CHALMERS
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Fate and Transport of Microplastic Particles in Small Highway-Adjacent Streams

A case study in Gothenburg region

Master thesis in Infrastructure and Environmental Engineering

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DIVISION OF WATER ENVIRONMENT TECHNOLOGY

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Cover:
The title page shows a collage with a photo taken by the author showing the case study highway stretch, and an extraction of a map from *Figure 4.6*, describing concentration and deposition in the fourth simulated scenario D4.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2021

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ABSTRACT

A large portion of the plastics contaminating the watercourses and oceans are the so called microplastics, derived from wear and tear of tyres. There is a lack of knowledge on where the microplastic particles are deposited. Therefore, the aim of this thesis is to present an estimation of the microplastic sources and sinks in a small case study stream crossing a rural highway. This is done based on a literature review of the transportation behaviour of road related microplastics and the surrounding environment factors affecting the fate and transport, and by building a compartment model of the case study stream.

To model the water pathways in connection to the case study road stretch between Jonsered and Lerum in western Sweden, the hydrological modelling tool SWAT was used, simulating the time dependent flow in the stream. With the SWAT modelled values as input data, a compartment model based on Stoke's law in combination with Hazen's surface loading theory was set up with the most affecting and feasible factors included. The factors included were road entrapment, wind transport, verge removal and settling of particles in the water phase. The model was built on a combination of field studies of the flow conditions and stream dimensions. Four scenarios based on real dates were simulated to show seasonal differences and to estimate the exposure of the natural environment in the area to the microplastics. To gain information about the impact of each factor, eight sensitivity analysis scenarios were set up, analysing each factor compared to a baseline scenario.

The particles were shown to deposit early in the system, and only the particles in the smallest range remained suspended in the water leaving the stream. The exposure to microplastics was simulated to be highest during the winter half-year, when the wear rate of tyres is increased and the flow in the stream is generally higher. Also, the number of antecedent dry days was shown crucial for the concentration in the outgoing road runoff and hence for the exposure of microplastics in the stream.

Knowing the fate and transport of microplastics in the environment is essential to assess the scale of the problem, and to build a base for implementation of microplastic reduction measures for a cleaner environment.

Keywords: Compartment modelling, hydrological modelling, microplastics, SWAT-modelling, stormwater, water quality modelling.

Transport av mikroplastpartiklar i bäckar korsande motorvägar
En fallstudie i göteborgsområdet.

Examensarbete inom mastersprogrammet Infrastruktur och Miljöteknik

SARA HAGSTRÖM

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SAMMANFATTNING

En stor del av all plast som förorenar vattendrag och hav utgörs av så kallade mikroplastpartiklar, uppkomna genom förslitning av däck. En kunskapslucka finns om var mikroplasterna hamnar, varför syftet med denna studie är att presentera en uppskattning av mikroplasternas transport i en bäck som passerar en motorväg i ett naturområde. Syftet uppfylls genom en litteraturstudie av hur partiklarna transporteras och av den omgivning som påverkar transporten, samt genom att bygga en boxmodell av bäcken.

För att modellera vattendragen i kontakt med motorvägen i fallstudieområdet som ligger mellan Jonsered och Lerum i västra Sverige, användes det hydrologiska programmet SWAT. Med SWAT kan ett tidsberoende vattenflöde i bäcken modelleras. Med flödet som indata sattes en delmodell upp baserad på Stokes lag i kombination med Hazens ytbelastningsteori upp, samt med de viktigaste och modelleringsmöjliga faktorer inkluderande. De inkluderade faktorerna var väginfångning, vindtransport, dikesavskiljning och sedimentation av partiklar i vattenfasen. Modellen byggdes av en kombination av fältstudier av flödesmönster och bäckens dimensioner. Fyra scenarier baserade på verkliga datum simulerades för att visa på säsongsvariationer och för att uppskatta exponeringen av mikroplaster på naturen i området. För att validera scenarierna och för att skapa förståelse om varje faktors påverkan sattes åtta känslighetsanalysscenarier upp. Dessa behandlade varje faktor för sig och jämförde dem med ett baslinjescenario.

Partiklarna visade sig deponeras tidigt i systemet, och bara partiklar i den minsta storleksordningen fortsatte vara suspenderade i vattnet som lämnade bäcken. Exponeringen mikroplaster var högst under vinterhalvåret när både förslitningen av väg och däck och flödet i bäcken generellt sett är högre. I tillägg var antalet torra dagar innan det simulerade scenariot avgörande för koncentrationen i vattnet.

Kunskap om depositionen och transporten av mikroplaster i miljön är viktigt för att kunna utvärdera storleken av problemet, och för att bygga en bas för miljöskyddande åtgärder.

Nyckelord: Dagvatten, hydrologisk modellering, mikroplaster, SWAT-modellering, vattenkvalitetsmodellering.

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PREFACE

This Master thesis was part of the M. Sc. in Infrastructure and Environmental Engineering at Chalmers University of Technology and was carried out individually.

First, I would like to thank my examiner Mia Bondelind and my supervisor Ekaterina Sokolova for the support and guidance I received during the whole process. Thank you for letting me explore the fields of science which I find the most interesting, but also for challenging me with new, sometimes uncomfortable ideas making the work even more interesting in the end.

I would also like to send my gratitude to Viktor Bergion at Chalmers University of Technology for his help when SWAT was not on my side, and for providing me the necessary translating tables for soil data.

I would like to thank my family, for always believing in me. In this pandemic year, I would also like to thank my study colleague and friend Miri, for hours of thesis discussions and good coffee. Finally, my gratitude is directed to you Oskar, for always cheering me up and giving me your love and support no matter what.

Göteborg, January 2021

Sara Hagström

1. Introduction

The world is facing an enormous challenge concerning human derived contamination of the environment. One of the materials of recent concern is the synthetic organic compound plastic, with many positive properties such as light weight and high plasticity. This makes the area of application for plastics wide and the production of plastic is increasing every year (UNEP, 2014). However, some negative consequeses of using plastic are the persistence and that the material can be fragmented into particles invisible to the eye. These are called micro- or nanoplastics, dependent on the size (<0,001-5 mm, here collectively named as microplastics). Due to the space these particles occupy, consumption poses a threat for living organisms and may cause starving. The particles are small enough to be consumed even by macroinvertebrates (Windsor et al., 2018). However, starving is not the only problem with microplastic particles in freshwater. In a recent study by Tian et al. (2020), acute mortality in salmons exposed to road runoff was found, caused by the ubiquitous tyre rubber antioxidant N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD). The rubber material can be toxic itself, but the particles can as well be carriers of other contaminants adsorbed from the environment such as heavy metals or organic compounds like polycyclic aromatic hydrocarbons (PAHs) (Vogelsang et al., 2019). Observations of microplastic particles in biota have been made at all trophic levels, which means it might enhance biomagnification of toxic substances in biotic tissue. Microplastic particles are as well a concern for the health of the human body, but is primary linked to the inhalation of particles emitted to the air (Baensch-Baltruschat et al., 2020), and no studies were made on the risk related to intake via the food chain. Wagner et al. (2008) report acute toxic effects for aquatic species at concentrations from 25 to 100 000 mg/L, and Wik and Dave (2009) showed chronic toxic effects for reproduction on fish species at concentrations from 10 to 1 800 mg/L.

The sources of microplastics emitted in Sweden have been analysed by Magnusson et al. (2017), where road wear and abrasion of tyres turns out to be the most contributing factor with an emission of about 8000 tonnes per year, and over 60 % of the total yearly emission, see *Figure 1.1*.

