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Published in:
Water Science and Technology

DOI (link to publication from Publisher):
10.2166/wst.2023.232

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Water Science & Technology

Water Science & Technology Vol 88 No 4, 874 doi: 10.2166/wst.2023.232

Study of traffic-related pollution and its treatment with a particular focus on microplastics in tunnel wash and road runoff water

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ABSTRACT

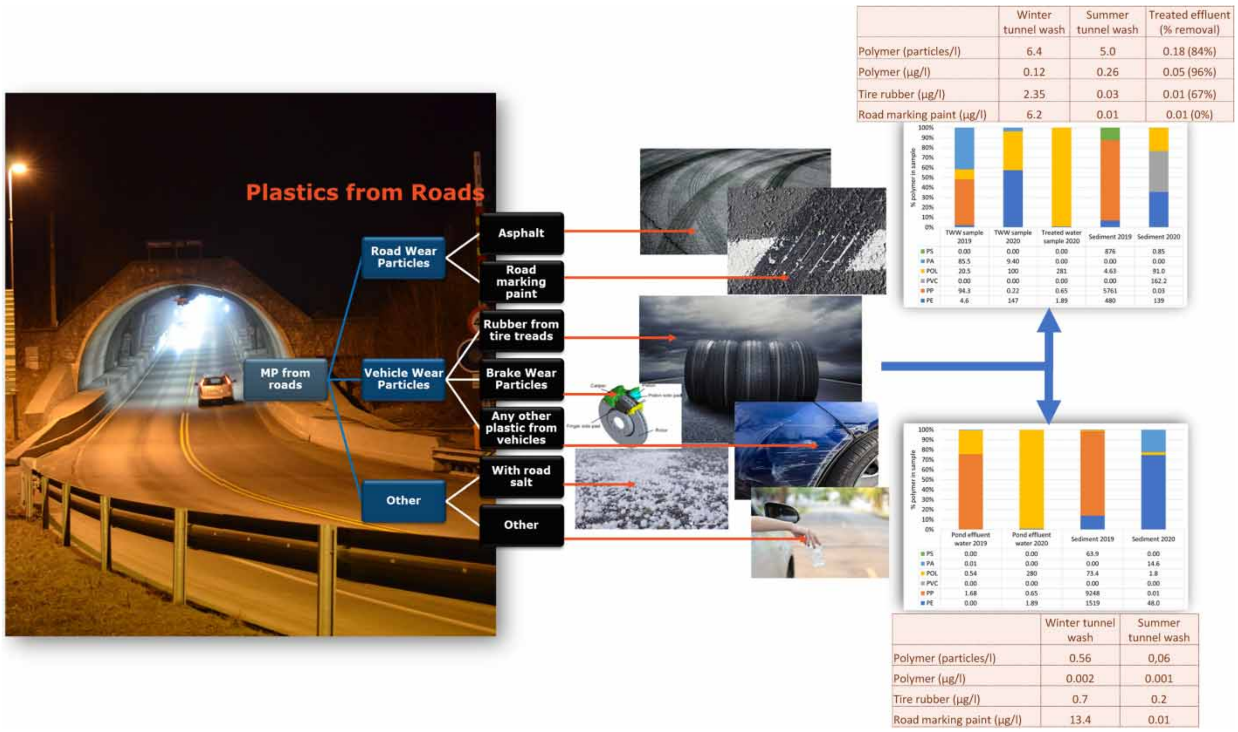
Treatment of tunnel wash runoff water and road runoff water before it reaches the environment is recommended to limit the negative consequences of traffic-related pollution. The efficiency of existing water treatment systems to remove traffic-related microplastic (MP) has not been sufficiently documented. Expanding the knowledge about traffic-related MP and documenting the treatment efficiency of MP in road tunnel wash water (TWW) and road runoff (RRW) treatment systems were the objectives of the presented project. TWW from the Tåsen tunnel, Norway, and RRW from the Fossbekken sedimentation pond were investigated in summer and winter situations. Six commonly available polymer types, tire rubber tread particles (TRP), and road marking paints (RMP) were analyzed in the selected samples. About 0.12 and 0.26 μg/L of polymers were identified in winter and summer TWWs. Significantly higher tire rubber and road marking paint concentrations were identified in the winter sample compared to summer sample. Suspended particle concentration in the Fossbekken RRW treatment pond effluent was lower in the summer than in the winter sample. About 0.002 and 0.0008 μg/L polymer masses were identified in winter and summer samples, respectively. TRP in the winter and summer samples were 0.7 and 0.2 μg7/L, and 13.4 μg/L RMP was found in the winter sample, while it was only 0.008 μg/L in the summer sample.

Key words: microplastics, road runoff water, tunnel wash water

HIGHLIGHTS

- Microplastic contamination of road runoff water (RRW) and tunnel wash water (TWW) was investigated.
- Heavy metal pollution and microplastic particles larger than 10 μm were measured.
- Six commonly available polymer types, tire rubber tread particles (TRP), and road marking paint (RMP) in RRW and TWW samples were analyzed.
- The treatment efficiencies of a roadside pond and a TWW sedimentation tank was evaluated.

GRAPHICAL ABSTRACT



INTRODUCTION

Even though a number of studies have been carried out related to microplastic (MP), there are still significant knowledge gaps related to its occurrence, spread, and effects. There are still challenges with the analytical methods for quantifying microplastics.

