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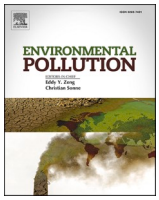

Tyre wear particles and metals in highway roadside ditches: Occurrence and potential transport pathways☆

Maria Polukarova [a,b,*], Elly Lucia Gaggini [b], Elisabeth Rødland [c], Ekaterina Sokolova [d], Mia Bondelind [b], Mats Gustafsson [e], Ann-Margret Strömvall [b], Yvonne Andersson-Sköld [a,f]

[a] Swedish National Road and Transport Research Institute Gothenborg (VTI), Regnbågsgatan 1, 417 55, Gothenburg, Sweden
[b] Chalmers University of Technology, Department of Architecture and Civil Engineering, Water Environment Technology, SE-412 96, Gothenburg, Sweden
[c] Norwegian Institute for Water Research, Økernveien 94, NO-0579, Oslo, Norway
[d] Uppsala University, Department of Earth Sciences, SE-752 36, Uppsala, Sweden
[e] Swedish National Road and Transport Research Institute Linköping (VTI), SE-581 95, Linköping, Sweden
[f] Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Geology and Geotechnics, SE-412 96, Gothenburg, Sweden

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ABSTRACT

Tyre wear particles (TWP) pose significant environmental concerns, necessitating a comprehensive understanding of their environmental distribution for accurate risk assessment. Roadside soil has not been extensively studied for TWP occurrence and distribution. This study aims to characterise the occurrence and distribution of TWP and associated metals in roadside soils and to investigate the correlations between these contaminants. Soil samples were collected from two road ditches along a Swedish national motorway at varying depths and distances from the contamination source. TWP in fractions <500 μm were analysed using PYR-GC/MS. Results indicated that TWP concentrations in soil samples ranged from 0.74 ± 0.20 to 12.40 ± 1.88 mg/kg d.w., consistent with other studies, and decreased with distance from the road, similar to Zn. In one ditch, TWP concentrations remained constant with depth, unlike concentrations of Co and Cr, which increased, while in the other ditch, TWP and most metals did not decrease with depth or distance from the outlet. Strong correlations were found between concentrations of TWP and Zn in one, but not the other, where Zn might have followed different transport due to leaching. Metal correlations in both ditches suggest traffic-related but not necessarily tyre wear origins. These findings are crucial for risk assessments of traffic-related pollutants, particularly TWP, and their spread into soils.

1. Introduction

A cocktail of environmental contaminants such as microplastics, metals and organic pollutants is continually released by vehicles into urban environments, and emissions are particularly significant in highly trafficked areas (Björklund et al., 2009; Järlskog et al., 2020, 2022; Markiewicz et al., 2017; Polukarova et al., 2020). Amongst traffic-related non-exhaust particles, microplastics from tyre wear have been identified as a matter of great concern in recent years (Baensch-Baltruschat et al., 2020; Galafassi et al., 2019). Annual emissions of tyre wear in different countries are summarized by Baensch-Baltruschat et al. (2020), and estimates by Kole et al. (2017) indicate that global emissions total reach nearly 6 million tonnes per year. In Sweden, their annual release into the environment has been estimated to be 11,000–12,000 metric tonnes (Polukarova et al., 2024). The question of understanding and quantifying the risk of microplastic particles released into the environment is highly relevant, and it has been addressed by the EU (European Commission, n.d.).

Previous studies have reported the presence of tyre wear particles (TWP) in different environmental matrices such as water runoff, road dust and sediments (Baensch-Baltruschat et al., 2020; Gaggini et al., 2024; Järlskog et al., 2022; Khan et al., 2024; Rødland et al., 2023a; Wang et al., 2024; Ertel et al., 2023). It is clear from current articles and reviews that gaps in our knowledge still exist, especially regarding TWP

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* Corresponding author. VTI, Box 8072, SE-402 78, Gothenburg, Sweden.
E-mail address: maria.polukarova@vti.se (M. Polukarova).

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in more complex matrices such as soil from road ditches. Only a few studies have been identified that have investigated this issue (Müller et al., 2022; Rødland et al., 2023b). Information regarding the occurrence, distribution and transport pathways of TWP in road ditches is valuable to assess their risk. These data are also needed for developing effective management strategies to control the pollutants near the sources. The unique characteristics of TWP, which are found in various size fractions in the environment (Järlskog et al., 2022), thus play a crucial role. The rubber's physical properties, such as its lower density compared to mineral particles, and its chemical property of high hydrophobicity, might affect its behaviour in soil. Additionally, the chemical reactivity of the metals and minerals embedded within these particles, along with the additives used to enhance the mechanical properties of tyres (e.g. accelerators such as metallic oxides, peroxides and sulphur), further complicate the transport dynamic. The degradation pathways of TWP remain largely unexplored, which adds another layer of complexity to understanding their environmental impact. These multifaceted interactions need to be investigated to determine if and how the transport pathways of TWP differ from those of other traffic-related contaminants.

A range of metals are added to tyres during production, either intentionally, such as ZnO and MgO, which are used as accelerators in the vulcanisation process, or unintentionally, such as the trace elements found in crude oil (Rogers, 2020). In addition, metals from other vehicle-related sources or the environment may be mistakenly attributed to coming from tyres during driving (Wagner et al., 2024). Metals such as Ca, Cd, Cr, Cu, Fe, Ni, Pb, Sb, Ti and Zn may originate from tyre and/or brake wear (Adamiec et al., 2016; Grigoratos & Martini, 2014; Hjortenkrans, 2008; Jeong, 2022; Wagner et al., 2024). Brake lining dust is also associated with metals such as As, Ba, Co, Mg, Mn, Mo, Na, Sr, Sb, Se, Pd and Zr (Adamiec et al., 2016; Grigoratos & Martini, 2015). Added metals can be leached out from TWP or physically sorbed or sorbed through surface complexation onto TWP (Glaubitz et al., 2023; Rocha Vogel et al., 2024; Xu et al., 2024). The transport of metals in soil can be affected by various factors such as oxygen level, organic matter, soil moisture and pH, and microbial activity. The factors and processes that affect the movement of metals from the road surface to the road ditch may also apply to TWP. Therefore, by analysing the occurrence, distribution and transport pathways of metals, we can gain insights into the behaviour and impact of TWP.

For the analysis of tyre wear particles, several methods have been explored, and their potential and limitations have been described (Rødland et al., 2023a). Methods such as thermal extraction and desorption-gas chromatography/mass spectrometry (TED-GC/MS) (Eisentraut et al., 2018) and pyrolysis-gas chromatography/mass spectrometry (PYR-GC/MS) (Parker-Jurd et al., 2021; Rauert et al., 2021; Rødland et al., 2022; Unice et al., 2012, 2013) are currently the most-used analytical methods for TWP. TWP in soil have previously been analysed using TED-GC/MS (Müller et al., 2022) and PYR-GC/MS (Rødland et al., 2023a). The method proposed by Rødland et al. (2022) includes an improved step for calculating the amount of tyre and road wear in a sample based on the measured rubber content and site-specific traffic data for each location. The rubber content is estimated using a marker combination of benzene, α-methylstyrene, ethylstyrene and butadiene trimers. Rødland et al. (2022). showed that this combination of marker compounds yielded a lower variation in styrene-butadiene (SBR) + butadiene (BR) concentrations compared to other markers (4-vinylcyclohexene (4-VCH), SB dimer, and SBB trimers), thereby enhancing the method's precision and reliability for this study.

The main aim is to characterise the occurrence and distribution of TWP and associated metals in roadside soils and to investigate the correlations between these contaminants. The specific objectives of this study were to investigate (1) the occurrence of TWP and metals in a transect and soil depth of a ditch, (2) the occurrence of TWP and metals from a stormwater system at different distances and depths in the receiving ditch, and (3) correlations between the occurrence of metals and TWP in the investigated ditches. This information will contribute to a better understanding of how TWP and metals are transported from roads to the surrounding environment, which will then help to form a basis for identifying the risks TWP may cause to humans and the environment today and in the future.

2. Material and methods

To be able to achieve the goal of this study, soil samples were collected in ditches adjacent to highway E18 at the Testsite E18 road research facility. Measurements of TWP concentrations in soil adjacent to the highway at different distances and depths using PYR-GC/MS were performed together with measurements of the concentrations of metals using inductively coupled plasma mass spectrometry (ICP-MS).

2.1. Sampling locations

Soil samples were collected from road ditches along a stretch of Highway E18 (Fig. A1 in Supplementary Material) next to the Testsite E18 research station, owned by the Swedish Transport Administration and situated between Enköping and Västerås in Sweden. This stretch of highway is located in a flat farmland area, and the surroundings consist of grass and scrubs. The soils in the area are post-glacial and glacial clays interspersed with sandy till regions. This composition results in low hydraulic conductivity, but cracks in the soil may facilitate preferential transport. No contaminants other than those related to long-distance transportation, farming, road traffic, and road construction and maintenance activities are expected to be found in the soil. The road maintenance includes annual sweeping in spring and de-icing with a salt solution or dry salt during winter.