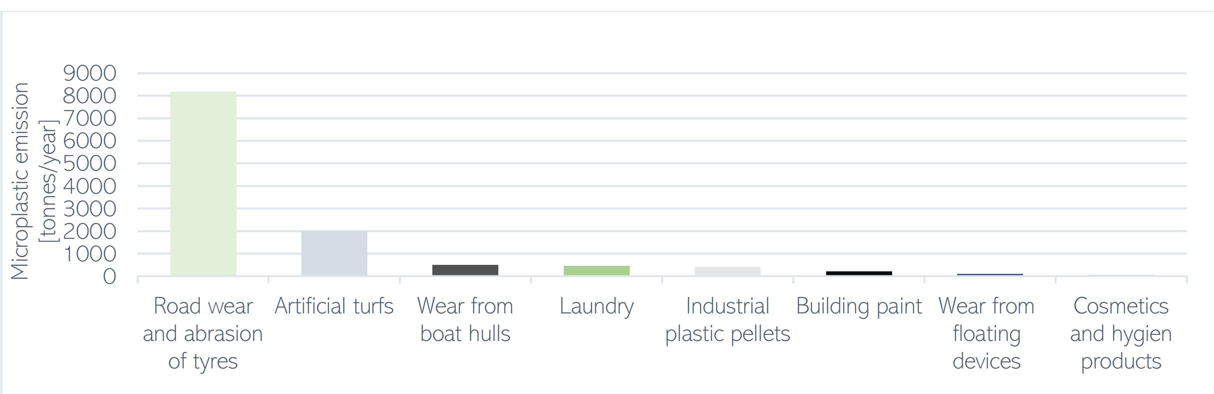

Figure 1.1. Distribution of estimated microplastic sources in Sweden in tonnes per year (Magnusson et al. 2017).

The fragment of science made on microplastics derived from roads has focused on the amount of microplastics entering the marine environment, but a lack of knowledge exists on the transportation pathways of microplastics between the roads and the larger streams, and where the microplastic particles that do not reach the estuary end up. Since not only the size but also the density and shape of microplastics vary, their ability to move varies as well, which makes it challenging to track, especially where stormwater from roads is released into nature areas.

Andersson-Sköld et al. (2020) expresses that the two most fundamental questions needed to be answered is if the exposure of microplastic particles is a significant environmental or health problem, and which measures can be taken to reduce the impact. Previous studies have highlighted the lack of information about exposure level for different organisms and areas (Andersson-Sköld et al., 2020). To be able to protect organisms in sensitive terrestrial areas such as wetlands and forests, a first step is to detect the spatial distribution and magnitude of exposure of road-related microplastics.

According to the Swedish Environmental Code (SFS 1998:808, chapter 9, 2nd and 7th §§), water that is drained within a detailed planned area is defined as wastewater and is to be treated so that no inconvenience occurs to human or the environment. Rural highways however, are not always within detail planned areas and are hence not covered by this regulation. The Swedish Transport Administration, with the role of road operator, has the responsibility for the environmental impact of the Swedish road network and is specially pointed out to produce a knowledge base of possible measures to reduce the impact of road stormwater to ground- and surface waters (The Swedish Water Authorities, n.d.). These measures can be applied as purification requirements to fulfil environmental quality standards in water courses, organised by the Environmental Administration in Gothenburg (2017), but the requirements and environmental quality standards do not include microplastics. Kole et al. (2017) empathises previous statement in many cases also outside of Sweden, surface runoff from roads is not collected and might accumulate and be transported further. Knowing the concentrations and deposition of microplastics in the environment is essential to assess the scale of the problem, and to build a base for implementation of microplastic reduction measures.

1.1. Aim and objectives

The aim of the thesis is to study the transportation and behaviour of road related microplastic particles in small waterways connected to a rural highway and to estimate the exposure to road related microplastic particles in a natural environment. To fulfil this, the following objectives have been set up:

- Review the transportation behaviour of road related microplastic particles through a literature study.
- Model the pathways of water connected to a section of the road.
- Apply the reviewed road related microplastic particle fate and transport behaviour in a compartment mass balance model.
- Visually present an estimation of the microplastic sources and sinks, as well as concentrations on a study area close to Gothenburg.

1.2. Research questions

The following questions have been formulated to fulfil the aim and objectives:

- How large amounts of microplastic particles are released on roads and how do the seasonal changes affect the amount and properties of released microplastic particles?
- How are the size, density and shape of the particles distributed in traffic related runoff?
- Which are the dominant processes affecting the microplastic particles from emission stage to recipient release?
- Which environmental factors are crucial when analysing water and particle transport?

1.3. Limitations

The proposed approach is applied on a case study area nearby Jonsered and limited to a 1 200 m long stream with a watershed of approximately 0.75 km^2. The watershed is crossed by the two-lane highway E20, stretching between Göteborg and Örebro in Sweden. The studied emission area within the watershed is about 315 m along both directions on E20 between Jonsered and Lerum.

The input data used in the model are based on assumptions supported by the literature study, and no validation of microplastic occurrence could be made due to limited time and resources. In the discussions of seasonal changes, the seasons were limited to only winter and summer half years, where the winter half spans between October and March.

2. Literature review

Several internal and external factors confound the predictions on how far a particle will travel from source to destination, which will be reviewed in the following chapter.

First, the specific properties of road related microplastics are presented to create an understanding of the behaviour of the particles. When released, hydrodynamic and particle settling properties are the main factors affecting the spatial distribution in aquatic areas (Helcoski et al., 2019). Settling is strongly related to the size, density and shape of the particles (Wijesiri et al., 2016), and these might change due to environmental factors, described in Section 2.4. Also, the hydrodynamics are dependent on environmental factors such as precipitation, vegetation and geological conditions. A summarizing conceptual model of the literature study is shown in *Figure 2.1*.

Due to the limited number of specific studies made on microplastic particles, many studies of Total Suspended Solids (TSS) are reviewed. TSS is in some other studies used as a substitute to microplastic particles. Vogelsang et al. (2018) state that 78 % of TSS measures in road runoff is tyre wear. When TSS is the measured parameter and the paper is discussed in the thesis, it is not presented as microplastic.

