each day between the 18th–30 June 2016 (USGS, 2016).

To calculate the proportional flow rate of the top 18 cm (with the assumption the flow rate is constant throughout all depths, which we are aware is an over simplification). The proportion of interest (D_p) was calculated from the depth of interest D_i (18 cm) divided by the total depth D_t (Eq. (2)).

$$D_p = \frac{D_i}{D_t} \tag{2}$$

with D_p being multiplied by the flow rate (F_l)

$$F_i = F_l \times D_p \tag{3}$$

This was then timed by the number of microfibers L^{-1} measured in the study (C_p) to determine an approximation of number of fibers flowing though that part of the river N_p (Eq. (4)).

$$N_P = F_i \times C_P \quad (4)$$

3. Results

A total of 233 microfibers were recorded in 142 samples (after subtracting the air blanks), resulting in a median average of 0.98 anthropogenic microfibers per L sample (anthropogenic, does not separate plastic and non-plastic microfibers). Microfibers on average were 1.24 ± 0.14 mm (mean ± SE) with a minimum length of 0.33 mm and a maximum length of 3.59 mm (based on 20 anthropogenic microfibers- SI.2). The most dominant color fiber was blue (n = 103), followed by black, (n = 58), transparent (n = 32), red (n = 23) and other colors (n = 21).

Fourteen fibers (10%) were analyzed by micro-FTIR to determine the proportion of synthetic fibers present. Fibers were identified as 43% cotton (6/14), 22% PET (3/14), 22% fluoro-polymer/Teflon (3/14) 7% Polypropylene (1/14) and 7% nitrocellulose/clay (1/14) (SI.3). We estimate 117 (50%) of the microfibers are plastic in origin with the other 50% of non-plastic origin (0.8 plastic microfibers L^{-1}).

Fig. 1 shows the abundance of microfibers along the Hudson River. There was no significant overall increase or decrease in the abundance of microfibers from river source to sea ($F_{1,141} = 0.00$, $p = 0.973$, $Log_{10} + 1$ transformed) (Fig. 2). However, there were two spikes in microplastic abundance at the source of the river and around sample site 80.

To determine the discharge of fibers along the river three different plastic concentrations (Cp) were used: the first lowest positive concentration in one sample (0.625 fibers L^{-1}); the medium number of fibers (0.98 fibers L^{-1}); and the 3rd quartile concentration (2.45 fibers L^{-1}). Results of this for 6 stations along the Hudson river is shown in Table 2.

This indicates that approximately between 200 and 800 million fibers could have been flowing down the Hudson River per day in June 2016 from North creek to Waterford just above Lock 1 with a median average of around 300 million. This represents 34.4% of the total watershed drainage area. Further up the river (Newcomb) this is more like 60 million.

Here we assume microfiber concentrations are around 0.98 fibers per L and that the proportional flow rate of the top 18 cm is accurate. To make this estimate more precise getting a more precise estimate of flow rate in the top 18 cm would be useful along with repeated sampling of fiber concentrations in each area. It is difficult to say how many of these fibers will end up in the Atlantic Ocean (at the mouth of the Hudson river) due to lack of reliable flowmeters and data corresponding to the dates of this study and changes in salinity and complex hydrodynamics from the mouth north to the first lock in Albany.

4. Discussion

This study indicates that an average of 300 million individual anthropogenic microfibers are discharged along the upper part of the Hudson River per day. Approximately 50% of the microfibers are plastic. Our estimate is conservative as we have only collected water from the top 18 cm of the water column. Without a vertical mixing model, we have not estimated abundance of microfibers beyond those top 18 cm; secondly the southernmost USGS flowmeter with data relevant to the dates of this study is just above Lock 1, which leaves 65.5% of the whole Hudson River watershed, from near Albany to Ambrose Light, unaccounted for in terms of volume of water (USGS, 2013, 2016). The southernmost flowmeter in the area of the river