The road consists of two lanes in each direction, and the road section studied has an annual average daily traffic (AADT) of approximately 1000 vehicles per highway direction, of which 1400 are heavy vehicles. The original pavement consisted of a polymer-free stone mastic asphalt (SMA), with the largest aggregate size measuring 16 mm (SMA 16, B 70/100). In 2016, the wheel tracks in the right lane were filled with SMA 11 and polymer-modified bitumen (PMB) 45/80-55, of which the binder contained 6.6 PMB. In 2021, the wheel tracks in the same lane were re-paved using SMA 16, B 70/100 without PMB. This new pavement was mixed with up to 10% of the previous wheel track asphalt, resulting in a maximum of 0.7% PMB in the binder in the right lane wheel tracks (or up to 0.02% of the asphalt).

Several studies have previously documented the occurrence of pollutants and road conditions at Testsite E18 and its surroundings (Arvidsson et al., 2021; Gaggini et al., 2024; Rasul et al., 2018; Svensson et al., 2022). Tyre and road wear particles had previously been sampled at the site on the road surface, in the water runoff and in the air (Järlskog et al., 2022).

Soil samples were collected at four different depths and at different distances at two locations along the road (Fig. A2 in Supplementary Material). These two locations were designated Ditch 1 and Ditch 2.

Ditch 1 collects the direct runoff and the splash and spray from the road (Fig. 1). On the other hand, Ditch 2 has a more complex contamination source. It collects the runoff and the splash and spray not only from the adjacent road stretch but also from another road stretch delimited by a kerb (Fig. A2 in Supplementary Material). The runoff from the road stretch delimited by the kerb flows into two gully pots connected to a collection well. This well also receives water from the median divider island and the adjacent artificial road ditch (Fig. A2 in Supplementary Material). The runoff from the collection well is discharged into Ditch 2 through a pipe at the bottom of the ditch.

The two road ditches serve as two different case studies for contaminant transport with runoff, i.e.: one for runoff flowing directly to the roadside (Ditch 1), common for non-urban roads globally, and the other (Ditch 2) receives runoff from a "point source" in the form of stormwater discharged through a collecting pipe, which is more

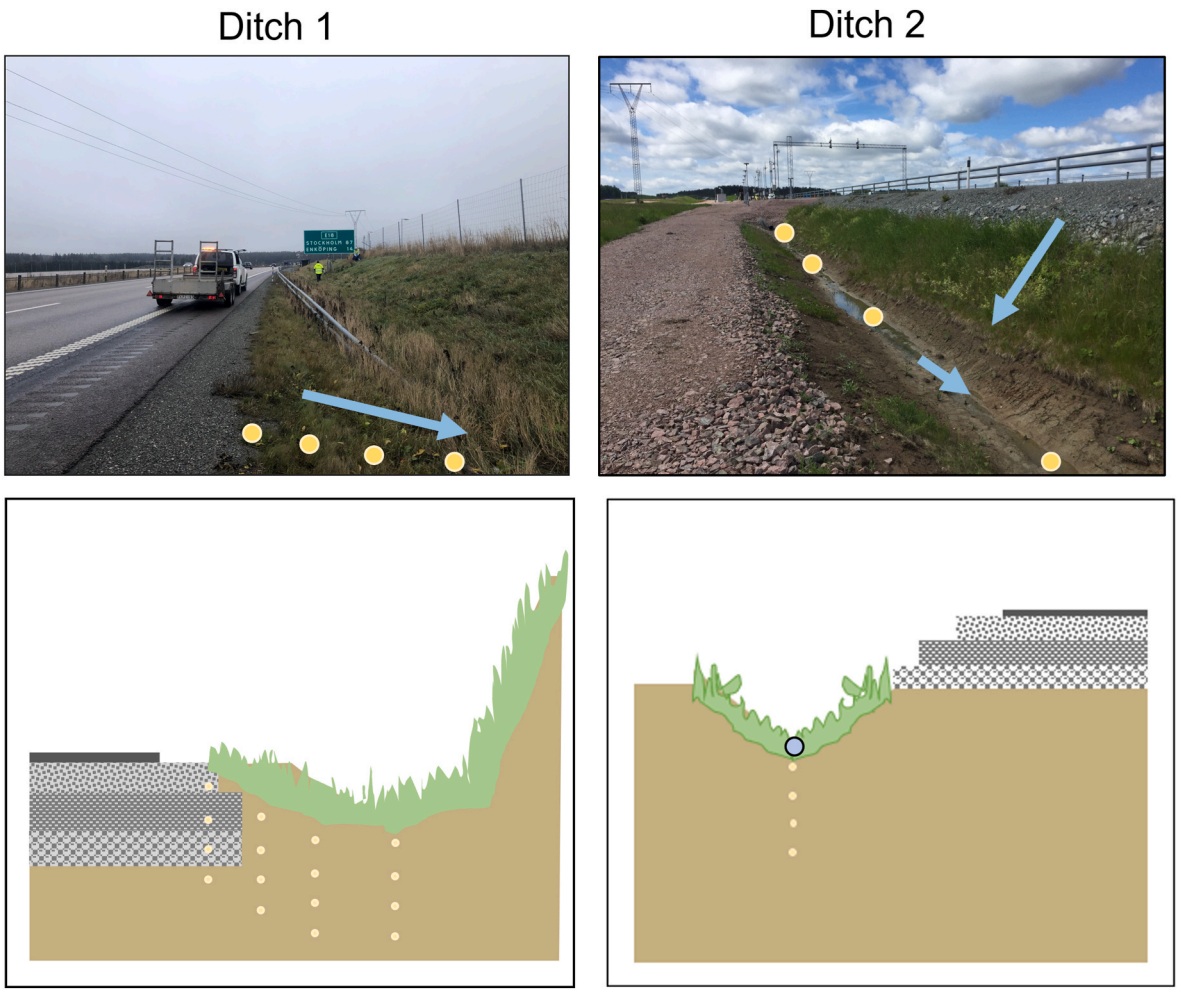

Fig. 1. Left: Ditch 1. Right: Ditch 2. Arrows illustrate runoff and splash and spray. Samples were collected from both ditches at four depths (0.1–0.2 m, 0.2–0.3 m, 0.3–0.4 m and 0.4–0.5 m). In Ditch 1, the samples were collected at four distances from the road edge (1.7 ± 0.1 m, 2.1 ± 0.1 m, 2.5 ± 0.1 m, and 3.1 ± 0.1 m), while in Ditch 2, they were collected at 0 m, 1.5 m, 3.0 m and 6.0 m from the runoff outlet of the collection well. Yellow dots represent the sampling points. The distances were measured horizontally (not bird's-eyed view). The blue dot in the right figure represents the runoff outflow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

representative for urbanised areas.

Ditch 1 has a depth of approximately 0.5 m (Fig. 1 left), and Ditch 2 (Fig. 1 right) has a depth of 2.5 m. The horizontal distance from the road edge to the bottom of Ditch 1 is 3.1 m, whereas the slope of Ditch 2 is longer (approximately 5 m). The slope of Ditch 1 during sampling was covered by 20% gravel and 80% vegetation, while in Ditch 2, vegetation only covered 50% of the slope (Fig. 1). The composition of the soil in the ditches is a mixture of dry-crust clay or silty clay, naturally abundant in the area, and gravel from the road construction material (Supplementary Material, Fig. A4 and Fig. A5). From visual observation, the road ditch material in the top layer (<0.2 m) nearest the road consisted mainly of sand and gravel, in contrast to the deeper samples which consisted mostly of clay and silt. Furthermore, these observations show that the material at the bottom of Ditch 2 was substantially more homogenous than the material at the bottom of Ditch 1. The bottom of Ditch 2 was filled with clay while in Ditch 1, the clay was mixed with gravel and vegetation roots, making both the sampling and the sample preparation more challenging.

2.2. Sampling procedure

In Ditch 1, the samples were collected at distances of 1.7 ± 0.1 m, 2.1 ± 0.1 m, 2.5 ± 0.1 m and 3.1 ± 0.1m perpendicular from the road edge (Fig. 1 and Fig. A2 (left) in Supplementary Material). Sampling was done with a powered auger (Fig. A3 in Supplementary Material A), and samples were collected from each sampling point at four depths: 0–0.2 m, 0.2–0.3 m, 0.3–0.4 m, and 0.4–0.5 m. The vegetation (including roots approximately 0.1 m in depth) from the top layer was removed from the drilling point during sampling. In Ditch 2, samples were collected from the ditch bottom at 0 m, 1.5 m, 3 m, and 6 m from the runoff outlet of the stormwater system (Fig. 1 and Fig. A2 (right) in Supplementary Material). At 0 m from the outlet, the samples were collected with a hand auger at a depth of 0–0.2 m, while further away from the outlet, the samples were collected with the power auger mentioned above at four different depths: 0–0.2 m, 0.2–0.3 m, 0.3–0.4 m and 0.4–0.5 m. The drilling auger is capable of handling a wide range of soil types and reaches greater depths than the hand auger. The drilling auger also provides more consistent and precise sampling due to its uniform power application. However, nearest the outlet the hand auger was used to avoid damaging the outlet pipe.