MP is defined as any type of plastic fragment that is less than 5 mm in length, that occurs in the environment because of plastic pollution (Britannica.com, Collignon *et al.* 2014). Microplastics are present in a large variety of products, from cosmetics to synthetic clothing to plastic bags and bottles. Many of these products readily enter the environment as waste. The Institute of Marine Research, Norway, assumes that around 80% of the MP in the Oslo fjord most likely originated from roads. Tire wear particles (TWP), road wear particles (RWP), and road marking paints (RMP) particles are identified as the three major sources of traffic-related microplastics (Horton *et al.* 2017; Vogelsang *et al.* 2018). Modern tires are manufactured using both natural and artificial rubber, and a wide variety of chemicals, fillers, and co-polymers. TWPs are generated by wearing and tiring of tire treads. RWPs are generated due to friction during driving on road surfaces. Bitumen and polymer-modified bitumen (PMB) are commonly used in asphalt pavements to increase the strength, stability, and adhesive properties of the pavement (Jørgensen *et al.* 2016). RMPs are used on paved roadways to provide guidance and information to drivers and pedestrians. Thermoplastic markers and water-based polymer paints are some of the most common types of road marking based on their balance between cost and performance longevity (Puffer & Nguyen 2017).

Kole *et al.* (2017) estimated traffic-related emissions of microplastics to be between 6,560,000 and 9,571,000 kg/year (an average of 7,884,000 kg/year) for Norway. Vogelsang *et al.* (2018) estimated that 4,300,000–5,700,000 kg of TWP, 28,000 kg of RWP, and 90,000–180,000 kg of RMP were formed in Norway every year and about 50% of that ended up in the sea. Kole *et al.* (2017) estimated global per capita emissions varied between 0.23 (India) and 4.7 (USA) kg/year, with an average of 0.81 kg/year. The estimated emission of Norway is 1.5 kg/capita/year. They summarized that the emission of tires is relatively larger than the other sources like brake wear particles (BWP) which make up approximately 8%, artificial turf 12–50%, and road marking approximately 5% of this. The relative proportion of tire particles related to the overall MP load that ends up in the sea is reported as 0.9% for the Netherlands and 31.9% for Norway.

In addition to MP, water from roads contains other contaminants, such as trace heavy metals and organic micropollutants like aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), and road salt (Paruch & Roseth 2008). The major fractions of traffic-related pollutants are expected to be found in the runoff from the roads (RRW) and the wash water from tunnels (TWW). A small portion gets exposed to air and moves with the wind. Many researchers have studied RRW and TWW compositions and their environmental impact. Many of these studies agree that traffic-related water contains a mixture of organic and inorganic pollutants originating from vehicle exhaust particles, tire wear, tunnel construction materials, asphalt, and surfactants in concentrations that can be harmful to the environment (Paruch & Roseth 2008; Kreider *et al.* 2010; Meland *et al.* 2010; Rathnaweera *et al.* 2019). Though some have estimated traffic-related MP pollution, investigations with road-water samples are rare.

Norway's road network consisted of 95,494 km in 2018, 599 km of which were highways, 10,713 km were main national roads, 44,639 km were secondary and regional roads paved, and 39,543 km were mentioned as other roads, which may include roads without a hard surface (Statistica website). The majority of the traffic-related pollutants that accumulate on the road surfaces are washed off with rain or snow melting and contaminate the roadside environment and nearby water bodies. There are over 1,200 tunnels in Norway with a combined tunnel stretch of over 1,400 km (Statens Vegvesen 2014). In tunnels with high traffic loading, fine particles from abrasion of brake wear, tires, road pavement, and exhaust fumes are deposited on the tunnel roads, walls, ceilings, road markings, road signs, and technical equipment. Cleaning of road tunnels is an important maintenance practice for maintaining traffic safety and increasing the lifespan of the tunnels (Statens Vegvesen 2014). The frequency of tunnel cleaning depends on several factors, including the average daily traffic load (AADT), the location, and other tunnel-specific and economic aspects. In general, Norwegian tunnels are washed on a regular basis, normally from two to 12 times a year (Paruch & Roseth 2008). The washing processes are distinguished between full and half wash. During a full wash, the tunnel sealings, ventilators, walls, carriageway, road marking, and technical gear are washed with soap and high-pressured water. Only the carriageway, road marking, and technical gears in the tunnel are washed during a half wash. Approximately 60–100 L of water mixed with 0.5–1% detergent is used for a full cleaning of a tunnel meter (Meland 2012). This results in a significant amount of polluted wash water, which unless properly treated will be a source of contamination to the receiving environment.

Norwegian as well as international road authorities require road runoff water (RRW) treatment systems installed in high-traffic loading areas and the roads in sensitive environments. Roadside treatment ponds for the treatment of RRW and sedimentation basins inside or outside tunnels for the treatment of TWW are the most commonly used systems in Norway. The performance and operational issues related to these treatment systems, especially MP, are rarely documented. This work seeks to expand knowledge and understanding about traffic-related MP, which is important to take measures to prevent traffic-related MP from ending up in freshwater and marine water systems. Another objective of this study was to document the effectiveness of TWW and RRW systems.