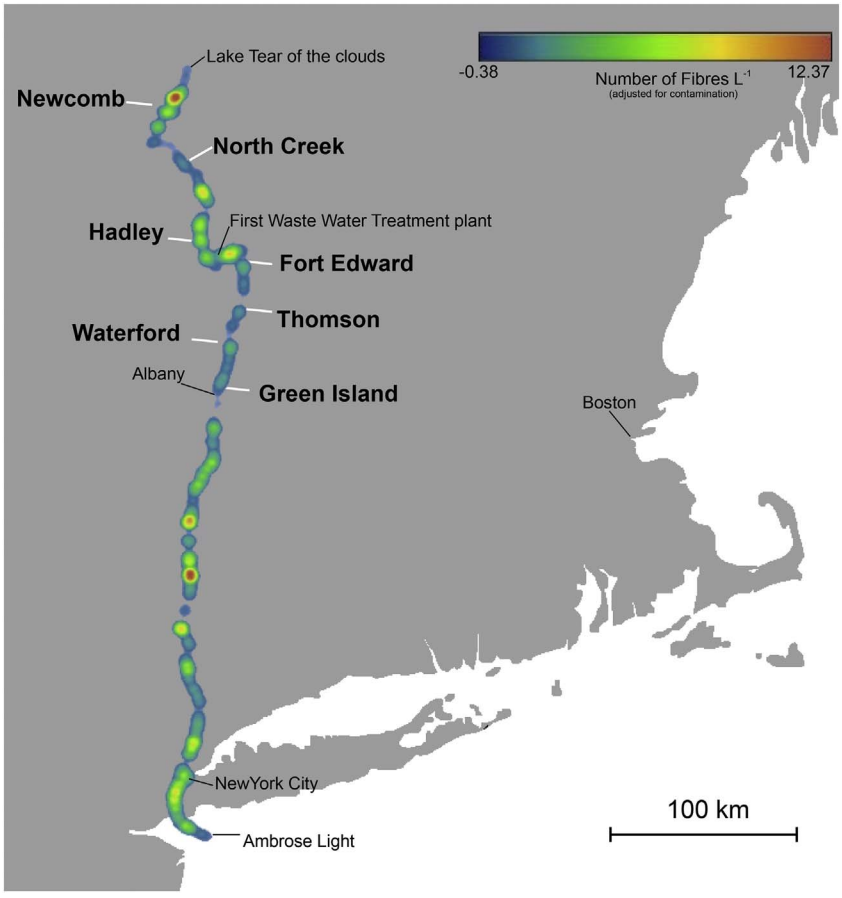

Fig. 1. Map of all sampling locations and the average microfibers L^{-1} found at each sample location. Numbers adjusted for contamination, see text. Large block text labels are the sites of the USGS flow rate sites (Table 2).