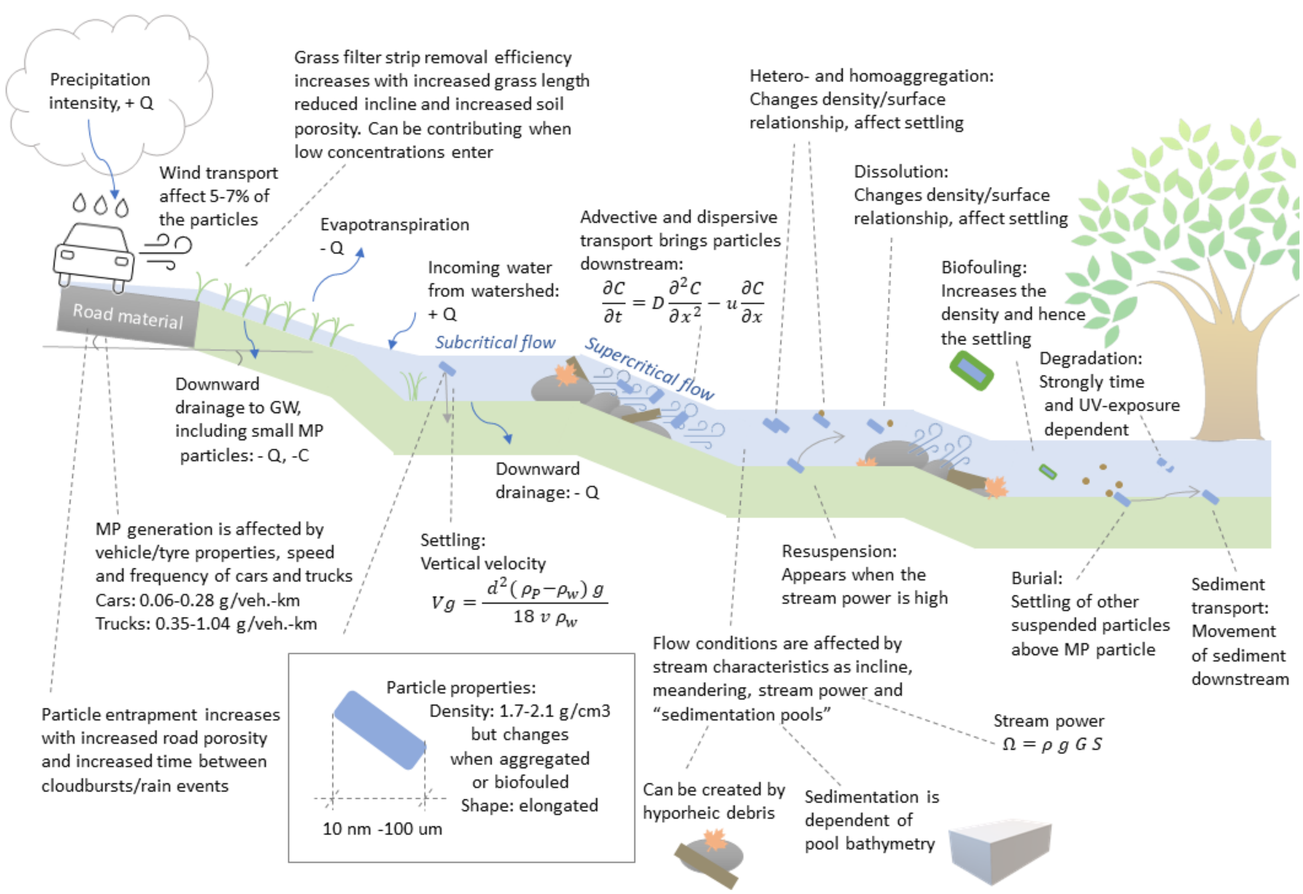

Figure 2.1. A conceptual model demonstrating the possible factors influencing the fate and transport of road related microplastic particles. Each factor is further described in the literature study.

2.1. Emission of road related microplastics

Tyre and road wear particles are often consisting of a mix of different materials, where about 50% of the tyre wear contains synthetic and natural polymers (Sommer et al., 2018). An established way to estimate the microplastic road emissions is to measure the concentrations of particles in the stormwater. However, Bondelind et al. (2020) states that the occurrence of microplastics in stormwater is still very uncertain and that only some monitoring studies exist. Another used method is the emitted tonnes per year per region or country (Vogelsang et al, 2018). Estimations of tyre wear emissions have also previously been done by estimations of the traffic load on a road section, in combination with tyre wear-factors from laboratory- or field tests. This approach gives results with the unit grams per vehicle kilometre (OSPAR commission, 2007). The total loss of microplastics per driven kilometre varies widely, and depends on the calculation method used, and several other factors, shown in *Figure 2.2*.

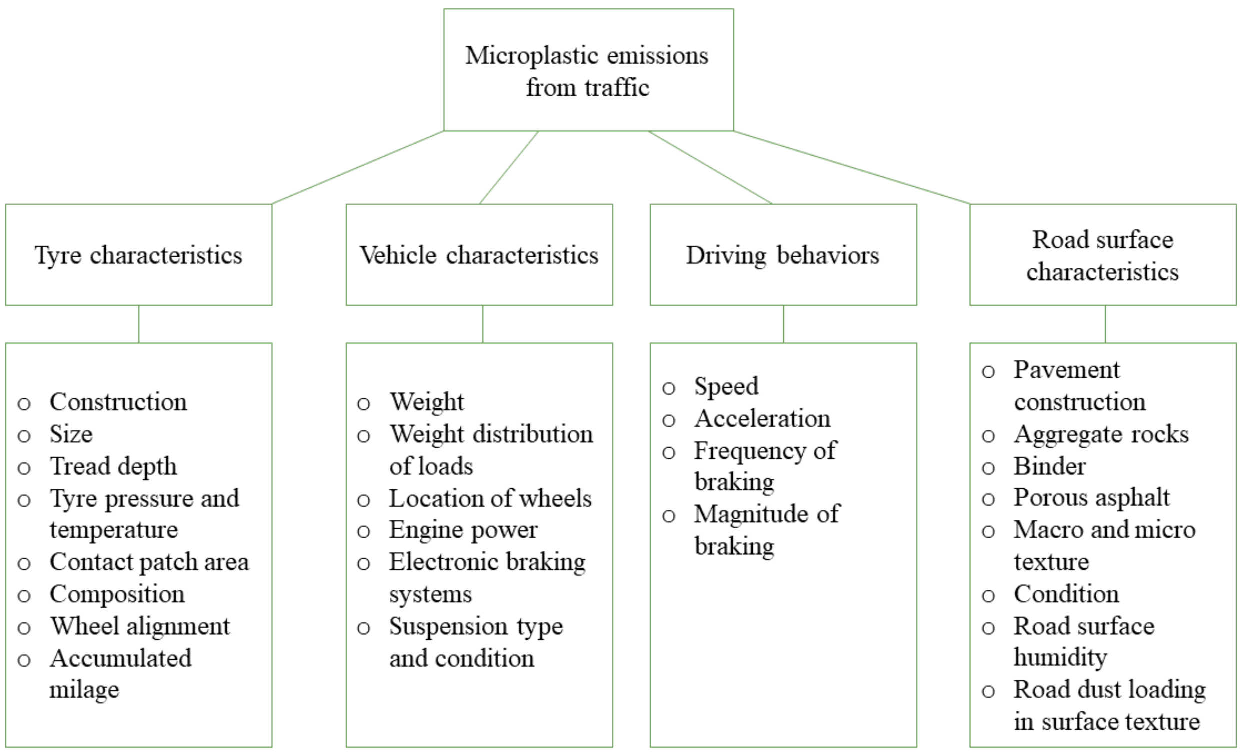

Figure 2.2. Division of the factors influencing the microplastic abrasion from tyres, which emphases the insecurities in calculations of emitted particles. Based on OSPAR commission (2017).

In the Netherlands, Klein et al. (2017) divided the emissions in whether the road was in an urban area (0.132 grams/vehicle-km), rural area (0.085 g/vkm) or if the road was a highway (0.104 g/vkm). The differences in wear rates were mostly due the start and stop behaviour used in a higher degree in urban compared to rural areas and highways. The emissions were also divided by vehicle type, where lorries and trucks showed about 6 times larger emissions compared to passenger cars. Gustafsson (2001) made a similar study, comparing the existing data available for Swedish emissions, but this was not divided by road type. The emission rates from this study were measured to 0.006-0.36 g/vkm for personal vehicles, and 1 g/vkm for lorries and busses. In Norway the emission rate was estimated to 0.132 g/vkm for passenger cars and 0.712 g/vkm for heavier vehicles (Sundt et al., 2014). Hann et al. (2018) complied several studies of emission rates on European roads, and concluded a rate of 0.104 g/highway-vkm, and 0.668 g/highway-lorry-km. However, this area of study is strongly dependent on how parameters and factors are treated in the different models and entails large uncertainties. A Dutch study showed that a distribution of 40 % of the total emission was on highways, 30 % on urban roads, and 30 % on rural roads (Verschoor et al., 2016). When comparing the total emission factors of Sweden and the Netherlands, Sweden showed a larger rate of 1.0-1.34 kg/capita/year compared to the Netherlands 0.9 kg/capita/year (Norén and Naustvoll, 2011; Verschoor et al., 2016). The micro-texture of the road is highly influencing the wear rate, where Lowne (1970) showed a 3 times severe wear on rough surfaces compared to smooth surfaces.

