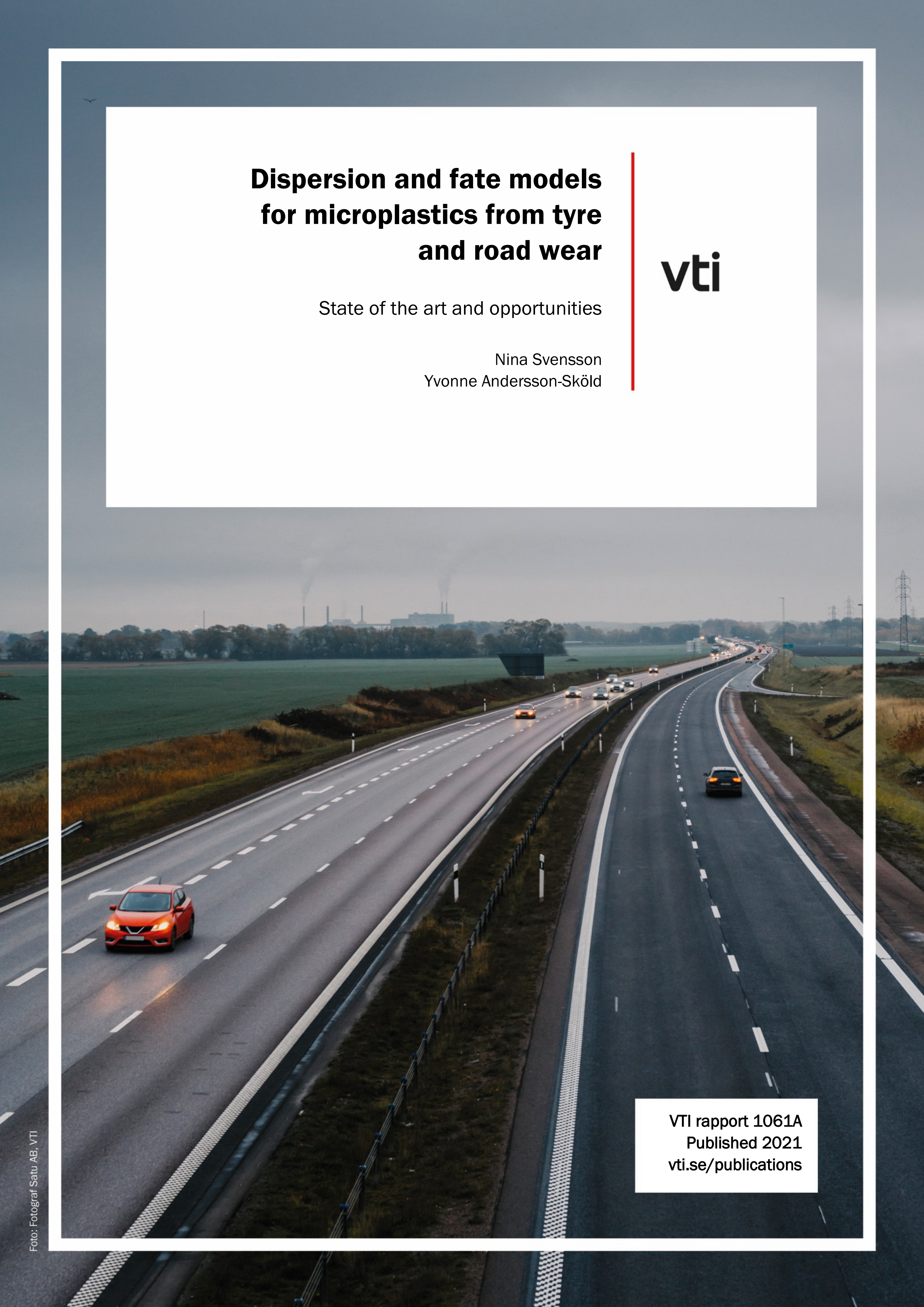

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State of the art and opportunities

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Kort sammanfattning

Mikroplast från däck- och vägslitage utgör en stor källa av föroreningar till naturen och mängden mikroplast i olika naturmiljöer och deras spridningsvägar är till stor del okända. I denna litteraturstudie presenteras modeller som kan användas för spridningsberäkningar av mikroplast i naturen och de befintliga studier som gjorts på detta område. Modeller för spridning i luft, dagvatten och sötvatten, mark och grundvatten, hav och kombinerad modellering i flera miljöer beskrivs.

Modellering av mikroplastspridning i luft är i nuläget möjligt med flertalet modeller. Hydrologiska modeller går också att användas kvantitativt för modellering i vattendrag, men behöver kalibreras mot mätningar. Nyligen har modeller specifikt för mikroplast i vattendrag och hav skapats, dock inte med fokus på däck- och vägslitagepartiklar. Markmodeller är ännu inte utvecklade för att kunna ta hänsyn till mikroplast, men här sker spridningen också långsammare.

Gemensamt för alla modeller är att det saknas indata i form av emissionsuppskattningar och att det behövs fler studier där det undersöks hur mikroplasternas specifika egenskaper (densitet, form, storlek) och processer (aggregering, nedbrytning, biobeväxning) påverkar transporten.

Nyckelord

Mikroplast, mikroplastspridning, mikroplast från däck- och vägslitage, atmosfäriska modeller, hydrologiska modeller

Abstract

Microplastics from tyre and road wear constitute a large source of pollutants entering the natural environment, and the amounts of microplastics in different environments and their dispersion in nature are to a large degree unknown. In this literature review, models that can be used for dispersion and fate modelling of microplastics in the environment are presented together with related available modelling studies. Models for dispersion in air, stormwater and freshwater, soil and groundwater, oceans, as well as combined models for multiple environments are described.

There are several models available for modelling of microplastic dispersion in air. Hydrological models can be used for quantitative modelling of pollutant transport in watercourses and groundwater. Recently, new models have been developed for modelling of microplastics in watercourses and the ocean, although these do not focus specifically on tyre and road wear. No models have yet been developed for modelling of microplastics in soil, but here the dispersion is also slower.

Common for all models is that better emission estimates are needed as input, and more studies of how the microplastic particles characteristics (density, shape, size) and the various processes (aggregation, degradation, biofouling) in different media affect the transport.

Keywords

Microplastics, microplastics transport, microplastics from tyre and road wear, atmospheric models, hydrological models

Sammanfattning

Mikroplaster har uppmätts i alla naturmiljöer: mark, vatten, luft, i polartrakter och i organismer. Förekomsten förväntas öka i alla miljöer och kunskapen om mikroplasters spridning är än så länge begränsad. Med de fortsatt stora emissionerna är det viktigt att kunna bedöma hur mikroplast sprids i naturen. Denna rapport beskriver kortfattat modeller för transport i luft, sötvatten och dagvatten, mark och grundvatten och hav samt kombinerad modellering i flera medier samt exempel från litteraturen av spridningsmodellering i olika medier. Fokus i rapporten är på mikroplast från däck- och vägslitage, vilket är en av de största utsläppskällorna av primär mikroplast. Utsläppen sker till den överlägset största delen från däckslitage och till en mindre del från asfalt som innehåller polymermodifierad bitumen och från vägmarkeringsfärg.

En mindre andel av mikroplastutsläppen från däck- och vägslitage avges till luft. Det finns många typer av modeller tillgängliga för att beräkna transport genom luft, från enklare plym- och puffmodeller som kan användas ett tiotal eller hundratal kilometer från källan, till mer avancerade trajektorie- och gridmodeller som kan användas på korta avstånd likaväl som globalt. Modellerna skulle kunna förbättras genom ökad kunskap om partiklarnas egenskaper i luft såsom storleksfördelning, sedimentationshastighet, aggregering med andra partiklar, nedbrytning etc. Endast några få studier av mikroplastspridning genom luft har utförts.