MATERIAL AND METHODS

TWW for this study was collected from the Tåsen tunnel, located on the highway Ring 3, Tåsen, Oslo, Norway. The tunnel is 1,338 m long and has two separate 10 m wide concrete tunnels. The annual average daily traffic (AADT) of Tåsen is approximately 50,000 vehicles. The tunnel is cleaned 10 times per year, two of which are full washes and the eight others are half washes. Two sampling campaigns were carried out, one from a full wash in winter 2019 (TWw) and one from a half wash in summer 2020 (TWs). In the tunnel, there are two sedimentation basins that can retain the TWW for 4 weeks. Treated water is routed to a water stream called Gaustadbekken, which ends up at the river, Frognerelva. Frognerelva ends at the Oslofjord.

The winter TWW sample (TWw-1) was collected directly from the sedimentation tanks about 0.5 h after the washing was completed. Further samples, TWw-2, TWw-4, and TWw-5, were taken after 1, 3, and 4 weeks of sedimentation. The summer TWW (TWs-1) sample was collected at the same time when the tunnel was washed. Two samples, TWs-3 and TWs-4, were collected after 2 and 3 weeks of sedimentation. TWw-1, TWs-1, and TWs-3 were sampled for MP analysis. Water samples from all samplings were used for laboratory investigations. During each sampling, the water depth, pH, conductivity, temperature, and redox potential were measured on-site for each basin. Of the two sedimentation tanks, only the right tank could be used for sediment sampling. Eight sediment samples were collected from different locations in the sedimentation tank and mixed to create a representative sediment sample for analysis. The Fossbekken sedimentation pond in Spydeberg, Norway, was sampled for RRW. The pond collects RRW from 18,706 m^2 road surface area of highway E18 (15,000 AADT). The pond consists of a pre-sedimentation chamber with a surface area of 130 m^2 followed by a main sedimentation basin with an area of 820 m^2. The average water depth at the normal water level is 1.5 m and the overflow level is 2 m. Treated water is discharged to the river Hobølelva. Collecting large volumes from the site during rainy days was not practical and therefore the pond inlet was not sampled. Treated water from the effluent end of the pond and the sediments distributed on the pond bottom were sampled in the winter of 2019 and summer of 2020.

In many cases, MP concentrations of water samples can be very small, which makes it necessary to analyze large amounts to get reliable results. Handling huge water volumes is neither economical nor practical. Therefore, a specially developed filtration unit made of metal with metal tubes with 10 μm stainless-steel mesh was used to concentrate particles of larger water volumes (Figure 1).

Raw TWW was rich in solids, so the 10 μm metal filters were clogged after filtration of only 45 and 35 L of winter and summer samples, respectively. But the filters were able to filter 870 L before becoming clogged with effluent samples (summer 2020). As the Fossbekken effluent samples were relatively free of large particles, the filters did not clog even after 1,963 and 2,712 L were filtered in the winter and summer, respectively. Furthermore, water samples were collected for laboratory investigations. Water temperature, pH, redox potential, and conductivity were measured at different places of the pond. Representative sediment samples were collected from the pond bottom.

MP sample preparation from stainless-steel filters and pyrolysis-GC-MS (Gas Chromatography Mass Spectrometry) (Bart 2001; Alexandre *et al.* 2022) analysis to identify rubber and RMP were carried out at NORCE Laboratory, Norway. Six commonly available polymer types, polyethene (PE), polyvinyl chloride (PVC), polypropylene (PP), polyester (POL), polyamide (PA), and polystyrene (PS), were analyzed at the Aalborg University, Denmark, using μ-FTIR spectroscopy (Yiyang *et al.* 2020), which is a technique that is typically used to determine the functional structure of organic chemicals. As samples were filtered with 10 μm mesh, only the MP particles larger than 10 μm diameter could be identified in this study.

Total and dissolved Cu and Zn concentrations (ICP-MS method) and suspended solids (TSS) were measured by an external laboratory. Whatman GF/C glass fiber filters were used for the filtration of samples and analysis of TSS. TSS was analyzed according to Standard Methods SM 2540 D and E (APHA/AWWA/WEF 2005). Particle size distribution (PSD) analyses were performed using laser diffraction analyses by Malvern Mastersizer 3000 (Malvern, UK).

RESULTS AND DISCUSSION

TWW: Table 1 summarizes the Tåsen TWW characteristics. Water temperature in summer was 3–4° higher than in the winter, but it did not significantly change during two sedimentation periods. Conductivity and pH did not show a considerable variation, but the redox potential was reduced with time. Redox potential was reduced faster to anoxic conditions (negative redox) in the winter samples than in the summer samples. This fast reduction of the redox potential can be explained by the effect of the remaining sediments in the tanks. Sediments in tanks were not removed before sampling in winter 2019, but tanks were cleaned upfront during the summer wash. Turbidity and suspended solids (TSS) in samples were reduced with sedimentation time. Filtered COD (FCOD), total COD (TCOD), and total organic carbon (TOC) were measured in all TWw samples and the TWs-1 sample.

Figure 1 | The filtering unit with metal tubing and metal pump head (a), metal filter (b), and aluminum sampling container (c).