The use of studded tyres increases the road dust production, but the increase in road particles seem to originate from the road material rather than from the tyre treads (Gustafsson, 2001). The tread is the rubber part of the tyre that gives grip and traction force (Andersson-Sköld et al., 2020). However, a division of the amount of tyre particles compared to road marking material was made by the Municipality of Gothenburg (2016) who estimated the emitted loss of microplastics from tyre wear in Gothenburg to 520 tonnes, compared to 20 tonnes from road markings. In a study of road dust at urban roads in Stockholm, it was found that at a recently paved road, or roads with higher surface texture the generation of particles were shown to be higher compared to a road with asphalt several years older (Gustafsson et al., 2019). Gustafsson et al. also found a relationship between particle generation over seasons, where primarily particles under 10 µm, PM_{10}, but also larger particles were generated in a higher degree during winter and early spring. The mass of particles accumulated at the road was higher during late autumn and winter, with a peak in February and March, to be lower in late spring to early autumn. LeMaitre et al. (1998) found a 50 % higher tyre wear in dry conditions than in wet conditions. Another observation by LeMaitre et al. showed a winter tyre wear rate that was 40 % higher than summer tyre wear rate.

Resuspension from the road surface is further an emission path, where the particles emitted on the surface are resuspended to the air medium. The emission factor is by Bringfelt et al. (1997) proved to be strongly dependent on the vehicle speed, where the resuspension increases proportionally with the quadrat of the vehicle speed. The resuspension emission factor is set to 5.16 g/vkm for a vehicle speed of 100 km/h, compared to 0,28 g/vkm when the vehicle speed is 20 km/h. However, the resuspended mass is likely to deposit at the road again after resuspension.

2.2. Specific properties of road related microplastics

The size, shape and density have a big influence of the fate and transport of microplastics (Wijesiri et al., 2016). Microplastics are often divided into primary and secondary microplastics, depending on when the particle has been formed to the present size and shape. The road related microplastics are often of the secondary type, since it has been derived by degradation (GESAMP, 2015).

The magnitude of the wear off is dependent on the properties of the tyre, the vehicle, the use of studded tyres, driving behaviours and type of road pavement (Wagner et al., 2018). The size distribution is dependent on the road pavement, vehicle speed, tyre temperature, tyre age and composition of the tyre (Kole et al., 2017). However, the studies made on size distribution of road related microplastics are made in different ways and show varying results. A merge of four studies shows a size range of 10 nm to several hundred µm (Kole et al., 2017; Kreider et al. 2010). Kreider et al. (2010) made a study with a trapping device placed right behind the wheel, and presented a size distribution in both volume share and particle size share, showed in *Figure 2.3 A.* It shows that larger particles make up the largest share of the total volume. However, when analysing the number size distribution it shows two peaks, the highest at 5 µm and the second highest at 25 µm, demonstrated in *Figure 2.3 B.* In the volume size distribution, less than 5 % of the volume share of the particles are smaller than 10 µm, which correlates with other studies by Cadle and Williams (1978) and Broeke et al. (2008). Still, due to measurement difficulties, there is a risk that smaller particles could be underrepresented in studies. Boulter (2006) estimated that less than 10 percent of all tyre and road material is released in size ranges smaller than 10 µm when driving passenger cars and light freight vehicles. Another study made by Aatmeeyata Kaul and Shrama (2009) showed a smaller size range of 0.3 - 20 µm. In this study, the paved material consisted of concrete with sand and granite bound to the cement. A study when different driving conditions such as braking, acceleration and swing were performed by Mathissen et al. (2011) and showed a much smaller distribution of 6 – 562 nm. The size generation of the particle is decreasing with increased speed (Dannis, 1974).

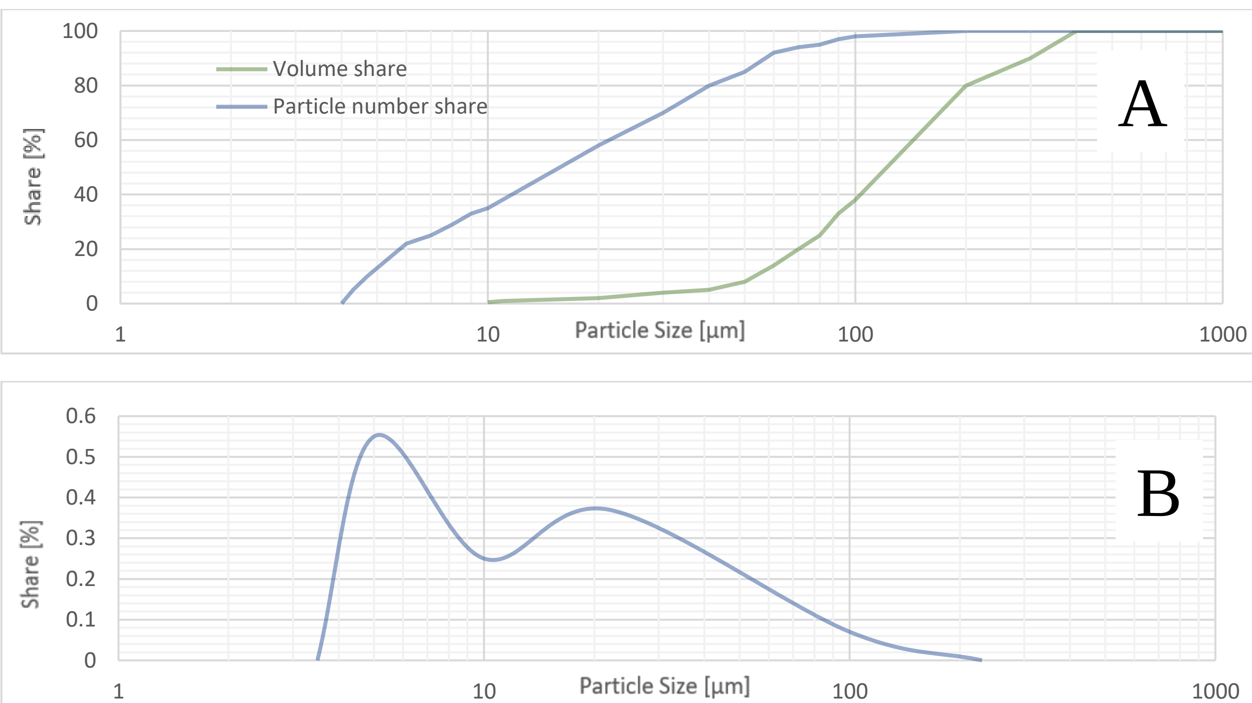

Figure 2.3. In A, the volume-particle size cumulative distribution (green) and number-particle size cumulative distribution (blue) by Kreider et al. (2010) is presented, remade by the author, smoothed over 16 respective 19 data points. In B, the distribution is shown where the two peaks at 5 and 25 µm are visible, remade by the author, smoothed over 6 data points: Both diagrams originally made by Kreider et al. (2010).

Tyre particles generated in a road simulator have shown an elongated, or curled shape (Kreider et al., 2010; Hassellöv et al., 2018). In previous studies, the equivalent sphere diameter d_{equi} *(Equation 2.1)* have been calculated with the Corey Shape Factor (CSF = $\frac{c}{\sqrt{ab}}$) (Waldschläger & Schüttrumpf, 2019) to simplify the shape factor.

$$d_{equi} = \sqrt[3]{abc} \qquad \text{Equation 2.1}$$

a = the longest side length

b = the middle side length

c = the shortest side length

The density is an important factor for the fate and transport of the microplastic particles. If the density is higher than water, the particle sinks, and if the density is lower it floats. Rubber, which is the main component in tyres, has a density lower than water (Scientific Polymer Products Inc., 2020). However, particles are not always clean and consist often of a mix of materials. Some densities are presented in *Table 2.1*. Sommer et al. (2018) calculated the density of "real world" tyre wear particles to 1.26 g/cm^3, based on the densities of rubber, minerals and iron. However, when additionally including road wear particles (bitumen and wear from road markings), the density increases. In a study by Unice et al. (2019) a mean particle density of 1.8 g/cm^3 was used, based on an observation of 50 % tread and 50 % mineral encrustations.