2.3. Analytical methodology

2.3.1. Sample processing and basic parameters

Before the analyses, both the metal and TWP samples were wet-sieved and dried in an oven at 95 °C. Wet sieving was chosen since the samples consisted mostly of clay and were thus easier to work with when wet. The samples from Ditch 1 were homogeneous and consisted

mostly of clay and silt. Each sample was mixed with water using a metal spoon, and a subsample of the slurry was sieved through a 500 μm metal sieve and collected in a ceramic mortar bowl. Sieving <500 μm was performed to adhere to the well-established TWP analysis method developed by Rødland et al. (2022). The reasoning for removing particles >500 μm is 1) studies have shown that TRWP is expected to be found in sizes <500 μm (Klöckner et al., 2021; Rødland et al., 2023b), 2) there is a need to have an upper size limit due to the volume constraints for the pyrolysis cups, 3) removing larger particles and debris that are not likely TRWP would help to concentrate the sample without using other techniques such as density separation or size fractionation in size classes.

Distilled water was used to wash/spray the sieve into the bowl to remove particles smaller than 500 μm. If the sample had cobbles or coarse gravel, presumably from road-building material, these were sprayed with distilled water and removed from the clay slurry. To ensure that no metal contamination of the soil samples could occur due to the use of the metal, the sieves were stored in distilled water for 24 h before the liquid was analysed for the presence of the metals Al, As, Ba, Ca, Cd, Co, Cr, Cu, Hg, Mn, Ni, V and Zn. The analysis showed that the sieves may leach Al and Ca along with smaller amounts of Mn, Cr and Cu (Table A1, Supplementary Material A2). That distilled water used for homogenising and sieving of the soil was later slowly evaporated in the oven. After drying at 95 °C the samples were crushed into a fine powder in the ceramic mortar and transferred to glass jars using a metal spoon and a scraper. The samples from Ditch 2 were heterogeneous and consisted mainly of clay and silt, although they also contained sand and gravel. Due to the heterogeneity of the samples, it was challenging to obtain representative subsamples for sieving. Therefore, an additional pretreatment was performed in which the slurry was mixed using magnetic stirrers, and subsamples were retrieved during the mixing process. These subsamples were then sieved using a 500 μm sieve. No chemical digestion or density separation was done because the organic matter in the samples was relatively low (between 3.3 and 7.6%) and most of the samples consisted of clay. The organic content in the sieved, dried and mortared soil was determined following the standardised SS 02 81 13 method for loss of ignition (LOI). The results are available in Table A2 in Supplementary Material A.2.

2.3.2. Metal analysis by ICP-MS

The soil and sieve water samples were analysed for concentrations of the following trace metals: As, Ba, Pb, Cd, Co, Cu, Cr, Hg, Ni, V and Zn. These analyses were performed by a commercial laboratory with inductively coupled plasma mass spectrometry (Agilent 7900 ICP-MS) according to the SS 28311:2017mod/SS-EN and ISO 11885:2009 standards for soil samples and SS-EN ISO 17294–2:2016 standard for water samples.

2.3.3. Tyre wear analysis by PYR-GC/MS

Samples were analysed with a multi-shot pyroliser (EGA/PY- 3030D) equipped with an auto-shot sampler (AS-1020E) (Frontier lab Ltd., Fukushima, Japan) coupled with a gas chromatograph-mass spectrometer (GC/MS) (5977B MSD with 8860 GC, Agilent Technologies Inc., CA, USA) following the methods established by Rødland et al. (2022) with some modifications. The combined concentration of SBR and BR was used to calculate the concentration of TWP in each sample. This calculation is based on the method described in Rødland et al. (2022), using the measured levels of SBR + BR in reference tyres (n = 31) relevant for the Nordic road environment and a Monte Carlo prediction model. This gives us an average concentration level of TWP in each sample, based on 100,000 model simulations, as well as the median values, standard deviations and percentiles. For further details see Supplementary Material Section A.3.

2.3.4. Grain size distribution of the road ditch material

The grain size distributions of the road ditch material in Ditch 1 and Ditch 2 were estimated by conducting a sieving analysis (for particles >0.63 μm) and sedimentation analysis (for 0.002–0.063 μm). The collected samples were analysed by a commercial laboratory according to the SS027123 mod and SS027124 mod methods, which provided the names of the soil types. The sieving analysis is a common method for estimating the grain size distribution of soil >0.63 μm. The sedimentation/hydrometer analysis is one of the methods commonly available for determining the grain size distribution for soils with finer particles. The benefits and drawbacks of these methods are listed and accessed in the Supplementary Material A.2.

2.4. Statistical analyses

Linear regression analyses (ordinary least squares) were used to assess the influence of various factors such as distance to the road and depth on TWP concentrations. To assess the correlation between the measured concentrations of metals and TWP, pairwise Pearson correlation coefficients were calculated for all combinations of these measured concentrations. All statistical analyses were conducted in StataNow, version 18 (standard edition).

3. Results and discussion

The results are divided into TWP concentrations and distributions in Ditch 1 and Ditch 2 respectively. The results for the metal concentrations and distributions in the two ditches comes next, followed by a comparison of the correlation between the TWP and metal concentrations, as well as the relationship between the different metals.

3.1. Tyre wear concentrations

3.1.1. Tyre wear concentrations in Ditch 1

The concentrations of SBR and BR in Ditch 1 ranged from 0.23 mg/kg to 3.90 mg/kg, with a mean value of 1.4 mg/kg (Table B1 in the Supplementary Material B). These results correspond to calculated TWP concentrations ranging from 0.74 ± 0.2 to 12.40 ± 1.88 g/kg (Fig. 2). Generally, the highest concentrations of TWP were detected in the samples collected closest to the road (Fig. 2). Raw data and illustration of standard deviation is shown in Fig. B1, Table B1 and Table B2 in Supplementary Material. The lowest concentrations in the samples were measured furthest away from the road (3.1 m from the road edge, 0.1–0.3 m from the surface). These differences were statistically significant ($p < 0.001$). However, it should be noted that the measured TWP concentrations were on average higher at 2.5 m from the road than at 2.1 m from the road. In general, the soil samples 3.1 m from the road consisted of silty clay and had a more homogenous soil texture than those found nearest to the road (Fig. A4 and Fig. A5 in Supplementary Material A.2). Despite the reduced concentrations farther away from the road, TWP were still measured at all sampling points, suggesting that TWP may be mobile even in low-permeability material. The tendency of TWP concentrations to decrease as the distance from the road increased was also described by Müller et al. (2022). However, Rødland et al. (2023b) found no significant difference in TWP concentrations between samples grouped by distance from the road and depth from the surface. These authors suggest that these differences could be influenced by snow deposition, road runoff to the surrounding terrain and the splash and spray effect since most of the roads in the study were rural, had light traffic and lacked specific construction for runoff treatment.

The measured TWP concentrations were on average higher at greater depths. However, these differences were not statistically significant ($p > 0.1$). The occurrence of TWP in the deepest layer nearest the road can be due to the higher porosity and larger particle size of the road bank material at this sampling point. Furthermore, medium-high concentrations were found at the middle depths (0.2–0.4 m) at 2.5 and 3.1 m from the road (Fig. 2). This may be due to the preferential flow of the infiltrated runoff through roots, cracks (formed during dry periods) and the

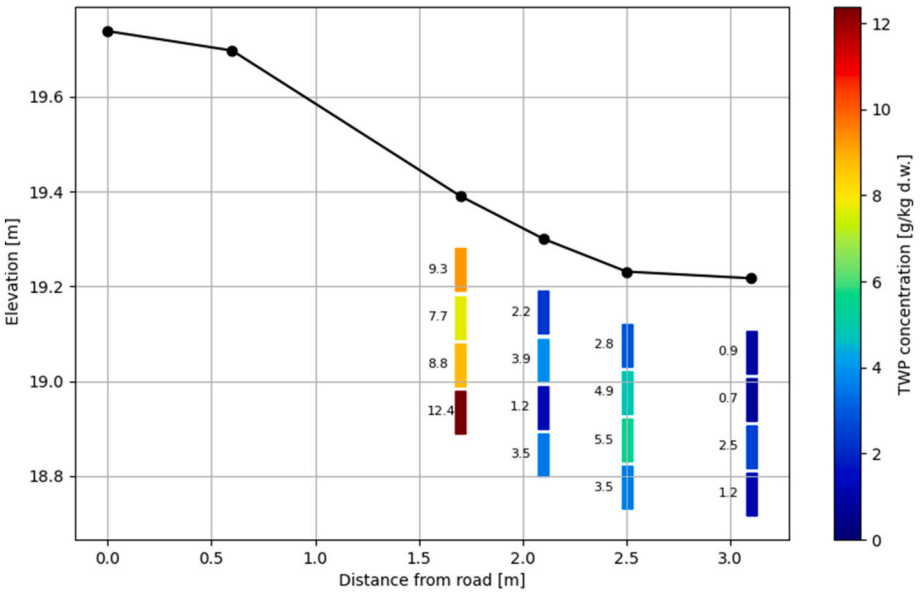

Fig. 2. Mean concentrations (n = 3) of TWP in samples collected in Ditch 1 at different distances from the roadside and at different depths at the sample points. The black line represents the elevation of the ditch slope.

gravel observed in the clay at all depths at this sampling point, which causes downward flows into the otherwise low-permeability clay in the ditch material (Fig. A4 and Fig. A5 in Supplementary Material A.2). Cross-contamination from the upper to lower layers due to the sampling method could have an effect on the results, thus highlighting the complexity of sampling in road ditches when it is not feasible to excavate a large volume of soil near the road, and minimising the impact on the existing road structure is a priority.