Table 1 | Analyses of the water samples taken from the Tåsen tunnel

Parameters	Unit	2019 Winter wash (full wash)					2020 Summer wash (half wash)			
		TWw-1	TWw-2	TWw-4	TWw-5	% removal	TWs-1	TWs-3	TWs-4	% removal
Sampling dates		31.10	07.11	21.11	27.11		07.06.	22.06.	25.06	
Temperature	°C	8.3	9.2	8.9			12.1	11.5	12.5	
pH		8.1	7.9	7.7			7.8	7.9	8.3	
Redox	mV	111	117	−75			190	201	97	
Conductivity	μS/cm	755	749	703			552	797	788	
Turbidity	NTU	413	160	59	70		694	21	22	
TCOD	mg/L	162	96	86	79		540			
FCOD	mg/L	61	59	72	63		48			
TOC	mg/L	35	27	28	24		39			
TSS	mg/L	361	110	30	39	92	1,063	20	23	98
Tot. Zn	μg/L	380	230	100	70	82	710	45	33	95
Filtered Zn	μg/L	110	85	61	52	53	32	10	29	<10
Tot Cu	μg/L	180	92	36	32	82	190	36	87	54
Filtered Cu	μg/L	55	26	23	18	58	13	16	85	-

TW-1 is the raw TWW collected during the tunnel wash. TW-2, TW-3, TW-4, and TW-5 are the samples taken from the sedimentation tanks after 1, 2, 3 and 4 weeks of sedimentation. Temperature, pH, redox potential, and conductivity are averages of measurements made on three different depths.

Considering the 'full tunnel wash' in winter (2019), the TWw-1 sample was expected to be more contaminated than the sample from the 'half wash' during the summer of 2020. However, turbidity and suspended solid concentrations in the two sampling series show that the summer sample was more contaminated than the winter sample. This was due to the sampling method. As tunnel washing took approximately 3 h and the winter TWw-1 was taken about 30 min after washing was completed, it is reasonable to assume that the largest and heaviest particles, which usually contribute the most to solids, had already settled before sampling. Figure 2 shows TSS, turbidity, TCOD, TOC, Zn, and Cu of TWw and TWs samples (left) and PSD of two samples (right). As the graph illustrates, the summer sample contains particles with diameters from 1 to 1,000 μm, while the winter sample has only particles with diameters up to 100 μm. Also, it is clear that the volume concentration of particles in the winter sample is significantly lower than in the summer sample. According to the left graph, all of the parameters in the summer TWW sample are higher than in the winter sample. This indicates the importance of proper and real-time sampling in future studies.

In winter, 82% of total Zn was removed during 4 weeks in the sedimentation tank, while in summer, 95% was removed in 3 weeks. It was observed that 81% of the total Cu was removed in 4 weeks during the winter, while the same percentage was removed after 14 days in the summer (from 190 to 36 g/L). This efficient removal was achieved due to better settling and high

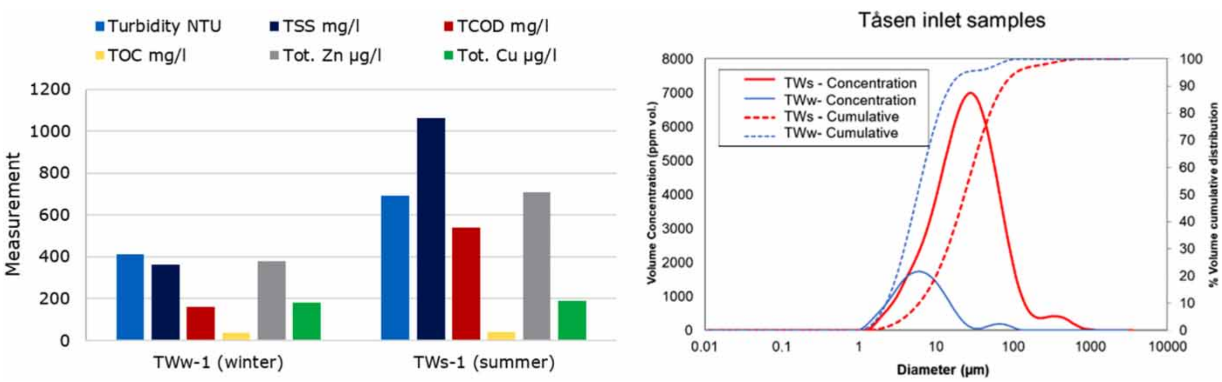


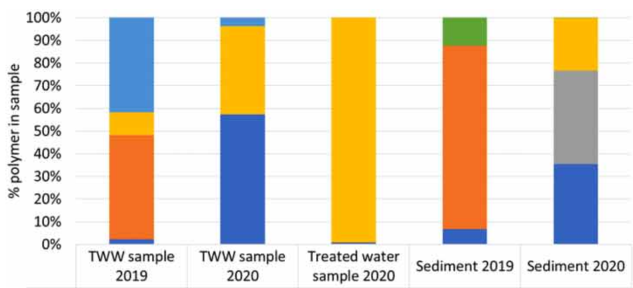
Figure 2 | Comparing TWW analyses of solids (TSS), turbidity, COD, TOC, Zn, Cu from winter and summer sampling campaigns (left). Right: comparison of the PSD in two samples.

microbial activities in summer temperatures. All the TWW samples were contaminated with detergents used for washing. Studies have shown that detergents used for tunnel washing mobilize and dissolve the heavy metals in water (Rathnaweera *et al.* 2019). Natural degradation of these soaps takes a long time and may not be completed during the TWW retention time in tanks. The removal of dissolved metals can be increased by anaerobic conditions, with low redox, where the metal can be precipitated as metal sulfides (Garshol *et al.* 2016; Rathnaweera *et al.* 2019). In contrast, we could observe an increase in both dissolved (85 μg/L) and total (87 μg/L) Cu concentrations after 3 weeks in summer. This can be caused by the remobilization of Cu from the sediments or is most likely caused by leaking surface runoff into the sedimentation tanks.