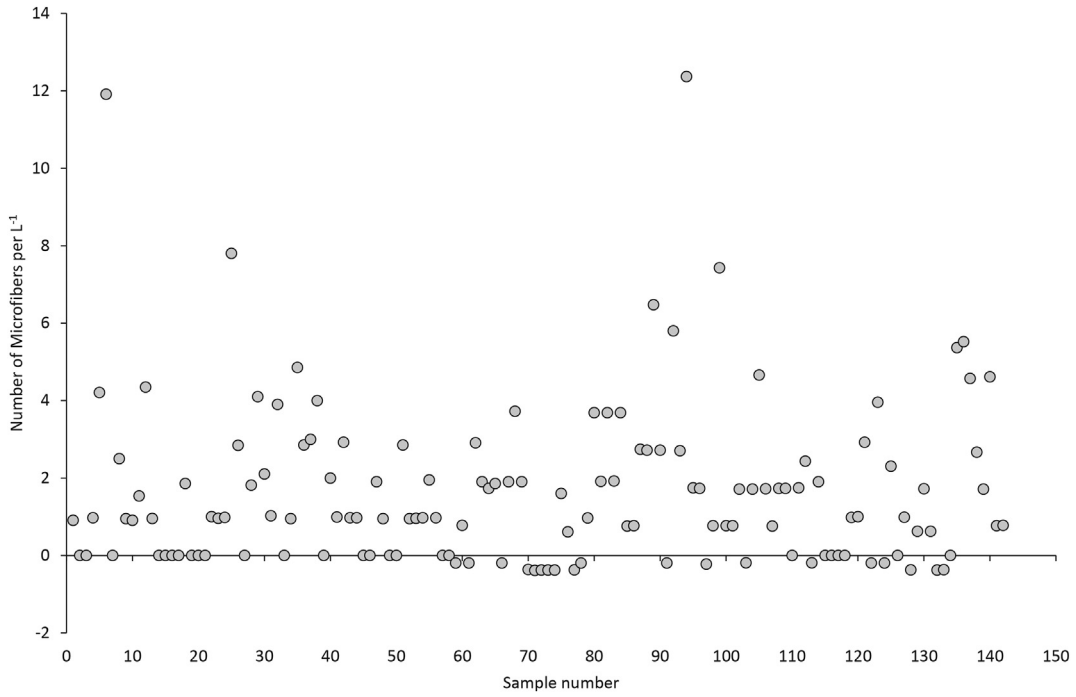

Fig. 2. Number of microfibers L^{-1} at each sampling location corrected for contamination sample location sample number one collected at the source of the Hudson River, Lake Tear of the clouds, and sample 130 taken at the mouth, Ambrose Light, where the Hudson River meets the Atlantic Ocean.

Table 2
Estimated discharge (N_p) of microfibers in 6 locations of the Hudson river, under three different microfiber concentrations (C_p) based on the first lowest positive concentration in one sample (0.625 fibers L^{-1}), the medium number of fibers (0.98 fibers L^{-1}) and the 3rd quartile concentration (2.45 fibers L^{-1}).

	F_m ($m^3\ s^{-1}$)	F_l ($L\ s^{-1}$)	D_t (cm)	D_p	F_i ($L\ s^{-1}$)	C_p = 0.625	C_p = 0.98	C_p = 2.45
Newcomb	3.18	3178.23	80	0.23	715.10	3.8×10^7	6.0×10^8	1.5×10^8
North Creek	14.86	14,857.61	80	0.23	3342.96	1.8×10^8	2.8×10^8	7.1×10^8
Hadley	26.07	26,068.88	190	0.09	2469.68	1.3×10^8	2.1×10^8	5.2×10^8
Fort Edward	65.00	64,997.95	300	0.06	3899.88	2.1×10^8	3.3×10^8	8.3×10^8
Thomson	70.42	70,421.70	330	0.05	3841.18	2.1×10^8	3.3×10^8	8.1×10^8
Waterford	90.05	90,047.42	390	0.05	4156.03	2.2×10^8	3.5×10^8	8.8×10^8
Green Island	463.95	463,953.85	440	0.04	18,979.93	1.0×10^9	1.6×10^9	4.0×10^9

F_m ($m^3\ s^{-1}$) Flow rate of the river, F_l ($L\ s^{-1}$) Flow rate of the river- full depth, D_i (cm) depth of the sample = 18 cm, D_t (cm) depth of the river, D_p proportion of the depth taken as a sample, F_i ($L\ s^{-1}$) Flow rate in the top 18 cm C_p concentration of microfibers, N_p number of fibers passing the top 18 cm of the water.

unaffected by tide is Greens Island. This covers 60% of the river and while data from June 2016 was not available, however if we take 2015 data from that date we would estimate that 1.6 Billion individual anthropogenic fibers could have discharged into the tidal section of the Hudson River per day.

Microfiber pollution in the Hudson river did not have a north to south linear increase. There were however some sample locations with relatively high numbers of microfibers. Table 2 shows all sample locations with 4 or more microfibers per L. Why could these areas be high in microfibers and not in others? Samples close to the river source (i.e. sample 3,4) are above the first WWTP therefore are not from sewage outfall. These locations are within the Adirondack Park and include a very busy trailhead/parking area. On the sample day, the area had high human activity. The spike in microfibers in these locations, especially site 4, could therefore be due to airborne contamination from fibers coming off the clothing of recreational visitors to this otherwise remote and protected region. Other potential sources are from run off from fields or septic tank systems. Sample 73 was taken from waters directly adjacent to the Poughkeepsie wastewater treatment plant. It is possible that the large number of microfibers in this sample was related to the proximity of this WWTP. This sample was the closest any of our samples were to a waste water outflow. Sample 78 with a much higher than average amount of microplastics is 3.5 miles downriver of two WWTPs with the towns of Beacon and Newburgh and corresponding housing developments on both sides (with municipal water). This location, like much of the lower Hudson River also has active rail systems on both sides of the river.