Overall, the TWP concentrations in this study are in the same range as the concentrations found in other studies (Table B3 in Supplementary Material); however, factors such as analysis method, particle size analysed, AADT, sampling depth and road age are not always reported in studies, making it challenging to perform comparison.

3.1.2. *Tyre wear concentration in Ditch 2*

The mean concentration of SBR & BR in Ditch 2 is 0.45 ± 0.12 mg/kg, corresponding to 0.830 ± 0.14 mg/kg of TWP (Fig. 3). As can be seen in Fig. 3, TWP concentrations in Ditch 2 vary at different depths and distances from the outlet. However, the differences in TWP concentrations for Ditch 2 based on depth and distance from the outlet were not found to be statistically significant ($p > 0.1$)

The highest TWP concentrations were found in the samples collected at a depth of 0.1–0.2 m at a distance of 3 m from the runoff discharge outlet (Fig. 3). This suggests that the horizontal mobility of TWP in the (clay and occasionally surface water-filled) ditch is high. This high mobility may be due to the transport of pollutants within the occasional free-running water from the outlet. Since the water's velocity decreases once it reaches the ditch and infiltrates in the soil, the TWP have more time to reach deeper.

3.2. *Metal concentrations in the two ditches*

The average metal concentrations at the different sampling points are summarized in Figs. 4 and 5 and in Tables B1 and B2 in Supplementary Material B. for Ditch 1 and Ditch 2, respectively. All the metal concentrations measured were lower than the Swedish EPA guideline

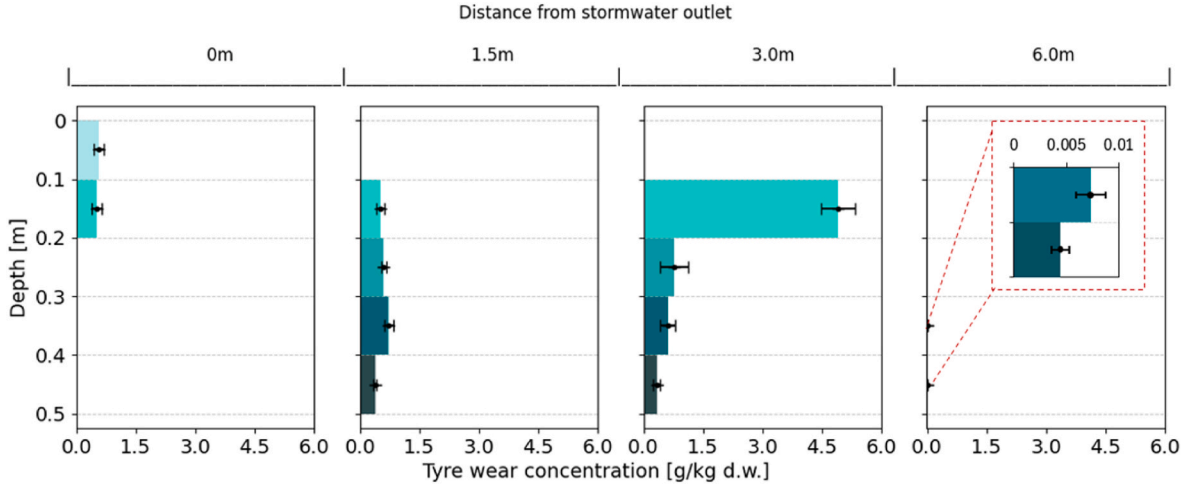

Fig. 3. TWP concentrations in samples collected at different depths and at different distances from the stormwater outlet. Samples were collected from Ditch 2 at Testsite E18 in Sweden. The colours represent the depth, not the concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

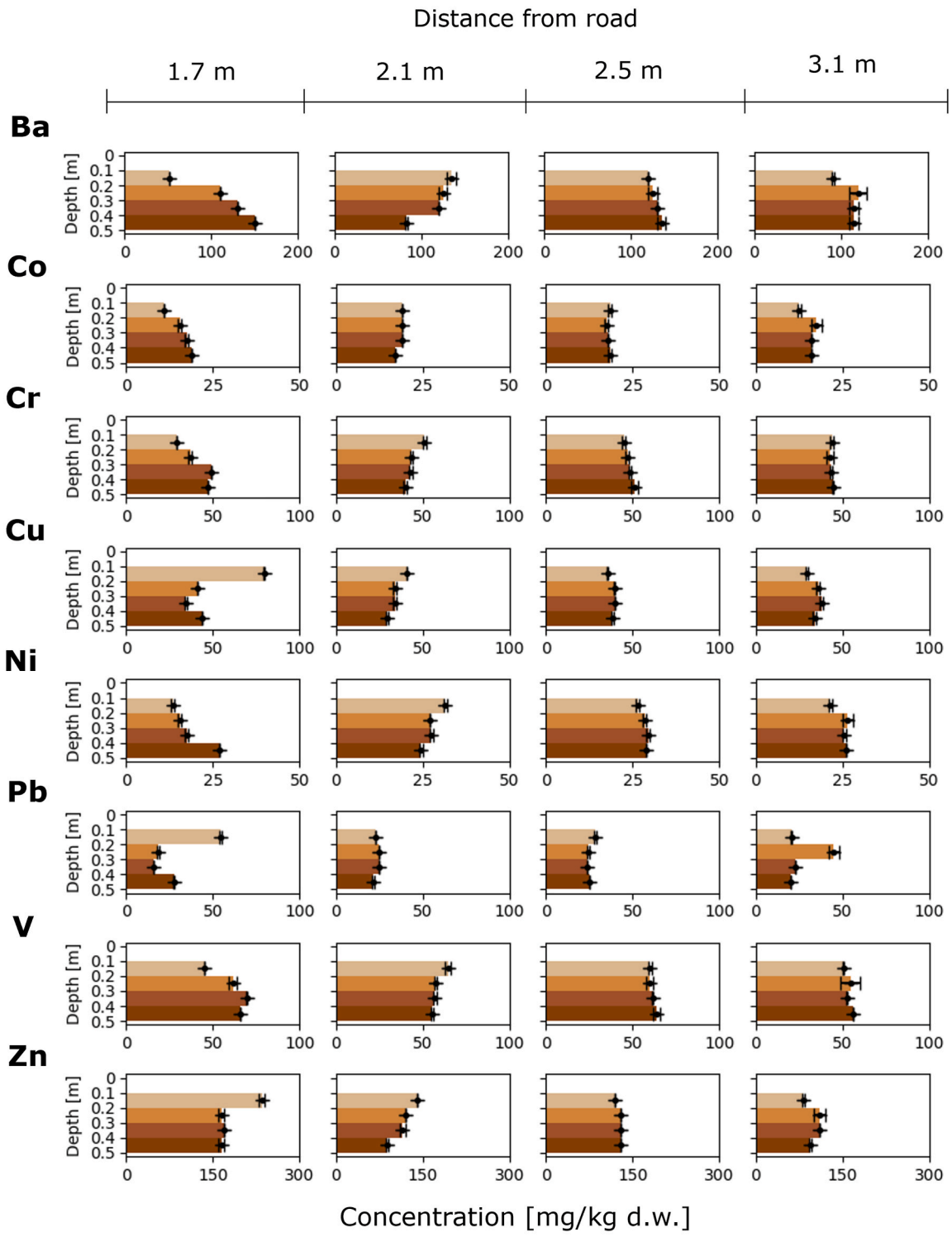

Fig. 4. Concentrations of metals in the soil at different distances (1.7 m, 2.1 m, 2.5 m and 3.1 m) from the road edge in Ditch 1 at Testsite E18 in Sweden. Cd was under the limit of quantification, which is illustrated in Table B1 in Supplementary Material. The missing bars at 0–0.1 m signify that no sampling was performed at this specific depth.

values for sensitive and less sensitive land use (Supplementary Material B) but considerably higher than the average background concentrations in the region, i.e. 2 – 6 times (Tables B1 and B2 in Supplementary Material B). For details on background concentration estimations please see Supplementary Material B.1 and Lax & Selinus (2005). Furthermore, (Tables B1 and B2 in Supplementary Material B). As can be seen in Figs. 4 and 5, however, the metal concentrations measured in Ditch 2 are all lower than those in Ditch 1. This can be explained by the dilution caused by the large amounts of rainwater in the collecting wells in Ditch 2 compared to Ditch 1. The median metal concentrations in both ditches follow a similar order: Zn > Ba > V > Cr > Cu > Ni > Pb > Co > Cd, all of which are traffic-related. In relation to background concentrations, the