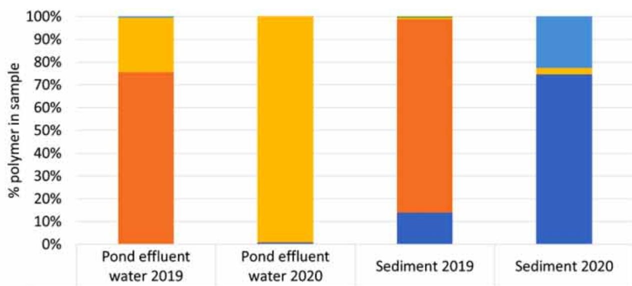
Six different MP polymer types, rubber particles, and RMP particles were measured. About 6.4 and 4.3 polymer particles per liter (#/L) with a mass of 0.12 and 0.26 μg/L were measured in TWw-1 (winter) and TWs-1 (summer), respectively. The graph and table on the right of Figure 3 describe the distribution of polymers. There were no PS and PVC measured in TW samples, but 876 ng PS was measured in the winter sediment sample. PP and PA were the two main polymer types in TWw-1, but POL and PE were prominent in TWs-1. PP contributed to 81% of the total measured polymer concentration in the winter sediment sample. All these polymers can be a component of RMP or they can be considered as day-to-day plastics rather than road-related MP. More investigations are needed to understand the origin of MP pollution and to confirm traffic-related MP types. Rubber particles and RMP particles in winter and summer TWs-1 samples were 2.35 and 6.2 μg/L and 0.03 and 0.01 μg/L, respectively. MP in the summer effluent (TWs-4) sample was analyzed and a 96% polymer reduction as the number of particles per liter and 80% reduction in mass (μg/L) were observed. Sixty-seven percent rubber particles were removed but no reduction was seen for RMP.

The Tåsen tunnel had a half tunnel wash on 2 October 2019, 28 days before the winter (2019) sampling (winter wash). A full wash took place on 22 April 2020, which was 39 days before the summer (2020) sampling. Considering that the MP concentrations in TWWs represent traffic-related MP emissions during the period between two consecutive washes, MP emission per km tunnel day was calculated (Table 2). When considering the TWw-1 in winter, the emission of ~12,000 polymer particles with a mass of 0.23 mg per km and day could be calculated. TWP and RMP emissions were 4.38 and 11.5 mg/km day, respectively. The summer emission was estimated at 6,000 particles with a mass of 0.35 mg polymer, 0.046 mg TWP, and 0.012 mg RMP/km day. Despite the influence of the sampling method, the 'full wash' in winter 2019 showed a higher emission of MP per km tunnel per day than the 'half wash' in summer 2020. Calculation suggests an average of 7 mg MP emission per km tunnel per day. As the traffic load was not available from the same period, it could not be accounted for. Kole *et al.* (2017) estimated average traffic-related MP emissions of 7,884,000 kg per year for Norway. The results in Table 2 may not be directly comparable to the theoretical calculations because the current study only measured MPs larger than 10 μm in size.

RRW: The Fossbekken RRW treatment pond was sampled on 2 December 2019 (winter sampling) and 11 June 2020 (summer sampling). Figure 4 shows the precipitation statistics at the Fossbekken (Hobøl meteorological station-www.yr.no) for 20 days before sampling days, and day 21 in the graph is the sampling day. The figure also shows the possible RRW



	TWW sample 2019	TWW sample 2020	Treated water sample 2020	Sediment 2019	Sediment 2020
PS	0.00	0.00	0.00	876	0.85
PA	85.5	9.40	0.00	0.00	0.00
POL	20.5	100	281	4.63	91.0
PVC	0.00	0.00	0.00	0.00	162.2
PP	94.3	0.22	0.65	5761	0.03
PE	4.6	147	1.89	480	139



	Pond effluent water 2019	Pond effluent water 2020	Sediment 2019	Sediment 2020
PS	0.00	0.00	63.9	0.00
PA	0.01	0.00	0.00	14.6
POL	0.54	280	73.4	1.8
PVC	0.00	0.00	0.00	0.00
PP	1.68	0.65	9248	0.01
PE	0.00	1.89	1519	48.0

Figure 3 | Distribution of different polymer types (determined using μ-FTR method) in the samples. The figure on the left depicts Tåsen tunnel TWW samples and the figure on the right depicts the results of Fosbekken RRW samples. Graphs depict the percentage composition of each polymer in samples. Tables show the measured masses in ng/L for water samples and ng/g DW for sediment samples. (PE, polyethene, PVC, poly vinyl chloride, PP, polypropylene (PP), POL, polyester, PA, polyamide and PS, polystyrene).