Den största andelen av mikroplastutsläpp från däck- och vägslitage sker till mark och vatten, men det är oklart hur förekomsterna fördelar sig mellan dessa medier. För spridning i sötvatten finns tidsupplösta hydrologiska modeller som beskriver hela den hydrologiska cykeln och vattenkvalitetsmodeller som beskriver transport endast i vatten. Hydrodynamiska tredimensionella modeller kan beskriva flödet med större noggrannhet i vattnet. Gemensamt för dessa modeller är att de behöver kalibreras och valideras mot mätningar, vilka i princip saknas för mikroplaster. Det finns också enklare steady-state-modeller som kan användas för ett stort antal vattendrag på upp till global skala. Några studier har utförts för att studera mängden mikroplast som transporteras till havet och hur partiklarnas egenskaper påverkar transporten. För att kunna beskriva transporten med större säkerhet behövs kunskap om hur mikroplaster med olika egenskaper (storlek, form, densitet) transporteras genom vattendrag och sjöar och hur de påverkas av andra processer såsom aggregering och biobeväxning. Den befintliga kunskapen behöver också implementeras i flera sötvattenmodeller.

Mikroplaster som hamnar på markytan kan transporteras långsamt nedåt och eventuellt nå grundvattnet. Transport genom mark och grundvatten kan beskrivas med modeller för transport i poröst material, men dessa modeller är inte anpassade för mikroplast, som har stora variationer i fysikaliska och kemiska egenskaper och i hög grad skiljer sig från de nära ideala partiklar som ofta studeras. Det finns också många processer som inte tas upp av dessa modeller, som transport genom sprickbildning, omblandning med hjälp av jordbruk eller djur. Mycket få modellstudier inom detta område har utförts.

Transport i hav sker på många olika sätt och kräver olika typer av modeller. Havet är ofta slutdestination för mikroplast från däck- och vägslitage som först transporteras genom mark, vatten och/eller luft och tenderar att sedimentera nära kuster.

Försök har också gjorts att modellera spridning genom flera medier. Nackdelen med dessa modeller är dock att de ännu inte kan förutspå transporten.

Sammanfattningsvis så finns det än så länge få modellstudier som beskriver mikroplasttransport i naturen och särskilt mikroplaster från däck- och vägslitage. Gemensamt för studier i alla medier är att det behövs:

- Fler och bättre mätningar. Mätstandarder behöver utvecklas så att studier blir jämförbara. Särskilt för tidsupplösta sötvattenmodeller behövs mätningar för kalibrering.

- Fler studier som inriktar sig på mikroplast med olika egenskaper (storlek, densitet, form, kemiska egenskaper).
- Fler studier om hur partiklarna förändras i naturen (aggregering, biobeväxning, nedbrytning etc.) och hur detta påverkar transporten.
- Bättre uppskattningar av emissioner och hur dessa fördelar sig mellan mark, vatten och luft.

Summary

Microplastics have been found in all environments: soil, water, air, the Polar Regions, and in organisms. Concentrations are expected to increase in all environments and there is limited knowledge on how microplastics disperse in nature. As emissions are expected to remain high, it is important to understand how microplastics are transported in the environment. In this report, dispersion and fate models for transport in air, freshwater, stormwater, soil, groundwater, and oceans, as well as combined modelling in multiple media are presented. The focus is on microplastics from tyre and road wear, which is one of the largest emission sources of primary microplastics. The emissions are mainly generated by tyre wear and, to a smaller degree, from asphalt containing polymer-modified bitumen and road markings, respectively.

A smaller fraction of the microplastic emissions from tyre and road wear is emitted to the atmosphere. There are many types of models available for air transport modelling, from simple plume and puff models which can be used tenth to hundreds of kilometres from the emission source to more advanced trajectory and grid models, which can be used at scales ranging from short distances from the source to globally. These models could be improved by increased knowledge of microplastic characteristics in air, such as size distribution, sedimentation speed, aggregation with other particles, degradation etc. Only a few studies on microplastic transport in air have yet been published.

The largest fraction of microplastic from tyre and road wear is emitted to soil and water, however it is not known how emissions are distributed between these media. Freshwater models include time-resolved hydrological models which describe the full hydrologic cycle, and water quality models which describe the transport in water only. Three-dimensional hydrodynamic models can be used to create a detailed description of the flow. All these models need to be validated against measurements, which are very scarce for microplastics. There are also simpler, steady-state models which can be used for a large number of watercourses, up to global scale. A few studies have looked at the amounts of microplastics that reach the sea, and how the particle characteristics influence the transport. To be able to describe this transport more accurately, knowledge of how microplastic characteristics (size, shape, density) influence the transport in both watercourses and lakes is needed. Knowledge on how the microplastics are affected by other processes, such as aggregation and biofouling, is also required.

Microplastics that end up on land surfaces can be transported slowly downwards and possibly reach the groundwater. Transport through soil and groundwater can be described by models for transport in porous materials, however these models are not adapted to microplastics, which have large variations in physical and chemical characteristics and frequently vastly different from the ideal particles which are often studied. There are also many processes which are not handled by these models, such as transport through cracks or turbation caused by farming or animals. Very few modelling studies of microplastics in soil have been performed.

Microplastics can be transported by different processes in the ocean, and different types of models are required to describe this. The ocean is often the final destination for microplastics from road and tyre wear, after transportation through soil, water and air and tend to settle in sediments close to coastlines.

There have been attempts to perform combined transport modelling through multiple media. The disadvantage is that they cannot yet be used to predict particle transportat.

In summary, there are so far few modelling studies describing microplastic transport in nature, and in particular microplastics from tyre and road wear. Research needs for modelling in all media include:

- More and better measurements. Measurement standards need to be developed for model validation. This is especially true for time-resolved freshwater models.
- More studies of microplastics characteristics (size, density, shape, chemical characteristics) and how the characteristics affects the transport in different media.

- More studies of how particles are transformed in nature (aggregation, biofouling, degradation etc.) and how this affects transport.
- Better emission data and data on how emissions are partitioned between soil, water and air.

Foreword

There is limited knowledge regarding microplastics, and in particular microplastics from road traffic. At the same time, tyre wear particles are deemed to be the biggest source of microplastic emissions in Sweden. For this reason, the Swedish government asked the National Road and Transport Research Institute (VTI) to develop and disseminate knowledge about microplastics from road traffic in 2018–2020. This knowledge compilation is one part of that task. The purpose of this report is to collate information about dispersion models for microplastics.

Stockholm, October 2020

Nina Svensson
Project leader

Granskare/Examiner

Ekaterina Sokolova, Chalmers.

Innehållsförteckning

1. Introduction

Microplastics have been found in in all environmental compartments; oceans, lakes, watercourses, land, air, and even in Polar Regions and in organisms [1]–[3]. Microplastics which are defined as plastic particles smaller than 5 mm, can be released into the environment either as primary or secondary microplastics. Primary microplastics refer to plastics which are already micro-sized at the time of release, whereas secondary microplastics are formed as larger plastics and later decomposed. Large amounts of plastics are manufactured in all segments of society and the residues frequently end up in the natural environment, in the shape of microplastics. As an example, 359 million tons of plastics were produced globally in 2018 [4] and a large part of this ends up in the environment. Road traffic has been identified as one of the main sources of primary microplastic emissions [5], [6].