We found that the Hudson river had on average 0.98 microfibers per liter. This abundance of microfibers in the Hudson River should be compared to abundances reported in other riverine and coastal locations around the world. Due to differences in collection methods and variability in analysis methods, it is difficult to make direct comparisons. Our data is three orders of magnitude greater than other studies of microfibers in rivers (Faure et al., 2015; Moore et al., 2011; Mani et al., 2015). It is likely this is due to different methodologies of microfiber collection. These studies use vast volumes of water though net sampling. They could be an under-estimate due to loss through the mesh of the net (Vermaire et al., 2017). Due to the small sample volume captured by the grab sample method, it is difficult to know if pollution concentration extrapolations are accurate. This methodology is susceptible to concentration variance caused by local water patterns. Increasing the volume of water collected with this method or pairing the method with a tow net would provide more effective data for large scale extrapolation and comparison. Barrows et al. (2017) showed that the water grab sample had 1000 times more plastic per liter than a neuston tow sample of the same area. To compare the microfiber load per liter,

it might be possible to use this as a conversion factor. This would bring other studies into the same magnitude of ours and of Desforges et al. (2014) that showed 9.18 fibers per L in the NE pacific however more work is needed to understand the effect of sample volume and representativeness of that sample.

It is also relevant to consider the abundance of microplastic found in the Hudson River compared to global estimates. Eriksen et al. (2014), estimates a global surface load of 4.85×10^{12} (4.85 trillion) pieces or 3.55×10^{4} tons of microplastic 0.33–4.75 mm in size and Jambeck et al. (2015) estimates 4.8–12.7 million metric tons of plastic entering the ocean each year. At a rate of 300 million microfibers per day, these numbers could indicate the Hudson River might contribute around 24.8% of the total surface load of global microplastics each year. At this stage however we need to be a little cautious with these extrapolations. Global averages of microplastics are made based on plastics between the 1–5 mm size range (2.8×10^{12} fibers year^{-1}). The size range of our fibers are 1.24 ± 0.14 mm as reported above. They also rely on net-tow surface sampling (neuston and manta tows). The method used in this study captured three orders of magnitude more plastic than net driven collection methods due to loss of microplastics through the mesh (Barrows et al., 2017). Other possible reasons for the absence of the smaller classes of microplastic in tow-net surface samples include this class of microplastics being deposited on shore, and sinking caused by biofouling and ingestion (Law et al., 2010; Andrady, 2011; Cózar et al., 2014). Assumptions have also been made in our model. First the flow rate will be constant throughout the rivers depth at each station. Therefore, allowing a proportional Flow Rate (F_i) to be calculated. These flow rates could be effected by river bed topography, items in the water (buoys) among others. It was the beyond the scope of this study to calculate these flow rate variations. In addition to being difficult to place the study results in current global estimates, it is also not known what proportion of the microfibers will leave the Hudson River and what will remain in the river.

Whether floating on the surface, suspended in the water column or found in the sediment, microfibers are likely to be available for consumption by aquatic species throughout the Hudson River Watershed and adjacent oceanic waters. Consumed microplastics have been shown to have negative heath impacts in a number of different species (Wright et al., 2013; Cole et al., 2015; Watts et al., 2015). Microfiber pollution may impact the diverse commercial and recreational fisheries contiguous to the mouth of the Hudson River. In addition to the risks posed by plastic microfibers, processed natural fibers, collected as part of this study could also pose a potential risk due to chemicals and dyes associated with clothing and textile manufacturing worldwide (Remy et al., 2015). These chemicals include flame-retardants (PBDEs) and other known carcinogens transferred from household textiles to rivers via washing machine effluent (Schreder and La Guardia, 2014).

Looking at the distribution of microfibers within the Hudson River itself, our study shows significant numbers of microfibers upstream of the first waste water treatment plant. This clearly indicates that WWTPs are not the only source of microfiber pollution in the Hudson River. Atmospheric fallout has been shown as a transport mechanism of microplastic (Dris et al., 2016). Dris et al. (2016) measured between 2 and 355 airborne microplastics per square meter in an urban study (population ca. 7900). The Hudson River watershed is approximately 34,700 km^2 (USGS) and passes through New York City, population 8,550,405 (US Census Bureau, 2016). These factors may contribute to atmospheric microplastic and could help to explain our study's numbers. Additional research is necessary to determine the sources of atmospheric microplastic, the differences between urban and rural areas, and transport mechanisms on land after they become fallout.