Table 2 | Calculation of MP emission per km tunnel

	TWw-1 (2019)		TWs-1 (2020)		TW-1 Average	
Parameter	**MP/km tunnel**	**MP/km tunnel/day**	**MP/km tunnel**	**MP/km tunnel/day**	**MP/km tunnel**	**MP/km tunnel/day**
# polymer particles	334,828	11,958	224,963	5,768	279,895	836
MP polymer (mg)	6.4	0.23	13.5	0.345	9.91	0.30
MP Rubber (mg)	123	4.4	1.8	0.046	62.28	1.86
RMP (mg)	324	11.6	0.5	0.012	162.4	4.85
Sum (mg)	**453**	**16.2**	**15.7**	**0.4**	**235**	**7.0**

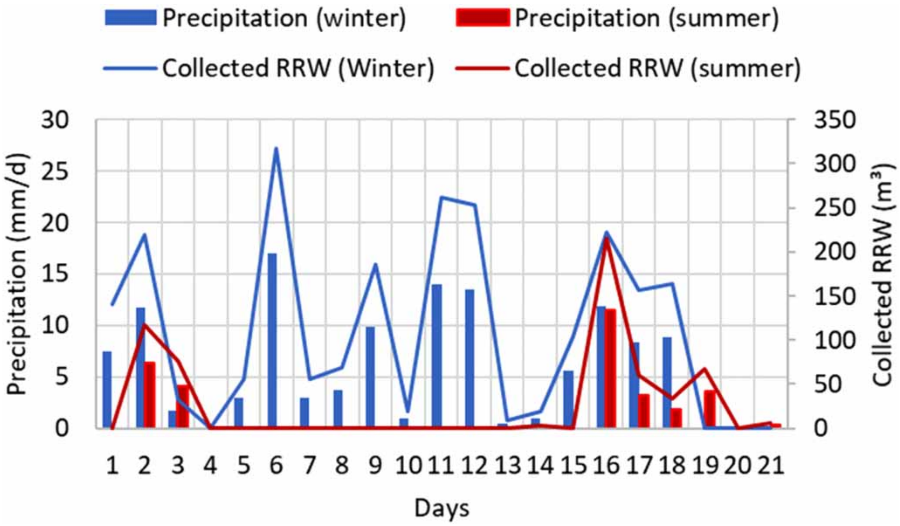


Figure 4 | Precipitation data of 20 days before sampling and the amount of RRW collected (assuming 100% ppt reaching the road surface is routed to the pond). Day 21 is the sampling date.

volumes collected at the pond, assuming 100% of the precipitated water from the road reached the pond. The total calculated precipitation before winter sampling is 2,286 m^3 (water) during the last 20 days. As it was winter, a substantial part of the precipitation may have remained as snow. However, in the last 3 days from 29 November there was no precipitation. When considering the summer sampling, it was 31 mm precipitation (580 m^3 RRW) during the 20 days before sampling. The volume has not been compensated for the evaporation and losses by infiltration at roadsides.

Table 3 shows the characteristics of effluent water samples collected from the Fossbekken RRW treatment pond. As we were not able to sample inlet RRW to the pond and the sediment samples we collected were not representative, it was not possible to estimate the mass balance and treatment efficiency of the pond. Water temperature during winter sampling was about 1 °C, and about 15 °C during the summer. Conductivity and pH in summer samples were higher than in winter samples. The winter sample was taken in December. Most of the water in the pond comes from melting of snow. The low conductivity measured in winter samples was due to the melted snow which has very low conductivity (2–20 μS/cm). Road salt (NaCl) is used for de-icing during heavy winter. The snow is also removed from the road surface by vehicles and piled along the roadside. Snow contaminated with road salts (on roadsides) was melted during the summer. The remaining traces of road salt that drained with melted snow is one possible reason for these high values in summer samples. The redox potential during both winter and summer was positive and almost the same. Therefore, efficient heavy metal removal by anaerobic microbial precipitation in this system can be rarely expected. As the water during summer sampling was clearer than in winter, the solid content in the winter sample was relatively higher (28 mg TSS/L) than in summer (4.6 mg TSS/L). The winter (2019) sample had higher concentrations of Zn and Cu (34 μg Zn/L and 43 μg Cu/L) compared to the summer (2020) sample (12 μg Zn/L and 11 μg Cu/L) and more than 75% of the Zn and Cu was in dissolved form.

Table 3 | Analyses of the water samples taken from the Fossbekken RRW pond

Parameter	Units	Winter 2019 FW 2019[a]	Summer 2020 FW 2020[a]
Temp[a]	°C	1	14.8
pH[a]		7.91	8.9
Redox potential[a]	mg/L	244,8	221.4
Conductivity[a]	μS/cm	331.1	778.3
Turbidity	NTU	78.6	4.53
FCOD	mg/L	30	
TCOD	mg/L	31	
TSS	mg/L	28	4.6
Tot. Zink (Zn)	μg/L	36	12
Filt. Zink (Zn)	μg/L	34	2.9
Tot. Copper (Cu)	μg/L	43	11
Filt. Copper (Cu)	μg/L	32	8.6

[a]Temperature, pH, redox potential, and conductivity are averages of 8–10 measurements made on the pond surface.