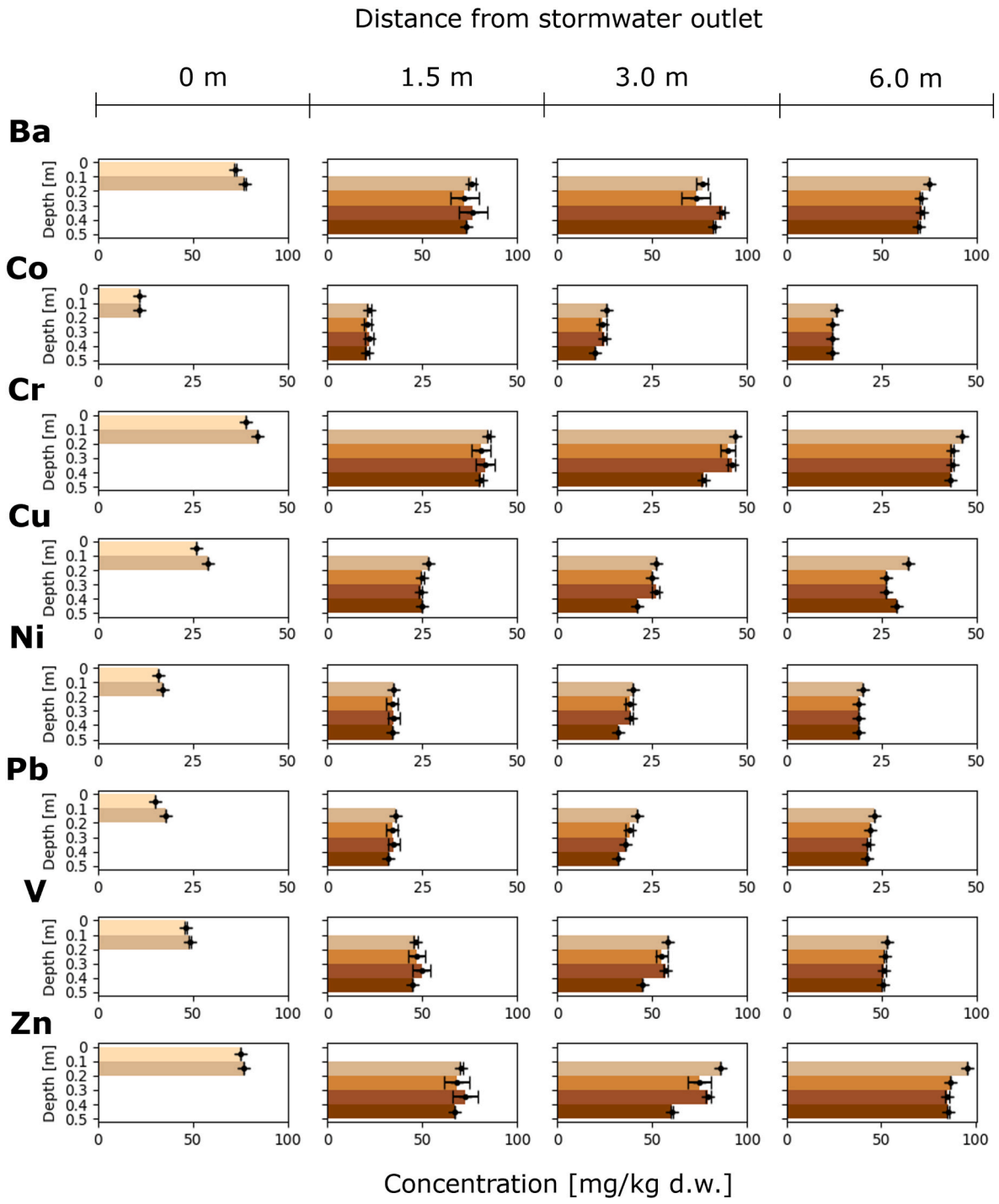

Fig. 5. Concentrations of metals in Ditch 2 at 0, 1.5, 3 and 6 m from the outlet. Cd was not detected in any of the samples from Ditch 2 (Table B2 in Supplementary Material). The missing bars at 0 m below the depth of 0.2 m and at 1.5, 3.0 and 6.0 m, at above the depth of 0.1 m signify that no sampling was performed at these specific depths. The missing bars at 0–0.1 m signify that no sampling was performed at this specific depth.

metal concentrations in Ditch 1 (median value minus the median background value from SGU (2024)) follow the same order apart from Ba > Zn. In Ditch 2, the detected concentrations minus the background concentrations follow the order: Ba > Zn > V ~ Cr > Cu > Pb ~ Ni > Co. These results indicate a rather low background level of Ba. In addition, the ranking may suggest that Zn, V and Pb are bound in or sorbed by the surface of larger TWP that were removed to a higher degree from the gully pots and wells than the other metals, which are assumed to be bound to smaller particles such as from brake wear. The high presence of the metals including Cu and Co in both ditches indicates their significance as traffic-related metals. The relatively high concentrations of Cu in the ditches compared to the background levels (Table B1 and B2 in Supplementary Material B) were expected since Cu is the second- or third-most common metal found in most stormwater samples (Becouze-Lareure et al., 2019; Gasperi et al., 2014; Järlskog et al., 2021; Johansson et al., 2024). The high concentration of Ba indicates traffic-related sources such as brake and bitumen wear as well as diesel combustion (which also explain the high concentration of V) (Woodyard, 2004).

The concentrations of Cd, Cr, Cu, Ni and Zn are in the same range as

those found at 64 different sites in 27 European studies according to Werkenthin et al. (2014) and in ditch soils alongside roads with an AADT of 69,000–73,000 vehicles, as analysed by Aljazzar & Kocher (2016). The concentrations are also in the same range as those in road dust from studies reviewed by Wagner et al. (2024). However, all three studies found higher concentrations of Pb, which could be explained by the EU ban on Pb in gasoline and the relatively young age of the studied road section compared to the roads studied by the above-mentioned authors.

3.2.1. Metal concentration profiles

3.2.1.1. Metal concentration profile in Ditch 1. Different metals exhibit varying distributions in the soil of Ditch 1. However, two noticeable trends in accumulation and distribution can be observed. These trends are best illustrated by the distribution of traffic-related metals, such as Cu and Ba respectively, where the trends are most evident (Fig. 6). As can be seen in Fig. 4, and as illustrated for Cu in Fig. 6 (left), the concentrations of Cu, Pb and Zn in Ditch 1 are highest in the upper soil layer nearest the road. At this location, concentrations are approximately 100% higher for Cu and Pb and approximately 50% higher for Zn compared to the concentrations measured in the other sampling points in Ditch 1. Additionally, Zn concentrations were found to be lower farther from the road compared to the 1.7 m distance ($p < 0.01$). The reduced concentrations away from the road may be due to the airborne emissions (particles) of TWP and metals (Järlskog et al., 2022) and amount of splash water from the road surface decreases with distance from the road(Golwer, 1991; Steiner et al., 2007). Nearest the road (1.7 m from the road edge), Zn, Cu and Pb have the highest concentrations in the surface layer (Figs. 4 and 6 (left)). Figs. 4 and 6 also show that these metals are transported, but their concentrations decrease with depth and distance from the road. This has also been found in road ditch depth profiles determined by Werkenthin et al. (2014) and transect profiles investigated by Aljazzar & Kocher (2016).

As can be seen in Fig. 4, and as illustrated for Ba in Fig. 6, the concentrations of Ba, Cd, Cr, Co, Ni and V in Ditch 1 differ from those of Cu, Pb and Zn in terms of depth and distance from the road. The highest concentrations of these metals do not occur near the surface closest to the road; instead, their highest concentrations were found deeper in the soil and some were also farther away from the road (Fig. 4) as previously found for Cd by Norrström (1998). In Ditch 1, Ba, Co, Cr and V have high concentrations both at the lowest depth nearest the road and farther away from the road (Figs. 4 and 6). The concentrations of Co and Cr were statistically determined to be higher at greater depths compared to their concentrations at the surface ($p < 0.001$). This could be explained by the fact that these metals are more capable of being carried by runoff through the highly porous and coarse upper layer of the material close to the road. De-icing salts could also enhance this capability since they contribute to the dispersion of clay particles and increase the desorption of metals (Flanagan et al., 2019; Behbahani et al., 2021).

The observed metal concentration profile in Ditch 1 can be explained by the steric and physical hindrance of particle-bound metals in the upper soil layers (Boivin et al., 2008), especially if the metals are bound in or sorbed by larger particles. It may also be because the content of organic matter is usually higher in the upper layers and known to absorb metal ions such as $Pb2+$, $Cd2+$, $Cu2+$ and $Zn2+$ (Turer et al., 2001). In Sphagnum peat with a high organic matter content, the metal ions were sorbed in the following order: $Pb2+ > Cu2+ > Ni2+ > Cd2+ > Zn2+$. This could be explained by stability constants for humic acids and ligand field stabilisation energy effects depending on the metal's electron configurations in complexes (Kalmykova et al., 2008).

In Ditch 1, Ni concentrations were found to be higher when measured farther from the road as compared to the measuring point closest to the road (Fig. 4). However, the concentrations did not linearly increase with distance and were found to be highest 2.5 m from the road. The Cd concentrations were found to be highest at the farthest distance from the road ($p < 0.001$), but no linear increase with distance was observed. The concentrations did not decrease linearly with distance, but the lowest concentrations were found at the farthest distance from the road.

3.2.1.2. Metal concentration profile in Ditch 2. The measured concentrations for Ni ($p < 0.05$) were higher at 3 m and 6 m from the road than at 0 m, and for Pb ($p < 0.01$), the concentrations were higher at 6 m from the road. The tendency of Ni to decrease away from the road edge in Ditch 1 and away from the outlet in Ditch 2 may suggest that Ni is a mobile metal.