Table 2.1. Clean rubber polymers are lighter than water, but when fragmented from the tyre-tread, the particles have a density slightly over the density of water. Tread-tyre particles with road particles on the surface are even heavier

Material	**Density [g/cm^3]**	**Reference / comment**
Freshwater	1.00	At 4 degrees
Clean tread-tyre particles	1.15-1.18	Vogelsang et al., 2019
Particle covered tread-tyre particles	1.7-2.1	Vogelsang et al., 2019, Unice et al., 2019
Rubber	0.900-0.965	Scientific Polymer Products, Inc., 2020

2.3. In water processes

Several processes affect the particle transport in water. Earlier studies describe them as advective transport, settling and resuspension, homo- and heteroaggregation, polymer degradation, presence of biofilm, release of attached particles, sedimentation transport and burial (Besseling et al. 2017; Unice et al., 2019). An overview of these processes is presented in Figure 2.4. The particle properties are governing the relative importance of the different transport processes. According to Hoellein et al. (2019), the retention of microplastics in small streams (~1.5 L/s) are primarily affected by a combination of particle shape, density and biofilm colonisation.

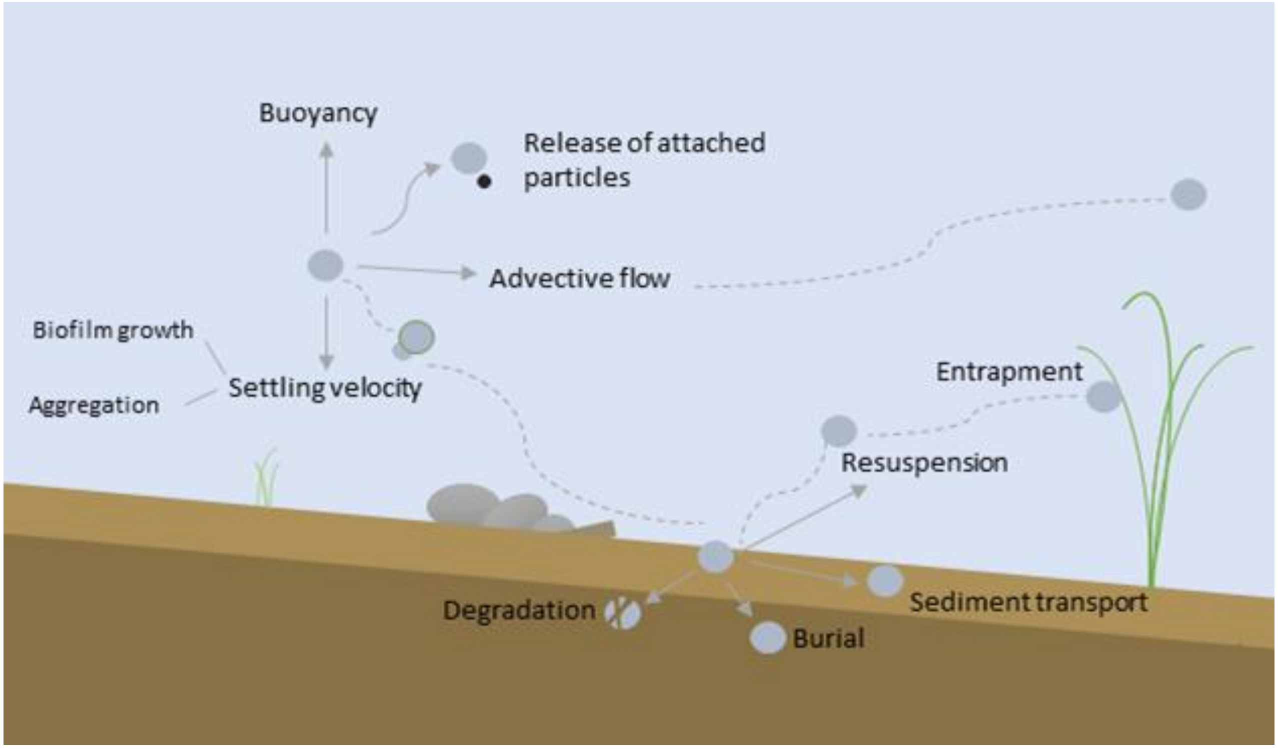

Figure 2.4. Schematic picture of the processes involved in microplastic transportation in small streams, based on the literature study.

2.3.1. Advective, diffuse and dispersive transport

The motion of particles in a fluid is a result of advective, diffuse and dispersive mass transfer (Besseling et al., 2017). Advection is dependent on the average flow velocity and refers to the longitudinal transport. Dispersive mass transfer is multidirectional and is the spreading of mass from a highly concentrated area to a less concentrated area due to turbulence, a result of nonideal flow patterns (Ji, 2017). The combined transport of particles in water bodies is often described with the one-dimensional advection-dispersion equation, presented in *Equation 2.2*, assuming steady and uniform flow.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x}$$ *Equation 2.2*

- *C = Concentration in water*
- *t = Time*
- *u = Pore water flow velocity*
- *x = Distance*
- *D = Hydrodynamic dispersion coefficient*

The analytical and numerical solution is useful when assessing the time and position at which the contaminants will start to affect the water eco-system in a negative way (Kumar Jaiswal et al., 2011). In rivers is the advective flow component larger than the dispersion component (Ji, 2017).

2.3.2. Settling, resuspension, sediment transport and burial

When entering a water body, the particles will be subject to the same transport processes as fine sediment particles (Horton & Dixon, 2017; Vianello et al., 2013), and since microplastics are in such small range, they can be considered as suspended solids, dissolved in the water. The settling process is by Metha et al. (1989) described to be in the scale of hours, while the settled bed is in the scale of years until the suspended solids are eroded, viewed in *Figure 2.5*.

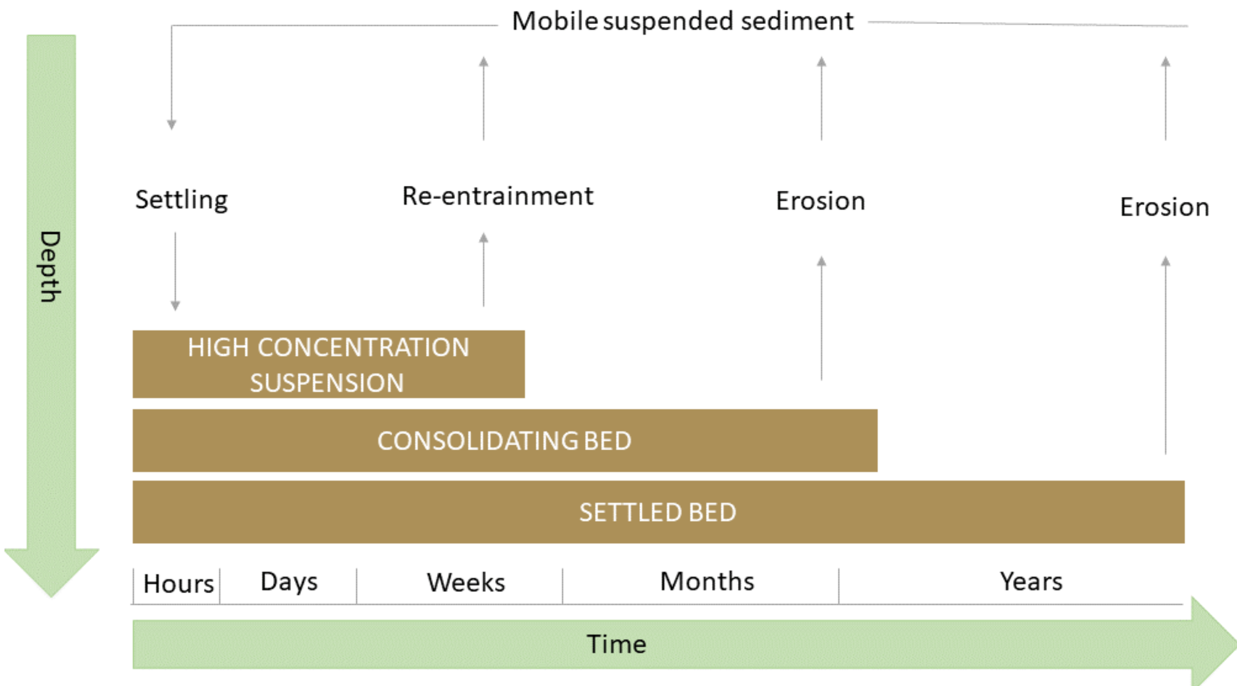

Figure 2.5. The sedimentation and related bed processes, with the corresponding time frame in a logarithmic scale. Based on Metha et al., (1989).