Traffic related microplastics are generated from both tyre and road wear, of which tyre wear is the significantly greater source [7]. 19 million tyres were manufactured globally in 2019, and the tread of a tyre is expected to wear down over a few years. The majority of tyre residues end up in the environment, either directly or via treatment plants for storm or wastewater.

In Sweden, microplastic emissions from road traffic take place all over the country and enter all types of natural environments. Attempts have been made to quantify the sources of microplastics from road traffic [6], however very little is known about the amounts that spread to the different environmental compartments, how they are transported within and between different compartments, and where the microplastics finally end up [1], [8], [9].

Using models, these aspects can begin to be understood, in the same way as have been done for several other types of pollutants. A limited number of modelling studies of microplastics have been carried out, mainly to study transport in oceans, but there are also a few studies on transport in watercourses, sediments, soil, and air [2], [3], [10]. Studies have so far focused mainly on transport in open waters and via watercourses to the oceans. Lately, there has also been an increased interest in other potential transport routes.

Very few models have been adapted to, calibrated for, and evaluated against measurements of microplastics in different media and environmental compartments, and many of the physical characteristics of these particles, including their shape and density, or chemical characteristics that impact their behaviour in air, soil and water, have not yet been studied.

The purpose of this report is to provide a brief description of existing models that could potentially be used to calculate the dispersion of microplastics from tyre and road wear in different environmental compartments, and give examples of studies where these have been used. There are also other types of models, each used to study a specific phenomenon, such as biofouling or sedimentation, the findings of which may provide important input data or offer supplementary information to the more general dispersion models described here. Many of the presented studies relate to microplastics in general, not solely microplastics from tyre and road wear, as there are hardly any studies specifically about this topic.

The report begins with a brief summary of the sources, prevalence and spread of microplastics from road and tyre wear. This is followed by descriptions of models that can be used to estimate dispersion, divided into sections based on the different media in which microplastics from road and tyre wear can be present and spread: Section 3, Air, Section 4 Stormwater and freshwater, Section 5 Soil and groundwater, Section 6 Oceans, and Section 7 Combined modelling for multiple environments. Discussion and conclusions are presented in Section 8.

2. Sources, presence and spread of microplastics from tyre and road wear

Emissions of microplastics from tyre and road wear are mainly generated due to the friction between the tyre and the road, which causes the tread to wear down. The tread is the part of the tyre that provides grip and traction against the road surface [11]. To a lesser extent, microplastics are also emitted from asphalt containing polymer-modified bitumen, and from the paints used for road markings, as these are worn down by traffic.

Different studies have shown that the size of the microplastic particles from tyre and road wear varies between 100 nm and hundreds of µm [11], which means that they can spread in many different ways and in different media. The particle density also differs between pure tyre particles, and tyre and road wear particles, which contain a mixture of rubber and stone materials from the road. This impacts particularly how far the particles are transported in water. Microplastic particles in general come in many different shapes, from round to fragments to fibre-like etc., and their shape has a significant effect on how they are transported in different media. It has been shown that microplastics from tyre wear are elongated or curled black rubber elastomers[12], [13], which are fully or partially covered in, or form aggregates with, smaller particles [12], [14] also in air [14]. This means that their characteristics (shape, density, toxicity, and degradability, etc.) change.

Microplastics generated as a result of the contact between a tyre and the road surface either enter the air immediately or remain on the road surface. Only a smaller proportion is released into the air. According to a report by Grigoriatos and Martini (2017) [15] 0.1–10 percent of the generated tyre wear particles are released as airborne PM_{10} (particles < 10 µm), although some studies have reported values of up to 30 percent. Runoff from roads in urban environments often enter stormwater systems, where rain and meltwater from hard surfaces such as buildings and streets are either led straight into surface water recipients (watercourses, lakes or oceans) or to a stormwater facility. Some of the stormwater is lead to a wastewater treatment plant, after which a significant portion of the microplastics remain in the sewage sludge. Sewage sludge used as fertilizer can therefore be a source of microplastics on farmland. Pollution transported by runoff from roads outside urban areas often end up on the side of the road, in ditches, or in stormwater facilities, although the actual amounts are still unknown [7]. The most common stormwater facilities in Sweden are ditches, dams and vegetated filter strips [16]. Snow masses stored on land or dumped in water can also contain microplastics, which are then dispersed to other recipients in the area. Microplastics that enter watercourses can be transported to the ocean, but are mostly expected to settle on route. Tyre wear particles are often aggregated to road wear materials (stones and bitumen), which have a higher density than pure tyre wear materials, why a sizeable proportion is expected to be present in sediments [17]. For this reason, sediment transport may also be an important, if slow, route of dissemination to recipients downstream. Some transport within the soil layer may also occur, both horizontally and vertically [18]. Microplastics can also be absorbed by plants [19], animals, and potentially even humans [1], [20].

Few studies have specified the amounts of microplastics from tyre and road wear being released into different environmental compartments, although a few estimates have been made for tyre wear in general. An estimation from the Netherlands claims that 12 percent of the tyre wear particles released from roads end up in the air, 67 percent on land, 12 percent in water, and 9 percent remains in sewage pipes [21]. Sieber et al. (2019) [22] estimated that 74 percent of the total annual emissions of rubber particles from tyres in Switzerland landed within 5 metres of the roadside, 22 percent ended up in watercourses and lakes, and 4 percent in other areas on land. There are obviously differences between different studies regarding a number of aspects, however the overall conclusion suggests that a large proportion of particles from tyre and road wear settles on land or in freshwater, which shows the importance of studying emissions, occurrence in different medias and dispersion routes, as well as sinks in these systems.

The amounts of microplastics being emitted from tyre and road wear depend on vehicle type, asphalt type, speed, tyre type, driving style, etc. As an example, tyre wear increases with higher loads, speeds, acceleration, , and decreases with increasing tyre diameter and width of the tyre tread [11]. Asphalt and painted road markings are worn down by traffic, and the use of studded tyres by a significant proportion of vehicles, as well as maintenance tasks, such as snow clearing, accelerate the process.

Estimations of tyre emissions are often based on estimations of traffic volumes in combination with wear factors for tyres, or on estimations of the number of sold and recycled tyres, combined with weighing of tyres after use. The focus of this report will not be on how the emissions can be calculated, but on how their dispersion and fate after emission can be calculated using different models.

3. Transport in air

Only a smaller portion (~10%) of microplastic emissions from tyre and road wear is emitted into the air, however this fraction can be transported long distances from the source, why it is important to describe it. Hardly any modelling studies looking at atmospheric transport of microplastics have been carried out.

3.1. Sources and transport processes

The sources of airborne microplastics from tyre and road wear comprise both emissions generated in the contact between the tyre and road surface, and released straight into the air, and those released from the road surface due to winds or vehicle-generated turbulence [11]. Particles can also be released from other surfaces where they have gathered. How the particles are further transported depends on their density, size, and shape, as well as on atmospheric motion, i.e., wind speed, wind direction, temperature etc. and the ways in which they are distributed horizontally and vertically in the atmosphere. Meteorological processes occur at different scales. Local wind patterns, such as sea breezes, are caused by variable warming of different surfaces and have a time scale of hours or days (spatial scale of 5 to around 100 km). Local wind patterns are affected by the texture and heat capacity of the surface, the topography, and local structures. Regional wind patterns, such as fronts, have a scale of up to a thousand kilometres and a time scale of tens of days, and can travel vast distances across land.