3.2.2. Correlation of metals with TWP

As can be seen in Fig. 7, there was a strong positive correlation in Ditch 1 between the concentrations of TWP and Zn at the different sampling points, whereas there were no strong correlations between TWP and the other metals analysed. The reason for this strong correlation could be that the Zn originates from the tyre material since Zn has been identified as the most abundant metallic element in tyre rubber (O'Loughlin et al., 2023), and organic Zn has recently been suggested as a tracer of TWP by Klöckner et al. (2019). In Ditch 2, however, there was no strong correlation between Zn and TWP concentrations at any of the soil sampling points (Fig. 7). One reason may be that Zn is easily leached from the TWP and transported primarily with the free and occasionally relatively high surface water flow originating from the stormwater system. Furthermore, the contact time between the TWP and the water in the gully pots and wells can be rather long depending on the frequency and amount of precipitation. Leaching of Zn from tyre wear debris in soil has been previously observed and described (Mohajerani et al., 2020, 2022).

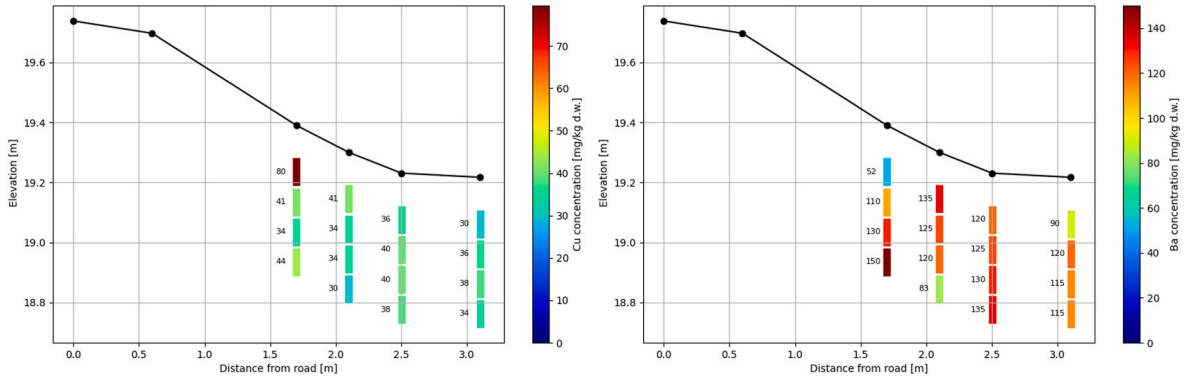

Fig. 6. Left: Concentrations of Cu [mg/kg d.w.] in road Ditch 1 at different distances from the road, and at different depths. Right: Concentrations of Ba [mg/kg d.w.] in road Ditch 1 at different distances from the road, and at different depths.

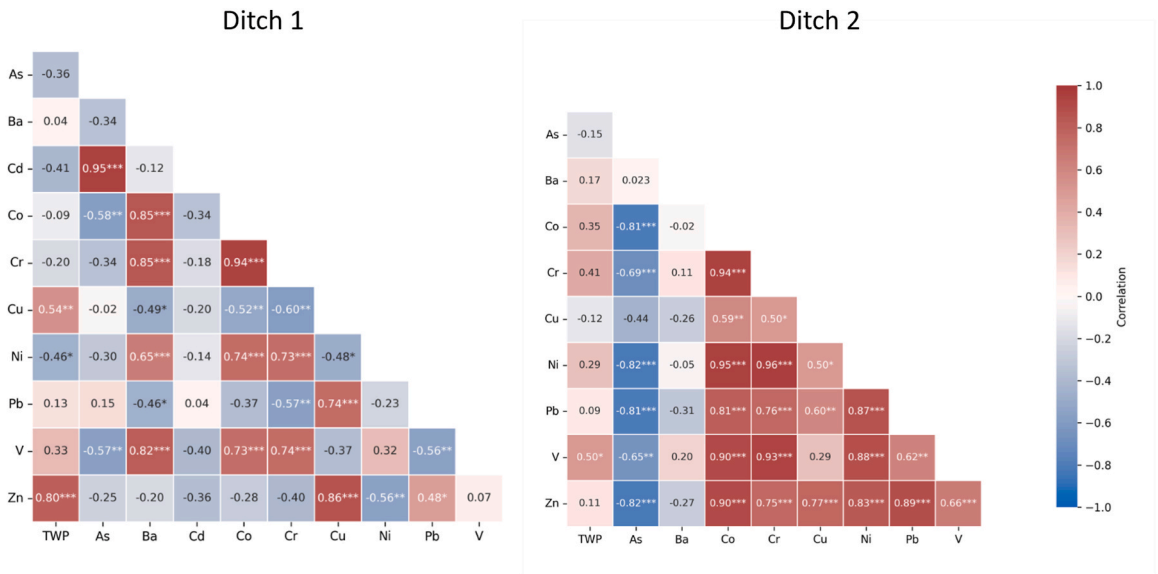

Fig. 7. Pearson correlation coefficients showing the relationships between TWP and various metals as well as the interrelationships between different metals in soil samples collected from Ditch 1 (left) and Ditch 2 (right). ***p < 0.01, **p < 0.05, *p < 0.1.

As can be seen in Fig. 7, there was a positive correlation between the concentrations of some metals, i.e. Cu and Pb, Cu and Zn, Ni and Co, and Ni and Cr, at the different measurement points in both Ditch 1 and Ditch 2. The correlation between Zn and Cu was strong and slightly less strong between Pb and Cu. Their sources, traffic, and behaviour in the soil were rather similar as described above in the Introduction. Contrary to O'Loughlin et al. (2023), who analysed 70 tyres for 19 elements in order to establish a tyre fingerprint, no strong correlation between Ni and Cu was found in the collected soil samples. This is in line with Ni being more mobile and the possibility that the Ni and Cu in our samples came from different traffic-related sources.

In summary, TWP and metals were detected in both ditches even at the deepest analysed layer (0.4–0.5 m), thus illustrating the mobility of these contaminants through road ditch material. Some sampling points exhibited high uncertainty (the ratio between the standard deviation divided by the mean value), up to 56–85% at a distance of 2.5 m in the sloping part of Ditch 1, thus indicating and highlighting the challenges associated with field sampling road ditch material, particularly in a sloping ditch containing a variety of filling, clay and soil materials (Fig. A4 and Fig. A5 in Supplementary Material). The findings in this study are important as a base for risk assessments regarding traffic-related pollutants, particularly TWP, and their ability to spread into and through ditches and other soils. For example, the knowledge gained from Ditch 2 shows that the well system reduces the spreading of pollutants into the ditch and that the pollutants accumulate some meters from the well water outlet (here ca 3 m). The knowledge gained from Ditch 1 is applicable as a basis for risk assessments of traffic-related contaminants in non-urban road ditches. The results show that the pollutants are sorbed in the soil material, and nearest to the road, following stormwater best management practices by managing the flow and pollutant load near the source, rather than sending it downstream through traditional piping.

However, this study is limited to one location with the same naturally abundant soil, so it cannot be applied to all types of soils. The TWP mobility in the soil is expected to be complicated and depend on many factors, such as soil mineralogy and texture, and potential redox processes/changes, which can be affected for instance by changes in soil moisture, pH and temperature changes, changes in microbial activities, oxygen availability (Ponting et al., 2021) and ditch geometry. Therefore, the behaviour of TWP and other pollutants needs to be studied in different types of soils. In the literature, there is a need to describe the ambient conditions, including the soil type, at the location from where the samples are taken. As highlighted by Werkenthin et al. (2014), this information is often lacking or limited in the literature. For risk assessments, it is also essential to better understand the toxicity of both new and aged TWP as well as the toxicity of tyre additives and their transformation products such as 6PPD-quinone (6 PPD-Q)(Hua & Wang, 2023). The transport and accumulation of these compounds also need to be thoroughly investigated. In addition, the cocktail-effect created by the presence of various metals may contribute to the toxicity of road pollution, of which Zn from tyres is recognised as the main toxicity driver (Mohajerani et al., 2020, 2022; Piotrowska et al., 2019). Other road- and traffic-related particles such as abrasion from the road surface and road markings, and particles released from vehicles, are additional possible vectors that transport metals within the road environment (Roy et al., 2022). At the same time, the topic of TWP contaminant transport is becoming increasingly important due to expected weather extremes due to global warming. In summary, for quantitative assessments for various recipients, for example through the use of transport models, additional studies of TWP and additional TWP-related pollutants in various soil materials and weather conditions are needed both for current and expected climate changes.

4. Conclusions

- TWP in fractions <500 μm were detected in all the soil samples analysed, with concentrations between 0.74 ± 0.20 and 12.40 ± 1.88 mg/kg d.w. These concentrations were in the same range as those reported in other studies.
- In Ditch 1, TWP concentrations decreased with distance from the road, as did the concentrations of Zn in general and Pb and Cu specifically within the 0.1–0.2 m layer. The concentration of TWP did not change with depth, contrary to the concentrations of Co and Cr, which increased with depth.
- In Ditch 2, the concentration of TWP did not decrease with depth and distance from the outlet, which was similar for most of the detected metals.
- In Ditch 1, the highest concentrations of metals were traffic-related, and they are ranked in the following order: Zn > Ba > V > Cr > Cu > Pb > Ni > Co > Cd. In Ditch 2, traffic-related metals also dominated, with the concentrations ranked as follows: Zn ~ Ba > V > Cr > Cu > Ni ~ Pb > Co.