No sediment had been removed from the pond since it was built, and nothing was removed (except for the samples) between the winter and the summer sampling. Sampling of sediments was difficult. A larger volume of sediments was found in the pre-sedimentation basin. Cu and Zn concentrations in summer sediment samples were higher than those found in the winter samples: 490 mg Zn/kg DW and 70 mg Cu/kg DW in the winter sample and 680 mg Zn/kg DW and 83 mg Cu/kg DW in the summer sample. These results agreed with the measurements of Enhuus (2020) who measured 84 mg Cu/kg and 668 mg Zn/kg in sediment samples of the same pond.

Table 4 shows the MP analysis of the Fossbekken samples. Analyses showed 0.56 and 0.06 polymer particles/L weighed 0.002 and 0.0008 μg/L in the winter and summer samples, respectively. The graph and table on the right of Figure 2 show the polymer contents in samples. Like in the TWW samples, no PS and PVC were detected in the Fossbekken water samples, but a small amount (64 ng/g DW) of PS was measured in winter sediments. Other than 280 ng/L POL in summer, all the other polymers were less than 2 ng/L in water samples. But the winter sediment sample contains considerably high amounts of PP and PE. PP and PE are some of the very common MPs found in the environment and they can also be components of RMP identified in winter sediment samples. TWP levels in summer and winter water samples were 0.07 and 0.02 μg/L, respectively. It was remarkable that 13.4 μg/L of RMP was found in the winter samples compared to only 0.008 μg/L in the summer samples. One possible explanation could be the low tolerance of RMPs in low temperatures and other winter conditions. If the road marking was newly painted that could also impact the results, but we could not investigate that.

An environmental risk assessment for MP was carried out based on the EU and OSPAR guidelines. According to Tamis & Jongbloed (2019), MPs were briefly discussed in the CEDR R&D project on environmental risk assessment of RRW initiated in 2017. They concluded that MPs in RRW may have unacceptable effects on organisms if exposed via water and sediment,

Table 4 | Total polymer, tire rubber particles (TWP), and road marking paint (RMP) particles (>10 μm) in effluent water and sludge samples from Fossbekken sedimentation pond

MP type		Winter 2019 Water (# or μg/L)	Winter 2019 Sediment (μg/g DW)	Summer 2020 Water (# or μg/L)	Summer 2020 Sediment (μg/g DW)
Polymer types (tot)	Count (#)	0.56	10.2	0.055	1.50
Polymer types (tot)	Mass (μg)	0.002	10.9	0.0008	0.22
TWP/rubber	Mass (μg)	0.073	349.7	0.020	880
RMP	Mass (μg)	13.4	15.7	0.008	69

Table 5 | Risk assessment of MP in untreated and treated water and sediments samples. Bold values indicate high PEC/PNEC levels that may pose potential environmental risks to the recipients

Samples	Treatment	Site	Dilution factor	MEC_{MP} (μg/L)	PEC_{MP} (μg/L)	PNEC[a] water (μg/L)	PEC/PNEC
TW-1(2019)	Untreated	Tåsen	10	8.7	0.87	0.14	**6.2**
TW-1(2020	Untreated		10	0.3	0.03	0.14	0.2
TW-4(2020)	Treated		10	0.3	0.03	0.14	0.2
FW(2019)	Treated	Fossbekken	10	13.5	1.35	0.14	**9.6**
FW(2020)	Treated		10	0.02	0.002	0.14	0.02
Samples	**Treatment**	**Site**	**Dilution factor**	**$MEC_{MP\text{-}sed}$ (mg/kgDS)**	**$PEC_{MP\text{-}sed}$ (mg/kgDS**	**$PNEC^{b}_{sed}$ (mg/kgDS)**	**PEC/PNEC**
TS(2019)	Sediment	Tåsen	10	13.5	1.4	30	0.05
FS(2019)	Sediment		10	11.3	1.1	30	0.04
FS(2020)	Sediment	Fossbekken	10	1.2	0.12	30	0.004

[a]VKM (2019).
[b]Besseling *et al.* (2019), Marine sediment NOEC/10.

and measurements of the predicted environmental concentration (PEC), predicted no-effect concentration (PNEC), and potentially affected fraction (PAF) for MPs should be interpreted with care due to the high uncertainty of measured PEC. Leakage of single substances from heavy metals like Zn and organic micropollutants in polymers/plastics are separately assessed, and they use the Besseling *et al.* (2019) data for MP as their basis for review. They also refer to work carried out using Whole Effluent Toxicity (WET)-tests, conducted to support the underlying risk assessment, which represents the toxicity of all present substances. WET-tests of road runoff from Germany and Sweden show no significant toxic effects for bacteria and crustacea. The algae growth inhibition test shows significant dose-related growth inhibition when exposed to the runoff samples.

There is an increased focus by the regulating authorities to require that environmental risk assessment is carried out for any activities leading to a potential environmental risk, and environmental risk assessment of MP is increasingly included in the requirements. An objective of this work was to suggest a method for risk assessment and to apply it to the sites investigated in this report.