Settling of particles is greater in calmer water, which means that the faster the water flows in a strem, and the more energy it has, the greater entrain and transport capacity it has (Horton & Dixon, 2017; Chapra 1997). Despite the buoyancy of microplastics, where the flow energy drops, it is likely that the particles will settle together with sediment particles. This sediment deposition can lead to burial of microplastics (Corcoran, Moore & Jazvac, 2014). The particles will due to their differences in size and density settle in different speed. Chapra (1997) describes the process as complex but that patterns have been shown that particles tend to collect in low energy areas. For streams, these low energy deposition zones are in basins and inside of bends in meandering sections, see *Figure 2.6*.

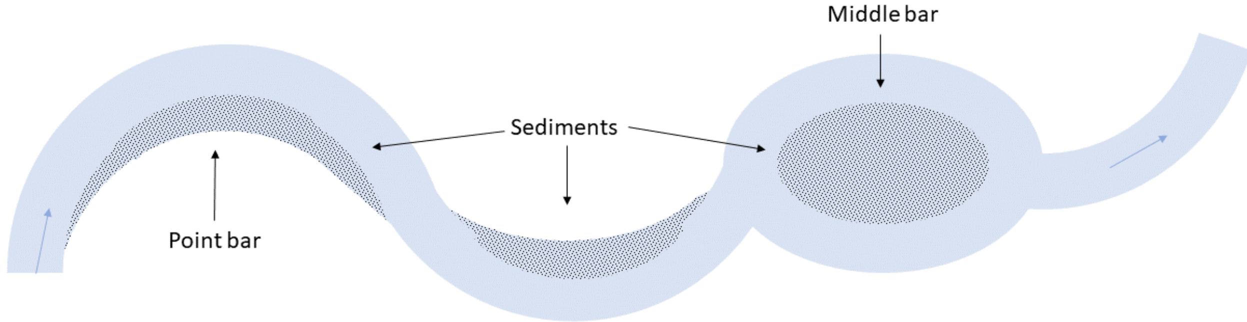

Figure 2.6. Patterns of distribution of fine sediments in natural waters, with a top view of a stream. Based on Chapra (1997)

Sedimentation can be described with Stokes law, *Equation 2.3*, which during laminar flow (no vertical mixing) describe the vertical sedimentation rate Vg [m/s].

$$Vg = \frac{d^2 \, (\rho_P - \rho_w) \, g}{18 \, v \, \rho_w} \qquad \textit{Equation 2.3}$$

- d = *Diameter of particle (spherical shape) [m]*
- ρ_P = *Particle density [kg/m^3]*
- ρ_w = *Fluid density [kg/m^3]*
- v = *Kinematic viscosity of the water [m^2/s]*
- g = *Gravitational constant [m/s^2]*

Laminar flow is a state which is rare during massive runoff (Vogelsang et al., 2019). In turbulent flow, Fornari et al. (2016) claim that the settling speed is reduced by 6-13% for spherical particles with a density slightly heavier than water. If the settling velocity is much smaller than the forward velocity of the water, the particle will travel downstream without settling to the bed of the stream.

In sedimentation tanks used for drinking water preparation and wastewater treatment, Hazen's surface load theory (1904) is commonly used, *Equation 2.4*. The theory uses the thoroughgoing flow divided by the horizontal surface area of the tank, which is assumed to be rectangular. If the surface loading for a tank is larger than the settling velocity of a particle, $V_f < V_g$, the particle will settle to the bottom before it leaves the tank.

$$V_f = \frac{Q}{A} \qquad \textit{Equation 2.4}$$

- Q = *Flow [m^3/s]*
- A = *Horizontal surface area [m^2]*

A test made by Hoellein et al. (2019) shows that polystyrene fibres compared to pellets are more likely to be retained by sinking, and these fragments would more likely resist resuspension in high flows in a higher grade. Hoellein et al. (2019) also claims that the microplastic deposition velocity in streams follow the pattern for organic matter particles, where the depositional velocity was affected by biofilm growth.

When a particle is settled to the bottom, it can either be remained at the place it settled, or it can be remobilised again at higher flow velocities. The flow velocity needed to resuspend the particles depends on the particle size, density and the properties of the stream bed bank (Harrison & Kammer, 2020). Large particles (> 0.1 mm) are often too heavy to be suspended and settle quick back, while small particles (< 1 µm) often are bonded together by substances generated by microorganisms, or wedged between larger particles in the stream bed (Harrison & Kammer, 2020; Waldschläger & Schüttrumpf, 2019). The critical velocity for resuspension u_{cr} [m/s] describes at which velocity the energy of the water is enough to entrain a particle of a certain size and can according to Harrison and Kammer (2020) be calculated with *Equation 2.5.*

$$u_{cr} = 2.8\left(\sqrt{\rho' g d} + 5.25\frac{v}{d}\right)c \qquad \textit{Equation 2.5}$$

- ρ' *= Relative density [kg/m³]*
- g *= Gavitational acceleration [m²/s]*
- d *= Grain size median [m]*
- v *= Water kinematic viscosity [m²/s]*
- c *= Coefficient for the critical velocity depending on the level of consolidation [-]*

The stream velocity is the greatest in the middle of the stream where it is the least affected by the shear stresses from the stream bed banks. The shear stress, *Equation 2.6,* is described as the force of friction from a fluid acting on the bed in the water path and is vital when estimating sediment transport and resuspension.

$$\tau = \gamma\ D\ S_W \qquad \textit{Equation 2.6}$$

- τ *= Shear stress [N/m²]*
- γ *= Weight density of water [N/m³]*
- *D = average water depth [m]*
- S_W *= Water surface slope [m/m]*

In a study made on erosion, or resuspension, of microplastics in the riverbed, the critical shear stress of the microplastic particles varied between 0.002 N/m² and 0.233 N/m². This was dependent on the particle and sediment properties, mostly the grain size of the sediment bed (lower shear stress was shown when the bed sediment was smooth, and higher with a bed of coarser grains) and the particle density (Waldschläger & Schüttrumpf, 2019).

Where the downward drainage flow through soils is high, contamination hotspots can occur at even 25 cm depth (Zubris & Richards, 2005). Retention within soils can be supported by processes such as bioturbation which drags the particles deeper into the soil (Lwanga, 2017).

2.3.3. Homo- and hetero aggregation and dissolution

Heteroaggregation is an aggregation process of particles of different types, e.g., microplastics and suspended solids. This process is highly dependent on the attachment efficiency between these particles, α_{het}, which for micro- and nanoplastic particles is unknown (Besseling et al., 2017). In the environment, heteroaggregation is expected to be more present than homoaggregation (Stoll & Seijo, n.d.). The heteroaggregation is increasing the sedimentation rate and retention of microplastics (Besseling et al. 2017). To calculate the heteroaggregation, Unice et al. (2019) used a simplification of the Smoluchowski coagulation equation by assuming that only one plastic particle can attach to one suspended solid particle. However, Unice at al. (2019) found heteroaggregation as relatively insignificant for the microplastic trapping efficiency.