Global circulation patterns emerge as a result of the heat distribution from the equator to the poles, and have a time scale spanning months. Wind patterns of different scales combine to form the local meteorological conditions. Once the particles have been transported through the air, they can fall out through wet or dry deposition, which depend on for example cloud and precipitation processes, and particle characteristics.

Microplastic particles of many different sizes can be transported through the atmosphere. Although measurements of airborne particles usually consider particles smaller than 10 µm, microplastic particles from atmospheric deposition have also been found in significantly larger sizes [23]–[25].

While being transported through the atmosphere, microplastics from tyre and road wear can also aggregate with other types of particles. Additionally, UV light can degrade the particles and affect their transport properties.

3.2. Types of models

Many types of models can be used to simulate transport through air, from simple ones to more advanced. In this report, models are divided into plume and puff models, grid models, and trajectory models, although the boundaries between the different types are not always clear.

3.2.1. Plume and puff models

Plume models are used to estimate the dispersion of emissions along a symmetrical plume originating from the source. The plume extends in the wind direction and widens depending on the turbulence of the atmosphere. Plume models assume that the wind direction and weather conditions remain the same as they were at the time of emission throughout the dispersion process. As this assumption is only reasonable for a limited period of time, these models should only be used for simulation of dispersion over a few hours or tens of kilometres. Examples of plume models include ADMS (Atmospheric Dispersion Modelling System) [26], AERMOD (American meteorological society/Environmental protection agency Regulatory MODel) [27], Airviro Gauss [28], [29], DEGADIS (DEnse GAs DISpersion model) [30], ISC3 (Industrial Source Complex) [31], and OML (Operationelle

Meteorologiske Luftkvalitetsmodeller) [32]. Of these, AERMOD, DEGADIS and ISC3 are freely available.

Puff models regard emissions as puffs rather than plumes, and can also take into account meteorological variations over time, why they can be used for distances of up to approximately 100 kilometres from the source. These models often use wind data in a three-dimensional grid. Examples of puff models include CALPUFF [33], RIMPUFF (RIsø Mesoscale PUFF model) [34], SAFE AIR (Simulation of Air pollution From Emissions Above Inhomogeneous Regions) [35], and SCIPUFF (Second-order Closure Integrated PUFF model) [36]. Of these, CALPUFF and SCIPUFF are freely available.

The sources considered in calculations using plume and puff models can be point, line, area, or volume sources, and the number of sources is often limited. These models require input from a meteorological model or weather observations. The models take into account a varied number of effects that may impact the dispersion, such as the ground reflection of the plume, inversions, wet and dry deposition, complex terrain and the effect of buildings.

Most of these models simulate lightweight gases that follow the winds, however some, e.g. DEGADIS, have been adapted for gases or particles with a density that is higher than the density of air.

Some plume models have been combined with traffic models to calculate emissions as a function of traffic volume, speed, vehicle type, meteorological conditions, etc. close to the road. Examples include HYROAD (HYbrid ROADway model) [37] and CAR-FMI (Contaminants in the Air froma Road) [38].

Advantages of plume and puff models include that they do not require much computer power and are relatively easy to use and interpret. The disadvantages include that they do not work well in low winds, unstable air stratification, or complicated wind conditions. They also do not take into account background concentrations that have built up over a longer period of time.

3.2.2. Grid models

Three-dimensional grid models are used to enable more detailed estimation of the dispersion. These models can also have different levels of complexity.

Meteorological grid models (also known as weather forecasting models) usually consist of a grid covering a bigger or smaller area. Equations for three-dimensional motion, continuity and thermodynamics are calculated for each cell in the grid. These can also include a greater or smaller number of parameterised processes, such as cloud physics and turbulent transport. The models are then connected to, or have an integrated, transport model for air pollution, used to calculate advection, dispersion, and deposition of selected air pollutants. The models can be used at scales from a few square kilometres to global, and for different time periods. Input for the initial state and the sides of the model domain can be retrieved from a global model. There are a number of prepared, historical datasets, so called reanalysis datasets, which can be used for this purpose. Examples of weather forecasting models with inbuilt pollution transport models include C-IFS (atmospheric Composition-Integrated Forecasting System) [39], COSMO-MUSCAT (COSMO-MUlti-SCale Atmospheric Transport) [40], [41], GEM- MACH [42], [43], TAPM [44], and WRF-Chem (Weather Research and Forecasting-Chemical transport model) [45]. Of these, COSMO-MUSCAT, GEM-MACH and WRF-Chem are freely available. Models of this type are, however, much more complicated and time-consuming to run. They also require a lot of experience.

Examples of chemical transport models that can be used independently based on inputs from weather forecasting models include CAMx (Comprehensive Air Quality Model with extensions) [46], CHIMERE [47], EMEP (European Monitoring and Evaluation Programme model) [48], MATCH

(Multi-scale Atmospheric Transport and CHemistry)[49], TCAM (Transport Chemical Aerosol Model) [50], and TM5 [51]. Of these, CAMx, CHIMERE, EMEP, and TM5 are freely available. One advantage of these models is that they can be applied using previously completed simulations as input, which saves time. Chemical transport models can be used at scales ranging from tens of kilometres to hundreds or thousands of kilometres from the source.

3.2.3. Trajectory models

Trajectory models are models whose calculations relate to individual, theoretical particles being transported through the atmosphere by wind and dispersion, which means that their positions can be calculated with high accuracy. The models can be used to calculate both forward and backward trajectories, i.e. the trajectories can either start from the source and follow the particles forward in time, or start from an endpoint and follow the particles backwards in time to identify potential source areas. Puff models are a form of trajectory model, which follow puffs rather than individual particles and often use simplified meteorological data.

Particles are transported within a three-dimensional grid containing meteorological variables produced by a weather forecasting model. Trajectory models can be used at any scale, from close to the source to global. The models can often be used to describe dry and wet deposition.

Examples of trajectory models include FLEXPART (FLEXible PARTicle dispersion model) [52], HYSPLIT (HYbrid Single Particle Lagrangian Integrated Trajectory model) [53]–[55], NAME (Numerical Atmospheric disperson Modelling Environment) [56], and STILT (Stochastic Time-Inverted Lagrangian Transport model) [57]. HYSPLIT can be used to model both puffs and particles. Of these, FLEXPART, HYSPLIT, and STILT are freely available. One example of a combined grid and trajectory model is HYPACT (HYbrid PArticle and Concentration Transport model), which simulates trajectories close to the source, where high resolution is important, and switches to a grid model further away from the source. This model is also freely available.

The advantage of trajectory models is that they work well even at low wind speeds and under complex meteorological conditions, and that they provide almost unlimited resolution. Trajectory models can be applied to good advantage to existing meteorological simulations. Disadvantages include the need for large numbers of particles to estimate how a plume would disperse, and the fact that the simulation time increases as the number of particles increases.

3.3. Discussion

The small number of modelling studies that have been carried out to study the dispersion of microplastic particles in air have used HYSPLIT to identify potential sources [58]. One reason for this may be that very few measurements of microplastics in atmospheric depositions are available, as research has mainly focused on microplastics in the oceans, and to some extent in freshwater and on land. However, lately the interest in airborne transport has increased, as studies have shown that microplastics are present even in remote places, far from any sources [23], [59].

One of the difficulties of modelling microplastics is that there are very few measurements to validate the results against, in particular when it comes to tyre and road wear particles. Additionally, there is limited information regarding the location and size of the sources. Many small sources are often more difficult to model than one large source. Modelling of atmospheric transport of microplastic from tyre wear should be fairly easy to perform using existing models. To be able to describe these transport processes in more detail will, however, require further research into a number of processes. There is for example little knowledge about how the shape and size of microplastic particles affect the transport, about how they change in the air through aggregation and degradation, and how effective microplastic particles are for ice nucleation [58].