- There was a strong correlation between the concentrations of TWP and Zn at the different sampling points in Ditch 1. In Ditch 2, however, there was no strong correlation between TWP and Zn, suggesting that Zn was more prevalent due to leaching during prolonged contact with water.
- In both Ditch 1 and Ditch 2, there was a rather strong correlation between the concentrations of Cr and Cu, Cu and Zn, Pb and Cu, Ni and Co, and Ni and Cr at the different measurement points, which may suggest that these metals are traffic-related but not necessarily tyre wear-related.

CRediT authorship contribution statement

Maria Polukarova: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elly Lucia Gaggini:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation. **Elisabeth Rødland:** Writing – review & editing, Methodology, Formal analysis. **Ekaterina Sokolova:** Writing – review & editing, Formal analysis. **Mia Bondelind:** Writing – review & editing. **Mats Gustafsson:** Writing – review & editing, Supervision. **Ann-Margret Strömvall:** Writing – review & editing, Supervision, Conceptualization. **Yvonne Andersson-Sköld:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.125971.

Data availability

All data is available in Supplementary material

References

Adamiec, E., Jarosz-Krzemińska, E., Wieszała, R., 2016. Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts. Environ. Monit. Assess. 188 (6), 369. https://doi.org/10.1007/s10661-016-5377-1.

Aljazzar, T., Kocher, B., 2016. Monitoring of contaminant input into roadside soil from road runoff and airborne deposition. Transp. Res. Procedia 14, 2714–2723. https://doi.org/10.1016/j.trpro.2016.05.451.

Arvidsson, A.K., Blomqvist, G., Stave, C., Wärme, M., Polukarova, M., Bäckström, A., 2021. Dynamisk prognosstyrd vinterväghållning – fas 3 & 4 : restsaltmodeller och automatisk saltspridning. In: VTI Resultat NV - 2021:4. Statens Väg- Och Transportforskningsinstitut.

Baensch-Baltruschat, B., Kocher, B., Stock, F., Reifferscheid, G., 2020. Tyre and road wear particles (TRWP) - a review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Sci. Total Environ. 733, 137823. https://doi.org/10.1016/j.scitotenv.2020.137823.

Becouze-Lareure, C., Dembélé, A., Coquery, M., Cren-Olivé, C., Bertrand-Krajewski, J.-L., 2019. Assessment of 34 dissolved and particulate organic and metallic micropollutants discharged at the outlet of two contrasted urban catchments. Sci. Total Environ. 651, 1810–1818. https://doi.org/10.1016/j.scitotenv.2018.10.042.

Björklund, K., Cousins, A.P., Strömvall, A.-M., Malmqvist, P.-A., 2009. Phthalates and nonylphenols in urban runoff: occurrence, distribution and area emission factors. Sci. Total Environ. 407 (16), 4665–4672. https://doi.org/10.1016/j.scitotenv.2009.04.040.

Boivin, P., Saadé, M., Pfeiffer, H.R.R., Hammecker, C., Degoumois, Y., 2008. Depuration of highway runoff water into grass-covered embankments. Environ. Technol. 29 (6), 709–720. https://doi.org/10.1080/09593330801986972.

Eisentraut, P., Dümichen, E., Ruhl, A.S., Jekel, M., Albrecht, M., Gehde, M., Braun, U., 2018. Two birds with one stone - fast and simultaneous analysis of microplastics: microparticles derived from thermoplastics and tire wear. Environ. Sci. Technol. Lett. 5 (10), 608–613. https://doi.org/10.1021/ACS.ESTLETT.8B00446/SUPPL_FILE/EZ8B00446_SI_001.PDF.

Ertel, B.M., Weinstein, J.E., Gray, A.D., 2023. Rising seas and roadway debris: microplastic and low-density tire wear particles in street-associated tidal floodwater. Mar. Pollut. Bull. 195, 115502. https://doi.org/10.1016/j.marpolbul.2023.115502.

European Commission. (n.d.). Microplastics. The EU aims to address the growing volume of microplastics in the environment. Retrieved September 1, 2023, from https://environment.ec.europa.eu.

Gaggini, E.L., Polukarova, M., Bondelind, M., Rødland, E., Strömvall, A.-M., Andersson-Sköld, Y., Sokolova, E., 2024. Assessment of fine and coarse tyre wear particles along a highway stormwater system and in receiving waters: occurrence and transport. J. Environ. Manag. 367, 121989. https://doi.org/10.1016/j.jenvman.2024.121989.

Galafassi, S., Nizzetto, L., Volta, P., 2019. Plastic sources: a survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci. Total Environ. 693, 133499. https://doi.org/10.1016/j.scitotenv.2019.07.305.

Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S., Wiest, L., Mirande, C., Caupos, E., Demare, D., Kessoo, M.D.K., Saad, M., Schwartz, J.J., Dubois, P., Fratta, C., Wolff, H., Moilleron, R., Chebbo, G., Cren, C., Millet, M., et al., 2014. Micropollutants in urban stormwater: occurrence, concentrations, and atmospheric contributions for a wide range of contaminants in three French catchments. Environ. Sci. Pollut. Control Ser. 21 (8), 5267–5281. https://doi.org/10.1007/s11356-013-2396-0.

Glaubitz, F., Rocha Vogel, A., Kolberg, Y., von Tümpling, W., Kahlert, H., 2023. Detailed insights in adsorption process of heavy metals on tire wear particles. Environ. Pollut. 335, 122293. https://doi.org/10.1016/j.envpol.2023.122293.

Grigoratos, T., Martini, G., 2014. Non-exhaust Traffic Related Emissions. Brake and Tyre Wear PM. European Commission. https://doi.org/10.4324/9781315596198-20.

Grigoratos, T., Martini, G., 2015. Brake wear particle emissions: a review. Environ. Sci. Pollut. Control Ser. 22 (4), 2491–2504. https://doi.org/10.1007/s11356-014-3696-8.

Hjortenkrans, D., 2008. Road traffic metals: sources and emissions. Dissertation series No 54 / University of Kalmar, Faculty of Natural Science, pp 1-27.

Hua, X., Wang, D., 2023. Tire-rubber related pollutant 6-PPD quinone: a review of its transformation, environmental distribution, bioavailability, and toxicity. J. Hazard Mater. 459, 132265. https://doi.org/10.1016/j.jhazmat.2023.132265.

Järlskog, I., Jaramillo-Vogel, D., Rausch, J., Gustafsson, M., Strömvall, A.-M., Andersson-Sköld, Y., 2022. Concentrations of tire wear microplastics and other traffic-derived non-exhaust particles in the road environment. Environ. Int. 170. https://doi.org/10.1016/j.envint.2022.107618.

Järlskog, I., Strömvall, A.-M.M., Magnusson, K., Gustafsson, M., Polukarova, M., Galfi, H., Aronsson, M., Andersson-Sköld, Y., 2020. Occurrence of tire and bitumen wear microplastics on urban streets and in sweepsand and washwater. Sci. Total Environ. 729, 138950. https://doi.org/10.1016/j.scitotenv.2020.138950.

Järlskog, I., Strömvall, A.-M., Magnusson, K., Galfi, H., Björklund, K., Polukarova, M., Garçao, R., Markiewicz, A., Aronsson, M., Gustafsson, M., Norin, M., Blom, L., Andersson-Sköld, Y., 2021. Traffic-related microplastic particles, metals, and organic pollutants in an urban area under reconstruction. Sci. Total Environ. 774, 145503. https://doi.org/10.1016/j.scitotenv.2021.145503.

Jeong, H., 2022. Toxic metal concentrations and Cu-Zn-Pb isotopic compositions in tires. Jeong Journal of Analytical Science and Technology 13 (2). https://doi.org/10.1186/s40543-021-00312-3.

Johansson, G., Fedje, K.K., Modin, O., Haeger-Eugensson, M., Uhl, W., Andersson-Sköld, Y., Strömvall, A.-M., 2024. Removal and release of microplastics and other environmental pollutants during the start-up of bioretention filters treating stormwater. J. Hazard Mater. 468, 133532. https://doi.org/10.1016/j.jhazmat.2024.133532.

Kalmykova, Y., Strömvall, A.-M., Steenari, B.-M., 2008. Adsorption of Cd, Cu, Ni, Pb and Zn on Sphagnum peat from solutions with low metal concentrations. J. Hazard Mater. 152 (2), 885–891. https://doi.org/10.1016/j.jhazmat.2007.07.062.

Kole, P.J., Lohr, A.J., Van Belleghem, F., Ragas, A.M.J., 2017. Wear and tear of tyres: a stealthy source of microplastics in the environment. Int. J. Environ. Res. Publ. Health 14, 31.

Khan, F.R., Rødland, E.S., Kole, P.J., Van Belleghem, F.G.A.J., Jaén-Gil, A., Hansen, S.F., Gomiero, A., 2024. An overview of the key topics related to the study of tire particles and their chemical leachates: from problems to solutions. TrAC, Trends Anal. Chem. 172, 117563. https://doi.org/10.1016/j.trac.2024.117563.