In the same way as particles can attach to each other, dissolution can occur (Besseling et al., 2017). This may be road particles of a different density attached to the surface of a microplastic particle, that due to turbulence or high external forces gets released and gives the former microplastic particle aggregation a new total density.

2.3.4. Polymer degradation

Microorganisms such as fungi, bacteria and biofilm can degrade microplastics, but is strongly dependent on microbial characteristics and environmental factors (Yuan et al., 2020). Degradation and abrasion processes are mostly affecting the fate and transport on a long time horizon. A maximum biodegradation weight loss of 1.75 % per month was observed by Harshvardan and Jha (2013). About the components in the tyres, Wagner et al. (2018) means that tyre wear particles in the aquatic environment are considered as persistent due to the long degradation time.

Fragmentation is the mechanical break-down of plastic particles by sediment or sand (Song et al. 2017): This process can be generated by water waves or changing directions of the water, creating a movement of the particle and hence a friction force against the sediment bed.

Photooxidation is considered as the most substantial weathering process and is described as the degradation of a polymer with radiant energy (such as UV) in an oxygen environment (Andrady et al., 2015). This may cause a degradation of the accumulated particles on the road surface if exposed to sunlight for a longer period. The shading of trees is named as highly crucial and has not been considered in previously mentioned study, why UV-degradation in streams might be highly affected. Currently, no studies are presented on the degradation of microplastic particles in an aquatic environment (Baensch-Baltruschat et al., 2020). However, Baensch-Baltruschat et al. (2020) assume that the photo-degradation may be hampered by the ability of the water layer to absorb light.

2.3.5. Presence of biofilm

Biofilm growth, or biofouling, is affecting the fate of microplastic particles with a possible change of shape, size, overall density but also attachment efficiency (Besseling et al., 2017). Particles with high specific surface against volume ratio, such as elongated or irregularly shaped plastics tend to sink faster because they can carry a larger volume of fouling organisms per volume of plastic, and then get a higher density (Ryan, 2015). In this discussion, the time scale is an important factor. Unfortunately, not many studies have been made in freshwater, but a study of microplastics in estuaries show that bacteria in a coastal environment were able to colonise light microplastic particles over just two weeks (Harrison et al., 2014).

2.4. Environmental factors

This chapter treats the environmental factors affecting the in-water processes. Most of the environmental factors are influencing the retention time and flow magnitude of water which consequently affect the settling rate.

2.4.1. Road design

Roads have different particle retention properties dependent on when, where, and how they are built. Although roads mostly are impervious, the porosity of the road is by Brodie (2007) named as one of the important factors. The entrapment of the particles increases with increased road porosity (Kole et al., 2017). Chiew et al. (1997) introduced a modelling study that state that storm events usually remove only a small fraction of the accumulated contamination load. Sartor and Gaboury (1984) describe the relationship to be non-linear due to wind, traffic and already filled up pores. This relationship is presented in Figure 2.7, where also the rain events are included to show the possible wash off. Street sweeping is a maintenance measure which have been proven to reduce the amounts of microplastics accumulated on the road (Sartor & Gaboury, 1984), but is rarely done on rural highways, and is hence not presented in Figure 2.7.

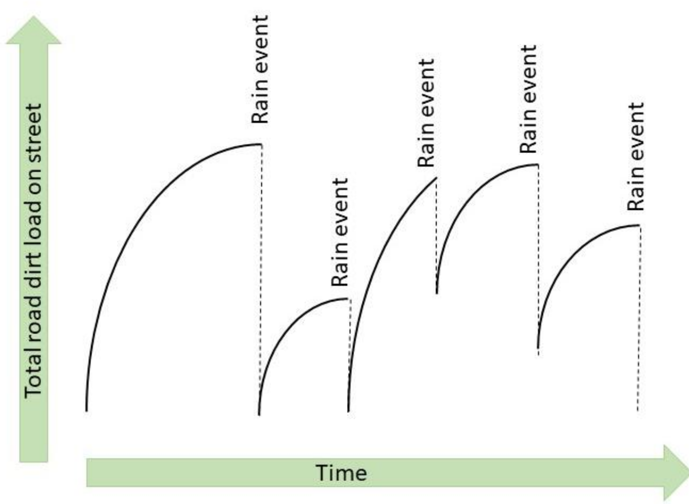

Figure 2.7. Schematic illustration of the hypothetical accumulation of particles dependent on the size of the rainfalls as well as the time between the rain events. The relationship curves have different incline and curvature due to different environmental factors such as weather and traffic intensity. Street sweeping affect the accumulation but is rarely made on rural highways and is not included. Based on Sartor and Gaboury (1984).

For roads built after 2015, the standard dimensions of the transverse slope are to be at least 2.5 %, and where that is not fulfilled should the lengthwise slope be at least 0.5 % and at most 3 % (The Swedish Transport Administration, 2015).

2.4.2. Verges

During precipitation, the tyre and road emissions are either transported to a drainage system with gutters or with the water from the road to the ground alongside the road to the verge. The verges and ditches are designed to transport received precipitation from the road by direct infiltration or to a closed or open stormwater system, to be released to a nearby recipient (Wagner et al., 2018). However, most of the particles are to be deposited relatively close to the road according to an older study by Cadle and Williams (1975).

Some studies have been made on the contamination removal effectiveness of ditches and swales adjacent to highways. Still, studies on microplastics are rare and the majority is focused on metals, hydrocarbons, and suspended solids (Vogelsang et al., 2019).

Filter strips, or grassed verges, are used to remove suspended solids, mostly due to the increased hydraulic retention time. However, the removal rate of both contaminants and water are widely distributed in reviewed literature. Generic indicators of verge removal were by Winston et al. (2016) found to be increased with decreased slope, increased length and decreased size of the watershed area. A normal verge is not considered as a treatment step but is mostly constructed to reduce the quantity of water from the road, nevertheless it might have an ability to retain particles. (Vogelsang et al., 2019). In contrast, ditches that are specifically constructed to clean the stormwater, called "*swales*", are covered by grass and have a flatter lengthwise incline (The Swedish Transport Administration, 2003). For good particle removal effect, the lengthwise incline of the swale should be in the interval 0.5-3 % according to The Swedish Transport Administration (1998). If the incline is steeper, the retention time is reduced as well as the particle removal. The removal efficiency of suspended solids has in swales been estimated to 60-90 % by Polmit (2002), supported by Åstebøl and Hvitved-Jacobsen (2014). Vogelsang et al. (2019) expected the removal of suspended solids to 57 %.

The soil type and transverse elevation are strongly governing factors for the treatment efficiency, where soils with high percolation potential such as sand achieve increased infiltration (Vogelsang et al., 2019). Vogelsang et al. presents an optimal infiltration rate in verges when the hydraulic conductivity is between $1.3 * 10^{-6}$ and $1.6 * 10^{-5}$ m/s, thus not too slow due to space requirements, but not too fast since it then limits sorption of particles. The hydraulic conductivity is shown to be positively related to vegetation due to the changes in soil structure created by biological activity (Grip & Rodhe, 2009). This indicates that a grass-covered mix of silt and sand in the verge area is the most effective contaminant remover material. During wintertime, when the ground is frozen, the infiltration may be reduced or stopped (Åstebøl & Hvidted-Jacobsen, 2014). Above-surface runoff, called Horton overland flow, presumes that the top layer of the soil is saturated (Grip & Rodhe, 2009).