4. Transport in stormwater and freshwater

Microplastics from tyre and road wear can end up in freshwater via a number of different transportation routes, and once there, may travel a longer or shorter distance further. A limited number of modelling studies have looked at transport of microplastics in freshwater systems. The objectives of these studies have been to investigate the amount of microplastics being transported via rivers to the ocean, or how much settles along the way [9]. There are almost no studies on transport in stormwater systems.

4.1. Sources of microplastics to stormwater and freshwater

Both the emissions and continued dispersion of microplastics from tyre wear to stormwater and freshwater systems depend on traffic volumes, speeds, driving behaviour, and the properties of the road surface [11]. As an example, the size of the cavities in the asphalt influences how much dust remains on the road surface [21]. Further spread also depends on the meteorological conditions. When the road surface is damp, particles are emitted through splash and spray from moving cars and end up either in watercourses or on the ground close to the road. During precipitation or snowmelt, water runs off from the road surface, bringing with it dust from the road. Heavier precipitation or faster melting result in greater flows, which can transport particles further from the source and remove even particles that have been present on the road surface for a long time. This means that both the volume and intensity of the precipitation are important factors that influence the number of particles emitted to stormwater and freshwater. Particles collecting in watercourses near the road or in stormwater systems can travel further, eventually reaching larger watercourses, lakes and oceans, or even stormwater facilities. Additional inputs to storm and freshwater systems come via groundwater or runoff from contaminated land, and via the air through dry and wet deposition.

4.2. Transport processes in freshwater systems

The way in which microplastics disperse in freshwater systems depends on a number of factors related both to the characteristics of the particles and to the freshwater system in which they are transported. Particle characteristics, such as size, density, shape, and porosity, determine how they are transported in water, as well as if and when they settle [9]. Particles with a density lower than that of water tend to float, while those with a higher density tend to sink and therefore not travel as far. Microplastics from tyre wear have a density similar to that of water, either just above or just below [11], whereas particles found on roads are often aggregates and also contain asphalt materials (stone and bitumen), which means that they have a higher density and are more likely to settle [17]. The shape of the particles also affect the speed at which they settle [60].

The flow rate, bathymetry, density of the water, etc. influence how the particles are transported in the water [2]. At high flow rates, particles that have settled may again become suspended and follow the water. During flooding, microplastic particles can be washed onto land and settle there. In dams and lakes, the water movement is much slower than in streams and rivers, increasing the likelihood of particles settling and collecting in immobile sediments. Microplastics may also be transported with the sediment [61].

In water, microplastic particles can aggregate with themselves or with other organic materials, thereby changing their size, shape, and density. Particles can also be affected by biofouling, which means that organisms stick to the surface of the particles, creating a film covering the surface and altering their size and density [2].

4.3. Types of models

Hydrological models are available in many different versions. These can include varying numbers of processes, and have different levels of detail and geographical coverage. A limited number of modelling studies have investigated transport in freshwater systems in different ways. The models used differ, from very simple steady-state models to hydrodynamic models in three dimensions, as well as one model combining transport across land and in water. These models are presented here together with examples of other models that could potentially be used to calculate dispersion of microplastics.

Models can be categorised in a number of different ways, however we have here chosen to divide them into steady-state models, hydrological transport models, water quality models, and three-dimensional hydrodynamic models.

4.4. Steady-state models

Steady-state models are simple non time-resolved models that use spatial resolution and are mainly based on estimations of the size of sources and effects of processes, rather than on physical relationships, which means that they can be used to model many different types of watercourses, up to global scale. Two examples of such models are GLOBAL-FATE [62] and Global NEWS (Global Nutrient Export from WaterSheds) [63].The former is designed for modelling of pharmaceuticals and the latter for modelling of for example nutrients. Of the two, GLOBAL-FATE is freely available.

Two studies in which steady-state models were used to estimate the transport of microplastics are presented here; one by Siegfried et al. (2017) [64] and one by van Wijnen et al. (2019) [65]. Both are based on the Global NEWS model. This model uses data on land use, socioeconomic data, and hydrological data as inputs from underlying models. Microplastics are only emitted as point source emissions from wastewater treatment plants, and calculated based on the average emissions of microplastics per capita in the area, the proportion of households connected to a treatment plant, and the treatment plants' removal efficiency for microplastics. The proportion of microplastic particles caught in the sediment on their way towards the ocean is set to a simplified factor that varies for a few typical particles and is also dependent on the length of the river. The amount that finally reaches the ocean also depends on the amount of water being extracted from the studied watercourse.

Siegfried et al. (2017) performed a modelling study describing transport of microplastics from wastewater treatment plants, via all European rivers to the oceans they join. Microplastics from 4 different types of direct sources to watercourses were simulated: personal care products, household dust, textiles, and tyre and road wear. The results offer an estimation of the annual flow of microplastics from the rivers of Europe to the oceans, under current conditions and for different future scenarios. They show that particles from tyre and road wear are the main source of particles entering the oceans, despite the fact that only point source emissions from wastewater treatment plants were considered and not diffuse sources, which are believed to be significantly larger.

Van Wijnen et al. (2019) have presented an updated version of Global NEWS, called GREMiS (Global Riverine Export of Microplastics into Seas). The study covered microplastics from personal care products, textiles, and tyre wear from direct sources, such as wastewater treatment plants, as well as microplastics formed as a result of fragmentation of macroplastics within the watercourses as a diffuse source. The model was applied at the global scale, to estimate the total emissions of microplastics to the oceans. This study showed that microplastics formed from macroplastics are the main source of emissions into the oceans and that tyre wear is the second biggest. There are some regional variations, tyre wear is for example an important source in the OECD countries, whereas microplastics generated from macroplastics is the dominating source in Africa, however fewer households in Africa are connected to common wastewater systems, which means that the direct sources are probably underestimated.

Advantages of this type of models include that they can be used both for continents and globally, to give large-scale estimates of the magnitude of the emissions to the oceans from different sources, and that they can also be used to investigate trends over time. Disadvantages include that they do not describe individual processes, but are based on very general assumptions and therefore cannot be used to understand transport processes, particle characteristics, etc.

4.5. Hydrological transport models and water quality models

Hydrological models describe water conditions and flows based on a number of different meteorological and hydrological parameters, such as precipitation, evaporation, runoff, and infiltration in one or a number of catchment areas. The models can take into account a large, or small, number of processes. They usually include modules for calculating soil moisture, snow accumulation, snowmelt, and groundwater levels and for describing the route the water takes within the catchment area, but may also consider further processes, such as transport of pollutants, nutrients, or sediment. In these models, the water flow is one-dimensional.

The models differ in for example scale, description of land areas, the hydrological processes considered, the way in which the catchment area is segmented, and the amount of input required. Examples of models include: AnnAGNPS (Annualized AGricultural Non-Point Source Pollution model) [66], GSSHA (Gridded Surface Subsurface Hydrologic Analysis) [67], HEC-HMS (Hydrologic EngineeringCenter-Hydrologic Modeling System) [68], HSPF [69], HYPE (HYdrological Predictions for the Environment) [70], MIKE SHE [71], and SWAT (Soil and Water Assessment Tool) [72]. Of these, all except MIKE SHE are freely available.