The available effect data are limited, but ingestion was considered the most frequent interaction between MP and biota, and filter feeders, deposit feeders, and planktonic suspension organisms were considered the most susceptible to MP ingestion (GESAMP 2015). After an intensive literature review, the recommendations from the VKM (2019) report, which has reviewed about 122 recent publications, were chosen to be used for the PNEC values for MP as a threshold for receiving water. The no observed effect concentration (NOEC)/10, suggested by Besseling *et al.* (2019), was used as PNEC for sediments. The PNEC value used for water was 0.14 μg/L (95% CI from 0.04 to 0.64) or 71.6 #/L (95% CI from 3.45 to 1991) (VKM 2019) and for sediment it was 30 mg/kgDS (Besseling *et al.* 2019).

Risk assessment was carried out by comparing measured concentrations (MEC) of MP from Tåsen and Fossbekken, suggesting a minimum dilution of 10 in receiving water to calculate the PEC. Table 5 summarizes the risk assessment. PEC/PNEC ratio <1 suggests that there is no significant risk associated with the environmental presence of the MP. When PEC/PNEC > 1 it indicates that MP could pose a toxic risk.

As shown in Table 5, TWW winter sample (2019) and Fossbekken effluent in winter 2019 have high PEC/PNEC values (6.2 and 9.6, respectively) indicating potential environmental risk to recipients due to the MP content. The other water and sediment samples were safe having PEC/PNEC < 1.

The high concentration of RMP particles during the winter was the main contributor to these results. Based on our results, we cannot exclude that untreated TWW and effluent water from RRW treatment ponds may pose an environmental risk to recipients. The database is, however, very limited, and the uncertainties are high.

CONCLUSIONS

The summer TWW sample was collected at the same time as tunnel washing and the winter sample was collected from sedimentation tanks about half an hour after the wash was completed. Two sample analyses showed a notable difference in solid concentrations. This indicates the importance of proper and real-time sampling in future studies.

Showing adequate particle settling in sedimentation basin 92 and 98% of solids were removed during the winter and summer settling periods. In winter, 82% of total Zn (from 380 to 70 μg/L) was removed in 4 weeks in the sedimentation tank, while 95% (from 710 to 33 μg/L) was removed in 3 weeks in summer. Filtered Zn was reduced from 110 to 52 μg/L (53%) in winter and from 32 to 28 μg/L (12%) in summer. Eighty-two percent total Cu removal (from 180 to 32 μg/L) was observed in 4 weeks during winter and the same percentage removal (from 190 to 36 μg/L) was achieved after 14 days in the summer. But it was increased from 36 to 87 μg/L in the effluent sample (after 3 weeks). Filtered Cu in the summer samples showed the same pattern as total Cu and it was increased from 16 to 85 μg/L after 3 weeks. Two possible causes for this can be remobilization of Cu from sediments or leakage of surface runoff from the sedimentation tank. Filtered Cu was reduced from 55 to 18 μg/L (52%) in winter 2019.

Six different MP polymer types, rubber particles, and road marking paint particles were measured. Measured polymer concentrations and number of particles in the inlet water were 0.12 and 0.26 μg/L and 6.4 and 5.0 particles/L of polymer in winter-2019 and summer 2020, respectively. The effluent sample was only measured in the summer sample showing 0.05 μL/L and 0.18 particles/L of polymer, indicating that 96 and 84% μg/L and particles/L were removed in the sedimentation basin. The amount of tire rubber tread particles (TRP) and RMP in TWW was significantly higher in winter (2.35 and 6.2 μg/L, respectively) than in summer samples (0.03 and 0.01 μg/L, respectively). The effluent sample in the summer 2020 had 0.01 μg/L TRP and 0.01 μg/L RMP, which was only 67 and 0% removal of TRP and RMP.

The effluent of the Fossbekken RRW pond was investigated. TSS and VSS in the summer samples were 4.6 and 1.2 mg/L and in winter samples were 28 and 4.2 mg/L, respectively. Zn and Cu concentrations in the effluent water samples were also lower in summer (12 μg tot Zn/L and 11 μg tot Cu/L) than in the winter samples (36 μg tot Zn/L and 43 μg tot Cu/L).

About 0.56 and 0.06 polymer particles/L with 0.002 and 0.0008 μg/L polymer masses were measured in winter and summer samples, respectively. TRP in the winter and summer samples were 0.7 and 0.2 μg/L. About 13.4 μg/L RMP was found in the winter sample, while it was only 0.008 μg/L in the summer sample. One possible explanation could be the lower tolerance of road paint to winter conditions such as cold temperatures and studded tires. Winter tolerance of RMP needs to be investigated in further studies.

According to the risk assessment, the MP content in TWW and RRW winter samples may pose a potential environmental risk to recipients. The database is, however, very limited, and the uncertainties are high.

The study demonstrated that the present treatment process is successful in removing MP particles that are larger than the size of the particles detected. It is necessary to continue to investigate further down (smaller) in MP particle size and the removal efficiency and cost-effectiveness of different water treatment systems.

ACKNOWLEDGEMENT

This activity was partially funded by the Norwegian Public Road Authority, Nye Veier AS and the Norwegian research council (grant 238995). The Norwegian Public Road Authority, Aalborg University, Denmark, NORSE and Aquateam COWI AS, Norway, provided valuable assistance. The publication was financially supported by the COWIfonden.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 31 January 2023; accepted in revised form 21 June 2023. Available online 27 July 2023