Klöckner, P., Reemtsma, T., Eisentraut, P., Braun, U., Ruhl, A.S., Wagner, S., 2019. Tire and road wear particles in road environment – quantification and assessment of particle dynamics by Zn determination after density separation. Chemosphere 222, 714–721. https://doi.org/10.1016/j.chemosphere.2019.01.176.

Klöckner, P., Seiwert, B., Weyrauch, S., Escher, B.I., Reemtsma, T., Wagner, S., 2021. Comprehensive characterization of tire and road wear particles in highway tunnel road dust by use of size and density fractionation. Chemosphere 279, 130530. https://doi.org/10.1016/j.chemosphere.2021.130530.

Lax, K., Selinus, O., 2005. Geochemical mapping at the geological Survey of Sweden. Geochem. Explor. Environ. Anal. 5, 337–346. https://doi.org/10.1144/1467-7873/05-07.

Markiewicz, A., Björklund, K., Eriksson, E., Kalmykova, Y., Strömvall, A.-M., Siopi, A., 2017. Emissions of organic pollutants from traffic and roads: priority pollutants selection and substance flow analysis. Sci. Total Environ. 580, 1162–1174. https://doi.org/10.1016/j.scitotenv.2016.12.074.

Mohajerani, A., Burnett, L., Smith, J.V., Markovski, S., Rodwell, G., Rahman, M.T., Kurmus, H., Mirzababaei, M., Arulrajah, A., Horpibulsuk, S., Maghool, F., 2020. Recycling waste rubber tyres in construction materials and associated environmental considerations: a review. Resour. Conserv. Recycl. 155, 104679. https://doi.org/10.1016/j.resconrec.2020.104679.

Mohajerani, A., Kurmus, H., Conti, D., Cash, L., Semcesen, A., Abdurahman, M., Rahman, M.T., 2022. Environmental impacts and leachate analysis of waste rubber incorporated in construction and road materials: a review. Sci. Total Environ. 835, 155269. https://doi.org/10.1016/j.scitotenv.2022.155269.

Müller, A., Kocher, B., Altmann, K., Braun, U., 2022. Determination of tire wear markers in soil samples and their distribution in a roadside soil. Chemosphere 294. https://doi.org/10.1016/j.chemosphere.2022.133653.

Norrström, A.-C., 1998. Concentration and fractionation of heavy metals inroadside soils receiving de-icing salts. Sci. Total Environ. 218, 161–174. http://kth.diva-portal.org/smash/get/diva2:581986/FULLTEXT01.pdf.

O'Loughlin, D.P., Haugen, M.J., Day, J., Brown, A.S., Braysher, E.C., Molden, N., Willis, A.E., MacFarlane, M., Boies, A.M., 2023. Multi-element analysis of tyre rubber for metal tracers. Environ. Int. 178, 108047. https://doi.org/10.1016/j.envint.2023.108047.

Parker-Jurd, F.N.F., Napper, I.E., Abbott, G.D., Hann, S., Thompson, R.C., 2021. Quantifying the release of tyre wear particles to the marine environment via multiple pathways. Mar. Pollut. Bull. 172. https://doi.org/10.1016/j.marpolbul.2021.112897.

Piotrowska, K., Kruszelnicka, W., Bałdowska-Witos, P., Kasner, R., Rudnicki, J., Tomporowski, A., Flizikowski, J., Opielak, M., 2019. Assessment of the environmental impact of a car tire throughout its lifecycle using the LCA method. Materials 12 (24). https://doi.org/10.3390/ma12244177.

Polukarova, M., Hjort, M., Gustafsson, M., 2024. Comprehensive approach to national tire wear emissions: challenges and implications. Sci. Total Environ. 924, 171391. https://doi.org/10.1016/j.scitotenv.2024.171391.

Polukarova, M., Markiewicz, A., Björklund, K., Strömvall, A.M., Galfi, H., Andersson-Sköld, Y., Gustafsson, M., Järlskog, I., Aronsson, M., 2020. Organic pollutants, nano- and microparticles in street sweeping road dust and washwater. Environ. Int. 135 (November 2019), 105337. https://doi.org/10.1016/j.envint.2019.105337.

Rasul, H., Earon, R., Olofsson, B., 2018. Detecting seasonal flow pathways in road structures using tracer tests and ERT. Water, Air, Soil Pollut. 229 (11), 358. https://doi.org/10.1007/s11270-018-4008-6.

Rauert, C., Rødland, E.S., Okoffo, E.D., Reid, M.J., Meland, S., Thomas, K.V., 2021. Challenges with quantifying tire road wear particles: recognizing the need for further refinement of the ISO technical specification. Environ. Sci. Technol. Lett. 8 (3), 231–236. https://doi.org/10.1021/acs.estlett.0c00949.

Rocha Vogel, A., Kolberg, Y., Schmidt, M., Kahlert, H., von Tümpling, W., 2024. Potential deterioration of chemical water quality due to trace metal adsorption onto tire and road wear particles – environmentally representative experiments. Environ. Pollut. 359, 124571. https://doi.org/10.1016/j.envpol.2024.124571.

Rødland, E.S., Gustafsson, M., Jaramillo-Vogel, D., Järlskog, I., Müller, K., Rauert, C., Rausch, J., Wagner, S., 2023a. Analytical challenges and possibilities for the quantification of tire-road wear particles. TrAC, Trends Anal. Chem. 165, 117121. https://doi.org/10.1016/j.trac.2023.117121.

Rødland, E.S., Heier, L.S., Lind, O.C.C., Meland, S., 2023b. High levels of tire wear particles in soils along low traffic roads. Sci. Total Environ., 166470 https://doi.org/10.1016/j.scitotenv.2023.166470.

Rødland, E.S., Samanipour, S., Rauert, C., Okoffo, E.D., Reid, M.J., Heier, L.S., Lind, O.C., Thomas, K.V., Meland, S., 2022. A novel method for the quantification of tire and polymer-modified bitumen particles in environmental samples by pyrolysis gas chromatography mass spectroscopy. J. Hazard Mater. 423 (Part A), 127092. https://doi.org/10.1016/j.jhazmat.2021.127092, 5 February 2022.

Rogers, B., 2020. Tire Engineering. An Introduction, first ed. CRC Press. https://doi.org/10.1201/9781003022961.

Roy, S., Gupta, S.K., Prakash, J., Habib, G., Kumar, P., 2022. A global perspective of the current state of heavy metal contamination in road dust. Environ. Sci. Pollut. Control Ser. 29 (22), 33230–33251. https://doi.org/10.1007/s11356-022-18583-7.

SGU, 2024. Geokemiska bakgrundshalter för morän i 2 mm fraktion Datapunkter inom cirkel med centrumkoordinater. SWEREF99-TM) och radie enligt: E: 607263 N: 6609764 Radie: 10 km). Accessed from. https://www.sgu.se/mineralnaring/geokemisk-kartlaggning/geokemiska-bakgrundshalter-i-mark/.

Svensson, N., Gustafsson, M., Blomqvist, G., 2022. Luftkvalitet vid Testsite E18 : analys av påverkansfaktorer TT - air quality at Testsite E18 : analyses of influencing factors (eng). In: VTI Rapport NV - 1104. Statens Väg- Och Transportforskningsinstitut.

Turer, D., Maynard, J.B.B., Sansalone, J.J.J., 2001. Heavy metal contamination in soils of urban highways comparison between runoff and soil concentrations at Cincinnati, Ohio. Water Air Soil Pollut. 132 (3), 293–314. https://doi.org/10.1023/A:1013290130089.

Unice, K.M., Kreider, M.L., Panko, J.M., 2012. Use of a deuterated internal standard with pyrolysis-GC/MS dimeric marker analysis to quantify tire tread particles in the environment. Int. J. Environ. Res. Publ. Health 9 (11), 4033–4055. https://doi.org/10.3390/ijerph9114033.

Unice, K.M., Kreider, M.L., Panko, J.M., 2013. Comparison of tire and road wear particle concentrations in sediment for watersheds in France, Japan, and the United States by quantitative pyrolysis GC/MS analysis. Environ. Sci. Technol. 47 (15), 8138–8147. https://doi.org/10.1021/es400871j.

Wagner, S., Funk, C.W., Mueller, K., Raithel, D.J., 2024. The chemical composition and sources of road dust, and of tire and road wear particles-A review. Sci. Total Environ. 926, 171694. https://doi.org/10.1016/j.scitotenv.2024.171694.

Wang, Y., Li, X., Yang, H., Wu, Y., Pu, Q., He, W., Li, X., 2024. A review of tire wear particles: occurrence, adverse effects, and control strategies. Ecotoxicol. Environ. Saf. 283, 116782. https://doi.org/10.1016/j.ecoenv.2024.116782.

Werkenthin, M., Kluge, B., Wessolek, G., 2014. Metals in European roadside soils and soil solution – a review. Environ. Pollut. 189, 98–110. https://doi.org/10.1016/j.envpol.2014.02.025.

Woodyard, D., 2004. Pounder's Marine Diesel Engines and Gas Turbines - 8th Edn.

Xu, Q., Kazmi, S.S.U.H., Li, G., 2024. Tracking the biogeochemical behavior of tire wear particles in the environment – a review. J. Hazard Mater. 480, 136184. https://doi.org/10.1016/j.jhazmat.2024.136184.