Water quality models (or so called fate models) are models which focus on transport of different types of pollutants in watercourses, but do not describe the entire hydrological cycle. These models require inputs from hydrological models or measurements/estimations of the water flow. Examples of this type of model include STREAM-EU (Spatially and Temporally Resolved Exposure Assessment Model for EUropean basins), which can be used to simulate transport of organic compounds and WASP (Water quality Analysis Simulation Program), which can be used to simulate a number of different pollutants, including nitrogen, phosphorus, metals, and pathogens.

A model study by Besseling et al. (2017) [73] adapted the model NanoDUFLOW, which is a water quality model for nanoparticles, to the modelling of microplastics. The model takes into account advective transport, aggregation, sedimentation, resuspension, degradation and storage in sediment of microplastic particles. The studied watercourse was divided into a number of stages, for which average characteristics were used. The study in question used a domain consisting of a 40-kilometre long stretch of the Dommel River in the Netherlands, which included a sedimentation basin and a number of dams. A constant flow of spherical microplastic particles were released upstream and no precipitation events or other weather events were simulated. The model was then used to calculate concentrations of microplastics in water and sediment along the river stretch. Their findings show that the factor that most influences the distance particles travels is their size. As an example, all particles bigger than 100 µm settled within a few kilometres of the point of release, whereas smaller particles spread along the entire length of the 40-kilometre long stretch of the river. The bigger the particles, the greater the proportion that aggregated to other particles. Aggregation to particles of the same sort was, however, negligible for all sizes. Where the particles settled depended to a large extent on the width, flow rate and depth of the river. The particle density impacted mainly medium-sized particles.

Nizzetto et al. (2016)[74] have presented a study in which the INCA-Contaminants model, a hydro-biogeochemical sediment model, was adapted for modelling of microplastics. The resulting method can be used to model transport of microplastics or other chemicals/pollutants in a drainage system. The studied river is divided into a number of stages, which include their respective catchment areas. Flows are calculated based on the average gradient in the area, vegetation, and land use. Microplastics can be added either via the ground (e.g. to simulate the spreading of sewage sludge on agricultural land) or via direct sources to the water flow (e.g. to imitate a wastewater treatment plant). Wet deposition can also be included.

With INCA-Contaminants, soil transport processes are simulated in a simplified way, with two soil layers, an overlying organic layer and an underlying mineral layer. Within, between and from these layers, transport can occur through diffusion, advection, bioturbation, and runoff. This means that particles can enter streams and rivers both from soil layers and from the surface. Runoff and water flow are calculated using a hydrological model based on climate data. The watercourses consist of a water column and two sediment layers. Microplastics are transported via advection in the water, diffusion between different parts of the system, settling and resuspension from sediments. The study simulated microplastic particles of a number of sizes and densities that are commonly occurring, in the River Thames. The model was calibrated against measured water flows and the presence of natural, suspended sediment to ensure it reflected reality as accurately as possible, however it was not possible to perform calibration or validation against microplastics, as neither the sources nor amount of microplastics in the estuary were known. The model does not consider biofouling or particle aggregation.

One aim of the study was to investigate how much of the microplastic emissions to soil and freshwater remain in the soil and sediment, respectively, rather than continue their journey into the sea. The results showed that 16–38 percent of the microplastics entering the soil remained there, while the rest carried on into the water system. Almost 100 percent of all particles larger than 0.2 mm, and with a density above 1,050 kg/L, remained in the sediment, whereas smaller and lighter particles continued to the sea. Size had a greater impact on transport than density. The model also gave information on the effect of flow rate on particles of different sizes and densities.

4.6. Three-dimensional hydrodynamic models

Models that calculate water flow transport, based on physical relationships, are known as hydrodynamic models. The models described in the previous section are one-dimensional in the flow direction. Three-dimensional hydrodynamic models can describe the flow within a watercourse or lake with high resolution. Models include MIKE modelling tools, such as MIKE 3 FM (DHI, 2009), TELEMAC [75], and Delft3D [76], of which TELEMAC and Delft3D are freely available.

A modelling study by Bondelind et al. 2018 [77] applied a three-dimensional hydrodynamic model, MIKE 3 FM, to a 16-kilometre long stretch of the river of Göta älv, close to its mouth, to simulate how microplastic emissions from stormwater are transported and settle along this part of the river. Other effects, such as re-suspension from sediment, biofouling, aggregation, and degradation were not considered. The model had a resolution of 20–30 metres horizontally and 1 metre vertically. The flow was dynamically estimated, based on measurements of the water flow in the river and the water level in the sea. This type of model can provide a very accurate description of the transport of microplastics, with high resolutions in both time and space. The disadvantage of this model, which is in common with most other models, is that there is a lack of measurements to verify against, and that the calculations are based on assumptions regarding the shape and density of microplastic particles.

4.7. Stormwater models

Stormwater is defined as rain and meltwater running off from hard surfaces like buildings and streets. Stormwater systems can consist of underground pipes, or be designed as open systems, and lead the water to canals and dams. A number of different models are used for assessments and analysis of stormwater systems.

SWMM (Storm Water Management Model) [78]–[80] is a hydrological, dynamic transport model, adapted to modelling of stormwater systems. It considers hydrological processes such as precipitation, evaporation and soil transport, but also transport through pipe systems, including different types of system components, like pumps etc. However it does not take into account particle-specific processes like sedimentation, aggregation, etc. within the flow.

StormTac [81] is a simple, steady-state model used to describe water quality in recipients, such as lakes and watercourses, based on the incoming flows (runoff, stormwater, groundwater, deposition) of a large number of different pollutants within a catchment area, including the option to describe the design of a stormwater system. WinSLAMM (Source Loading and Management Model for Windows) [82] is a distributed, time-resolved model for calculation of runoff volume and particle content in urban environments.

SWNano (Sewer-Water Nano) [83] has recently been developed to describe the transport of anthropogenic nanoparticles in a stormwater system. It is a detailed, dynamic model that requires a lot of inputs and describes the flow of particles through the grid, both in water and sediment, based on advection as well as diffusion. The model also considers homo- and heteroaggregation, sedimentation and resuspension from sediments.

4.8. Discussion

Many hydrological models and water quality models are available at present, and many studies have looked at other pollutants, at varying scales, and using different approaches. In particular, there is a lot to learn from modelling studies of nanoparticles, which are assumed to share certain characteristics with microplastics.

A major problem for microplastic modelling is that there is very little continuous measurement data from stormwater systems and watercourses to validate the models against, which is necessary to ensure that the results reflect reality. There are no standardised methods for measuring microplastics, and even less so for tyre and road wear particles in water, making it difficult to compare findings from different studies and to validate models against the available studies. There is also limited knowledge regarding the emissions and geographical locations of emissions. Consequently, more continuous measuring is required, and standardised methods need to be developed to enable more accurate dispersion modelling, so that we better can evaluate expected levels in, and exposure from, soil, water and air.

Very little is known about the way in which the characteristics of microplastic particles, such as shape, size and density, affect their transport in water, and about the impact of degradation and biofouling on these characteristics. This lack of knowledge applies to most sources of microplastics, including tyre and road wear. This means that more studies are required in this area, both in laboratories and in the field, using different modelling tools. Existing knowledge about microplastics also needs to be implemented in more hydrological and water quality models.

5. Transport in soil and groundwater

A significant portion of the microplastic emissions from tyre and road wear end up in or on the ground. Very few studies have looked at occurrence and dispersion of microplastics from tyre and road wear in soil and groundwater. A small number of these are presented below.