Further research is also necessary to consider how the buoyancy of different plastics that go into clothing affects microfiber concentration. For example, based on polymer density, polypropylene will float and PET will sink in fresh and salt water. One microfiber that was analyzed through the micro FTIR came back as Teflon (Polytetrafluoroethylene) which has a density of 2.2 g cm^{-3} therefore could be considered as contamination however was not seen in any of the blanks. We don't know about how these more dense particles behave with different flow rates, turbulences and other variables in the river. Bagaev et al. (2017) showed that due to upper layer turbulent motions fibers spend 'some (quite considerable) time in the surface layer'. This study was based on a marine system but water turbulence is also a factor in freshwater systems. We still need more research to better understand how microfibers behave in freshwater as it appears that high flow river systems may keep high density plastics suspended in the water column and/or surface waters for greater periods of time. It is also important to investigate the effect that weather has on the concentration of microplastics found on the surface (Cózar et al., 2014). Finally, exploring biological growth (Fazey and Ryan, 2016) on plastic and non-plastic fibers could help to gain a better understanding of the movement of fibers and their possible effect and availability in salt and fresh water environments.

Our samples were taken in June 2016 (111 samples) and October 2016 (6 samples). Since the Hudson River watershed sees significant seasons with extremes in temperature (> 100 °F range between summer and winter), there are significant differences in how people dress throughout the year. For example, in general, the population will wear more fleece or other heavy clothing during the winter months of November through March than the rest of the year. How seasonal differences influence the input of plastic and non-plastic fibers from households, via WWTPs or septic systems, is an area for future study. A recurrent study would lead to further understanding the concentration of microfibers in the Hudson River itself and the volume discharged into the Atlantic Ocean annually.

5. Conclusion

Our results demonstrate that anthropogenic microfibers are present throughout the Hudson River; in remote, alpine locations as well as rural; agricultural; industrial and urban areas. Microfibers have been processed, dyed, or treated with chemicals and chemical additives which studies have shown present a risk to aquatic organisms across trophic levels and throughout the food web. Our data support efforts to understand the implications to aquatic species and for human health; and develop solutions to curtail, prevent and remediate anthropogenic microfiber pollution in our public waterways, both fresh and marine.

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Appendix A. Supplementary data

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References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.

Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA Technical Memorandum NOS-OR & R-30 NOAA, Silver Spring, pp. 530.

Au, S.Y., Bruce, T.F., Bridges, W.C., Klaine, S.J., 2015. Responses of *Hyalella azteca* to acute and chronic microplastic exposures. Environ. Toxicol. Chem. 34 (11), 2564–2572.

Bagaev, A., Mizyuk, A., Khatmullina, L., Isachenko, I., Chubarenko, I., 2017. Anthropogenic fibres in the Baltic Sea water column: field data, laboratory and numerical testing of their motion. Sci. Total Environ. 599–600, 560–571.

Baldwin, A.K., Corsi, S.R., Mason, S.A., 2016. Plastic debris in 29 Great Lakes tributaries: relations to watershed attributes and hydrology. Environ. Sci. Technol. 50, 10377–10385.

Barrows, A.P.W., Neumann, C.A., Berger, M.L., Shaw, S.D., 2017. Grab vs. neuston tow net: a microplastic sampling performance comparison and possible advances in the field. Anal. Methods 9, 1446–1453.

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, 9175–9179.

Carr, S.A., 2017. Sources and dispersive modes of micro-fibers in the environment. Integr. Environ. Assess. Manag. 13 (3), 466–469.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S., 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ. Sci. Technol. 49, 1130–1137.

Cózar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á.T., Navarro, S., García-De-Lomas, J., Ruiz, A., Fernández-De-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. 111 (28), 10239–10244.

De Witte, B., Devriese, L., Bekaert, K., Hoffman, S., Vandermeersch, G., Cooreman, K., Robbens, J., 2014. Quality assessment of the blue mussel (*Mytilus edulis*): comparison between commercial and wild types. Mar. Pollut. Bull. 85, 146–155.

Desforges, J.-P.W., Galbraith, M., Dangerfield, N., Ross, P.S., 2014. Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar. Pollut. Bull. 79, 94–99.

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 (1–2), 290–293.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913.

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, 582–591.

Fazey, F.M.C., Ryan, P.G., 2016. Biofouling on buoyant marine plastics: an experimental study into the effect of size on surface longevity. Environ. Pollut. 210, 354–360.