5.1. Occurrence and sources

Microplastics in soil layers near the surface have been measured in a number of studies, however there is still a lot of uncertainty regarding current levels [84]. Much less research have been carried out on microplastics in soil than on microplastics in oceans [85]. Estimations based on plastic use in Europe suggest that the amount of microplastics released into land areas (soil and freshwater) is 4–23 times higher than the amounts released into oceans [2]. This estimate does not include microplastics from tyre and road wear, however it is deemed likely that these mainly end up on land, and that only a smaller portion is transported to the sea. As a sizeable proportion of the tyre wear is emitted as relatively large particles (>20 µm) and expected to be present as aggregates with road materials (stone and bitumen with higher densities than the tyre wear) it is likely that a significant portion of these particles can be found on the ground or in watercourses (and their sediments) close to the road [15]. In addition to entering the ground via runoff from the road surface during precipitation or snowmelt, a wet road surface can also emit particles via splash and spray caused by moving vehicles. Microplastics from tyre and road wear can also end up in soil in a different location, as part of snow masses being moved to depositing areas, where they melt. Road cleaning measures, such as street sweeping, can also cause particles to be deposited on the side of the road. Another source is microplastics introduced to the soil via sludge from wastewater treatment plants or at the final storage places for masses/sediment from stormwater facilities. Another source of microplastics from tyre and road wear is dry and wet deposition through the air, which can lead to particles being present even quite a long distance from the road.

When microplastics are transported through soil there is a risk that they reach the groundwater, from where they can travel further as part of the groundwater flow, reducing the water quality in watercourses. Only a small number of studies have shown microplastics in groundwater and where they are present, it is unclear whether they have been transported there via soil or wastewater from households [85].

5.2. Transport and degradation processes in soil

As soil consists of small granules, interspersed with voids, fluids can be transported vertically through the ground. Particles suspended in water can therefore be transported by the fluid both in the unsaturated, vadose zone, and in the saturated zone, i.e. the groundwater zone. Many experiments have looked at the transport of microplastics through porous materials, most commonly sand or glass beads [86].

Several factors impact the transport of particles through the pore water in soil, including the flow rate of the water and its ionic strength, the size and type of soil particles, the pH of the soil, the roughness of the surface, and the shape, size, hydrophobicity, and chemical composition of the particles [86], [87]. A number of secondary factors can also aid transport in soil [84], [86]. One example is agriculture, where ploughing in particular causes agitation, which can result in particles close to the surface being moved downwards. A few studies have shown that microplastics can be transported downwards in soil by animals, such as worms, moving particles that stick to them when they dig, or as a result of consumption and excretions. Microplastics and other particles can also adsorb to and be desorbed from the surface of grains of soil. In addition, transport can be affected by the growth, water uptake and degradation of plant roots. UV rays from the sun can cause degradation/fragmentation of particles on or close to the earth's surface, resulting in the formation of smaller particles, which can be transported through the soil more easily. Degradation can also be performed mechanically or by oxygen. Other aspects that may affect transport include draught, which may cause cracks through which microplastics and other particles can be transported more easily. Microplastics can also be suspended from the ground surface and transported by erosion caused by wind or water. Microplastics can also be absorbed by plants and animals, which may have an adverse effect on the plant or animal, as well as allow movement further up the food chain [18].

5.3. Types of models

The transport of particles, including microplastics, in soil and groundwater is mainly studied using transport models for porous media in localised areas. For larger-scale studies, hydrological models may be used.

5.4. Models for transport in porous media

Models for transport of colloids, i.e., nano- or micro-sized particles, in porous materials have been developed and used to study for example how bacteria, viruses and nanoparticles are transported vertically through soil [88]. When colloids are suspended in water, they are able to follow the downwards flow of the water through the soil.

Models of this type are based on descriptions of how particles are transported through the voids in the ground via advection (outer forces, such as water flows), dispersion (spreading between the soil granules), diffusion (due to differences in concentration), and filtration/retention in the soil [89]. Filtration occurs when particles come into contact with, or are close to, the surrounding soil granules and stick to their surface [90]. Whether or not the particles stick depends for example on electrostatic forces, dipole forces, and London-van der Waals forces. Hydration and hydrodynamic, hydrophobic, and steric interactions also have an effect [91]. There are also models at pore-scale, which calculate the forces on individual particles to study processes in more detail.

Transport within the unsaturated (vadose) zone and the saturated (groundwater) zone can more or less be described by the same processes, the difference being that the water flow is smaller in the vadose zone, there is air within the pores, and transport must therefore be described using more complicated interactions. Models describing colloid transport in both the vadose and the saturated zone include Hydrus-1D [92], Hydrus-2D/3D [93] and RT3D [94], which are all freely available (although not the graphical interface for RT3D).

The models work well for spherical particles in homogenous media, provided there are no repulsive electric forces between the particles and the soil granules [88]. When it comes to microplastics, and most other particles present in nature, these prerequisites are clearly not met. Most microplastics are not spherical, including those from tyre and road wear. Most models do not take into account the fact that soil is rarely made up of homogenous materials, and that soil granules are often negatively charged, which may lead to the formation of repulsive forces. Other processes not covered by models of this type is the possibility that particles get stuck if the voids between the soil granules are too small, thereby partially blocking the transport of colloids [91]. Processes such as transport via animals and plant roots, crack formation etc. can also not be described using these models.

Models of this type are very difficult to evaluate, as measurements are difficult to perform and they require either location-specific validation or evaluation for many different types of soils. Few studies have used models of this type to study the transport of microplastics. Engdahl (2018) [95] developed a modelling concept at pore-scale to describe the transport of fibre-like colloids in porous materials, aiming to enable description of microplastic particles. The model looks at transport of individual particles, why the scale is very small.

5.5. Hydrological models

The different hydrological models described under freshwater transport (Chapter 4) cover transport in lakes, watercourses, as well as in the unsaturated and saturated zones. These could potentially also be used for colloid modelling, to simulate integrated transport in an entire runoff system, however these models use a simplified description of the ground, which includes one or a small number of layers to describe the vadose zone, and a similar number for the groundwater zone. This means that it looks at very simplified, conceptual processes, and that the models almost only describe transport of dissolved substances rather than colloids. There are, however, some examples of colloid transport of metal pollutants carried out using two modules in the modelling tool GMS 10.3.4 [96], which may provide a starting point for determining the dispersion of microplastics in soil as well, under Swedish conditions.

5.6. Discussion

Transport of microplastics in soil, like transport of other pollutants, is a complex area to model, as the systems are very location-specific, heterogeneous and complex, which makes it difficult to perform general model set ups and universally applicable validations of any calculations. The lack of validation is particularly true for microplastics for which there are not yet any standardised measurement methods, and the analysis tools that do exist are expensive and difficult to use. In addition, the models that do exist need to be adapted to be able to describe those characteristics of tyre and road wear particles, and of other microplastics, that influence how they disperse in the ground.

Apart from the need for more measurements in the field to validate the modelling studies, there is also a need for more laboratory and modelling studies that describe the behaviour and dispersion of microplastics with different characteristics in soil under different conditions. As an example, most of the available studies look at spherical particles. There is also a need for further studies on transport processes not incorporated in current models, such as transport via animals. Quality data on emissions from roads to land are also needed, based for example on modelling and estimations of collected data.

6. Transport in oceans

Large amounts of microplastics enter the oceans every year. The particles have often travelled long distances through stormwater, soil, freshwater and/or air, and their characteristics may have altered along the way. There are several different mechanisms for dispersion in oceans and many different types of models for different purposes.

6.1. Sources and transport processes in marine environments

Microplastic particles enter the oceans via watercourses like rivers and streams, emissions from stormwater and wastewater treatment plants, and through dry and wet deposition from the air.

How the microplastic particles move through the ocean depends both on their own characteristics, such as density, shape and size, and the movements of the water. As an example, particles with low density float and are transported by waves and currents, whereas particles with higher density tend to sink and eventually settle. Settled particles can be resuspended from the sediment. Transport in surface water (to a depth of approximately 100 m) is controlled by winds and waves, resulting in Langmuir Circulation, Ekman Transport, and geostrophic currents (surface water currents). Tidal flows and flows around river mouths also have an effect on the transport of microplastic particles. The way in which fresh- and saltwater are distributed across an area, for example near the mouth of a river, also influence whether the particles float or sink. In deep water, particles are transported by the thermohaline circulation. Currents and turbulence in the water are influenced by the topography of the seabed. Topography and land use along the coastline have an impact on whether, and what proportion of, particles are washed up on land, and if they remain there.

A sizeable proportion of microplastics from tyre and road wear is expected to be present as aggregates with asphalt materials (stone and bitumen), and these particles are expected to have a high density and therefore be found mainly in marine sediments close to direct sources, wastewater, stormwater or surface water outlets. Both within the marine environment, and whilst being transported there, particles may be exposed to biofouling, which affects their density and size, and therefore the way in which they are transported. They may also be fragmented through photo degradation caused by UV rays and heat in surface water, or mechanical degradation on the seabed in coastal areas. [97]. Microplastic particles can also be taken up by organisms and moved through the food chain.

6.2. Modelling in oceans

A number of modelling studies have looked at the way in which microplastics are transported in oceans, at everything from the global scale to coastal areas of a few tens of kilometres. Modelling studies often use a particle tracing model to calculate the trajectories of particles. This can either be included in a hydrodynamic model or be used in combination with data from an ocean circulation or hydrodynamic model. The models may have different resolutions and the inputs to the models can include a greater or smaller number of factors, 4 waves or Stokes drift [98].

Some modelling studies assume that particles float and passively follow the flows of the water [99], [100], while other studies take into account more aspects, such as sinking/rising [101], sedimentation [102], [103], resuspension [102], sediment transport [102], stranding [101], [103], re-entry from beaches [103], and degradation of macroplastics into microplastics [103]. Transport of microplastic particles can occur in two or three dimensions.

Jalón-Rojas et al. 2019 [104] have presented a new model, specifically developed for simulation of plastics, TrackMPD. This is a model for particle tracing in three dimensions that take into account the density, size and shape of the particles, as well as the processes that influence their movements; advection, diffusion, wind effects, biofouling, degradation, sinking/rising, sedimentation, stranding and re-entry from beaches.

Lighter microplastic particles (such as pure rubber, polyethylene and polypropene) have a density which is lower than the density of seawater and can be transported long distances with the surface water, while tyre and road wear particles often have a higher density and tend to sink. In the studies carried out so far, tyre and road wear particles have only been identified in sediment close to the coastline [13], [105] indicating that further transport of these particles is not common in the studied areas. Additionally, the levels of tyre and road wear particles in seawater are unknown, and the amounts entering the oceans have not yet been evaluated. For this reason, there is less need to calculate the dispersion in the oceans, and more important to investigate the release into the oceans under different conditions.

7. Combined modelling in multiple environments

To assess the spread of microplastics from tyre and road wear requires combined models, able to handle dispersion in a number of different environments, as these environments are not separate from each other. This can be achieved by connecting a few more or less advanced modules or models to each other. Several of the hydrological models and modelling system mentioned previously can be used to model multiple land and water environments, including HSPF, HYPE, and SWAT, however they need to be adapted to transport of microplastics. Alternatively, simpler box models can be utilised. Box models have traditionally been used to study the amounts transported between different environments, such as oceans, freshwater, soil, air etc. as part of lifecycle assessments. Box models only calculate the flows between different environments, represented by boxes. No physical processes are evaluated, and the models do not provide any information regarding how pollutants are distributed geographically or over time.

A study by Unice et al. 2019 [106] presents a model encompassing both estimation of the sources of microplastics from tyre and road wear, and transport via soil and water into the sea. The annual emissions of microplastics from road traffic were estimated based on emission factors and number of vehicle kilometres driven, divided between a number of sub-runoff areas based on population density, road statistics, and land use. Literature-based factors were used to describe the proportion of the emitted particles that ended up in air, watercourses, and the ground, respectively. The model calculates mass flows between different parts of the environment and is connected to a hydrological model and a water quality model, which are used to estimate flows in watercourses and on land. The findings show that only 2 percent of the produced (on land) particles reached the ocean and that a large portion was retained in sediment or soil. This study was sponsored by the tyre industry.

The disadvantage with models that can describe multiple environments is that detailed models and modules have to be adapted to each other, which requires a lot of data capacity. Simplifications and simulations using simpler box models reduce the level of detail. The advantage of both approaches is that they can give a comprehensive picture of how particles spread, and where the main flows are found.

8. Discussion and conclusions

This report presents existing studies on the dispersion of microplastics, and the models that can potentially be used to analyse this. It shows that a number of different methods are required to describe the spread of microplastics from tyre and road wear to the environment. Since microplastics are present in all environmental compartments, in many different sizes, they have many dispersion pathways, and models which can describe all this is needed. Research has made some progress, but much is still unknown.

To perform modelling studies, emission estimates are required, and there is still a lot of uncertainty in existing data. Models for the generation of microplastics from tyres, asphalt, and road markings are needed to establish the connection between microplastic emissions and road traffic. More accurate data on the proportion of microplastics emitted to air, ground, and water, respectively, are also needed. There is also a high uncertainty regarding the amount of microplastics from tyre and road wear finding its way to stormwater facilities and sewage sludge; this needs to be known to enable estimation of the amounts of microplastics from tyre and road wear that could be dispersed e.g. via the stormwater network to surface water recipients, or via sewage sludge to agricultural land. There is very little knowledge about the initial spread from the road to adjacent areas under different meteorological conditions. To gather more information regarding this will require more measurements in the field and laboratory tests, as well as the development of models able to describe runoff, spray and splash from the road surface.

In relation to dispersion in air, there are a number of models that could be used immediately to model the spread of microplastics. These models require inputs on of emission estimates and size distribution, but also further studies on photodegradation and aggregation in air. However, it is difficult to validate air models with existing measurement methods.

A number of options are available for modelling microplastic particle transport in watercourses, although many of these models require adaptation to be able to simulate microplastics. To provide a basis for this adaptation, and to enable calibration and validation of the models, the huge shortage of continuous measurements of microplastics in watercourses must be addressed. Further research, both in laboratories and in the field, is also needed, to map the chemical and physical characteristics of particles, including density, shape and chemical composition, and to investigate how these factors affect the transport of microplastic particles in water and sediment. More knowledge is also required regarding how the physical and chemical characteristics change in the environment, i.e., impact of degradation, aggregation and biofouling in different soil, water, and meteorological conditions, and how these affect the transport in stormwater and surface water, respectively.

To enable more detailed studies of the transport of microplastics in soil, models especially adapted for this purpose are required. Current data show that particles generally move more slowly in the ground. This means that they will likely accumulate here, reducing the risk that they disperse further into watercourses and oceans.

Transport of microplastics in oceans has been studied more than in other environments, however there are still many unanswered questions, including how they are spread via different organisms, ocean currents, and sediments.

It would be desirable to be able to simulate the overall fate of microplastics in the environment, from emission via the various routes of transport, with account taken to how their physical and chemical characteristics change in different environments and under different conditions, however this would require a sound understanding of emissions and the different processes within all environmental compartments. Available global, regional and local estimations are currently very uncertain, but still give an important indication of the scale of this problem.

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