Gasperi, J., Dris, R., Rocher, V., Tassin, B., 2015. Microplastics in the continental area: an emerging challenge. Norman Bull. 4.

Habib, D., Locke, D.C., Cannone, L.J., 1998. Synthetic fibers as indicators of municipal sewage sludge, sludge products, and sewage treatment plant effluents. Water Air Soil Pollut. 103, 1–8.

Hartline, N.L., Bruce, N.J., Karba, S.N., Ruff, E.O., Sonar, S.U., Holden, P.A., 2016. Microfiber masses recovered from conventional machine washing of new or aged garments. Environ. Sci. Technol. 50, 11532–11538.

HELCOM, 2014. BASE Project 2012–2014: Preliminary Study on Synthetic Microfibers and Particles at a Municipal Waste Water Treatment Plant.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.

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, 768–771.

Jemec, A., Horvat, P., Kunej, U., Bele, M., Krzan, A., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. Environ. Pollut. 219, 201–209.

Kang, J.-H., Kwon, O.-Y., Shim, W.J., 2015. Potential threat of microplastics to zooplanktivores in the surface waters of the Southern Sea of Korea. Arch. Environ. Contam. Toxicol. 69, 340–351.

Klein, S., Worch, E., Knepper, T.P., 2015. Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-main area in Germany. Environ. Sci. Technol. 49, 6070–6076.

Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.

Lechner, A., Ramler, D., 2015. The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation. Environ. Pollut. 200, 159–160.

Li, L., Frey, M., Browning, K.J., 2010. Biodegradability study on cotton and polyester fabrics. J. Eng. Fibers Fabr. 5 (4), 42–53.

Lusher, A.L., Burke, A., O'connor, I., Officer, R., 2014. Microplastic pollution in the Northeast Atlantic Ocean: validated and opportunistic sampling. Mar. Pollut. Bull. 88, 325–333.

Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. Sci Rep 5, 17988.

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., Fink, P., Papazissimos, D., Rogers, D.L., 2016. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environ. Pollut. 218, 1045–1054.

Moore, C.J., Lattin, G.L., Zellers, A.F., 2011. Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. J. Integr. Coast. Zone Manag. 11 (1), 65–73.

Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217.

Naidoo, T., Glassom, D., Smit, A.J., 2015. Plastic pollution in five urban estuaries of KwaZulu-Natal, South Africa. Mar. Pollut. Bull. 101 (1), 473–480.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112 (1–2), 39–45.

Pirc, U., Vidmar, M., Mozer, A., Krzan, A., 2016. Emissions of microplastic fibers from microfiber fleece during domestic washing. Environ. Sci. Pollut. Res. 23 (21), 22206–22211.

Remy, F.O., Collard, F., Gilbert, B., CompèRe, P., Eppe, G., Lepoint, G., 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environ. Sci. Technol. 49 (18), 11158–11166.

Schreder, E.D., La Guardia, M.J., 2014. Flame retardant transfers from U.S. households (dust and laundry wastewater) to the aquatic environment. Environ. Sci. Technol. 48, 11575–11583.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., Mcgonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.

U.S.G.S., 2013. National Water Quality Assessment Program - The Hudson River Basin. Available online. http://ny.water.usgs.gov/projects/hdsn/fctsht/su.html#HDR0 (Accessed November 25, 2016).

U.S.G.S., 2016. Hudson River Streamflow Measurements. National Water Information System Data. Available online. http://waterdata.usgs.gov/nwis/measurements?site_no=01372058&agency_cd=USGS&format=html_table_expanded (accessed November 20, 2016).

US Census Bureau, 2016. Population of New York City. Available online. https://www.census.gov/quickfacts/table/PST045216/36 (Accessed November 25, 2016).

Vermaire, J.C., Pomeroy, C., Herczegh, S.M., Haggart, O., Murphy, M., 2017. Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. FACETS 2, 301.

Watts, A.J.R., Urbina, M.A., Corr, S., Lewis, C., Galloway, T.S., 2015. Ingestion of plastic microfibers by the crab *Carcinus maenas* and its effect on food consumption and energy balance. Environ. Sci. Technol. 49, 14597–14604.

Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, R1031–R1033.

Zubris, K.A.V., Richards, B.K., 2005. Synthetic fibers as an indicator of land application of sludge. Environ. Pollut. 138, 201–211.