Another study was made by Bäckström et al. (2006) on suspended solids removal in swales in Luleå, Sweden. The main findings were that once particles were trapped in soil or vegetation, they are not permanently bound to that spot, but can be released in another storm event. Bäcktröm et al. mean that a swale rather is a facility that mitigates the peaks in contaminant loading, instead of a water treatment process itself. Negative removal effects, that the swale released previously trapped contaminations, were observed when the swale received low contaminant concentrated road runoff. This phenomenon is hence termed contribution. Another finding was that the removal effect can be connected to the impervious against the grassed area ratio. In this study, the verge area constituted of 50 % of the road area, and an average particle reduction of 15-20 % was measured (Bäckström et al., 2006). Regarding the runoff volume in the same study, 90 % of the runoff water infiltrated in the swale at a rain event after a three-week long period of dry weather. However, for the less extreme events with more precipitation in the antecedent days and when the inflow rate to the swale approached 1 L/s, the infiltration was shown to be relatively small. Road runoff quality as well as swale runoff quality varied a lot during every event, but suspended solid concentrations were higher during the first hours of the event. The particle size distribution tests showed that the concentration of particles between 4 and 120 µm in the road runoff were 100 million particles per litre, and 70 million in swale runoff. More than half of the particles were smaller than 6 µm. However, the number of small particles 4 - 9 µm, varied a lot between events, while the number of larger particles, > 25 µm were more constant during the study period (Bäckström et al., 2006). During high contamination loading rates, the grassed swale retained larger amounts of contaminations, mostly due to sedimentation, but almost only large particles,>25 µm, were retained, while smaller sizes passed through the swale. Particles in the size interval 9 - 15 µm seemed to be the most easily transported sizes out of the swale. A representation of an event mean concentration of all events in the study is shown in *Figure 2.8,* with both contributing and removing effects. However, when flow rates increase, the water can carry larger particles. The removal is exponentially positively connected to retention time, and in another study by Bäckström (2003) a removal rate of 90 % of the particles >25 µm during a residence time of 5-7 min in a grassed swale was shown. Contribution from the verge was shown when the swale received low contamination concentrations, also in this study. However, Bäckström et al. (2006) points out that it is difficult assign out a specific removal rate for a grassed swale.

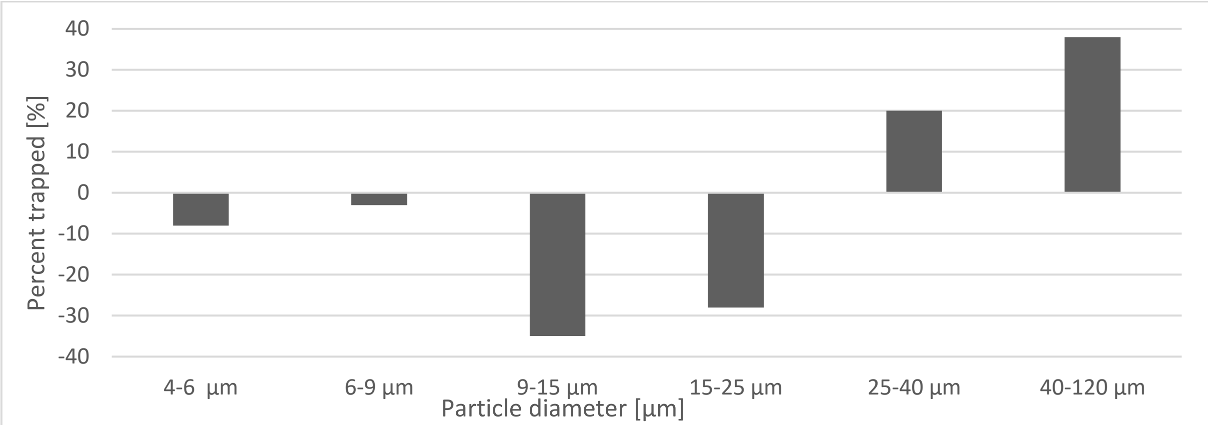

Figure 2.8. Particle removal and contribution observed in a 110 m long swale in Luleå, by Bäckström et al. (2006), modified by the author. Here defined as the average event mean concentration in the outgoing water during seven rain events.

Blok (2005) describes that road runoff is likely to infiltrate within 0.75-1.5 m, presented in Figure 2.9. Due to air transport and splash, particles can also be transported to the verge. Broeke et al. (2008) means that only 10% of the tyre and wear particles are released from rural roads into surface waters while 90% remain in soil. However, when applying the removal rates in models, estimations have to be done. Unice et al. (2019) estimated a portion of 49% for soil, 49% for runoff and 2% for airborne transport.

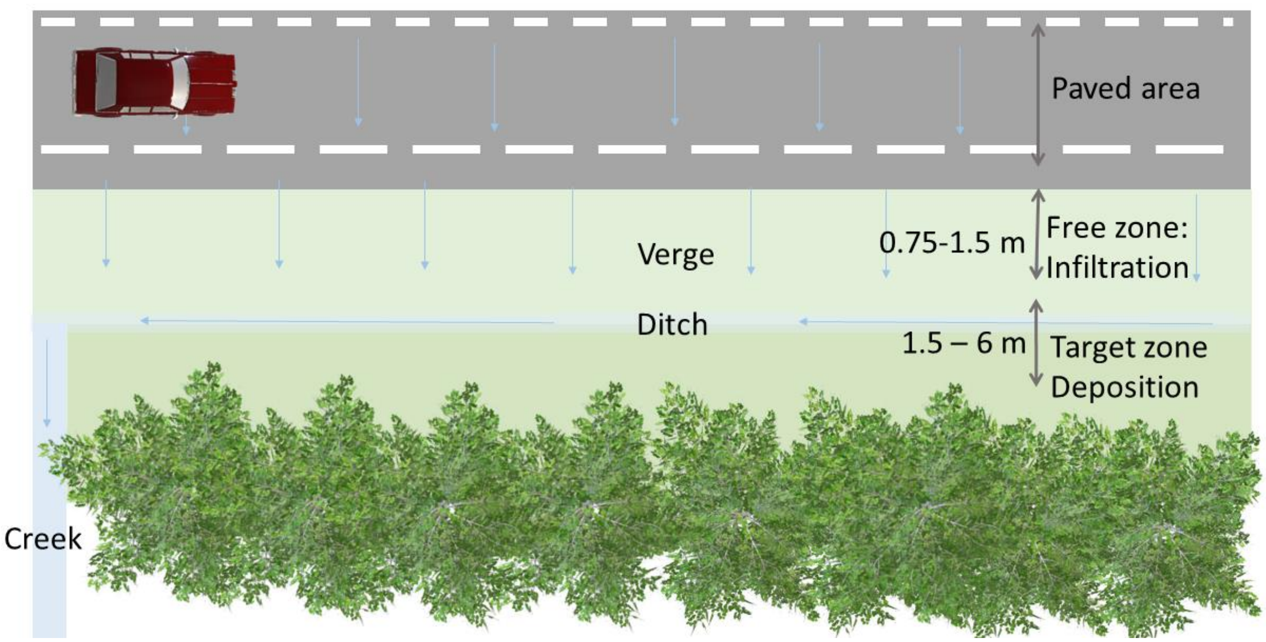

Figure 2.9. The different zones in the road area, from Blok (2005) modified by author.

Regarding the effect of grass cover, a study by Montaldo et al. (2020) shows that the runoff coefficient was reduced with 30 % when the grass was at its maximum height (25 cm) compared to no grass cover.

Biodegradation in the grassed areas alongside the road has shown effect of contaminant concentrations. Cadle and Williams (1979) showed in a study made in California that the half-life of microplastics is about 16 months in dry conditions. But this calculation is noted to be strongly site and condition specific.

Not all verges are constructed in a standardised way due to local variations and current technology and knowledge. Older rural roads are having slightly steeper ditches compared to the ones constructed today, which might derive from that stormwater traditionally has been an issue of quantity instead of quality (M. Lindqvist, personal communication September 29th, 2020). According to current regulations is a ditch to be constructed with a minimum alongside slope of 5‰ and have the shape of a trapeze (The Swedish Transport Administration, 2016; The Swedish Transport Administration, 1994).

2.4.3. Vegetation and organic matter

Wetlands are highly efficient in removing contaminants owing to the plants. Plants also help keeping the speed of the water down, which creates a better environment for particles to settle out (Ji, 2017).

Plant debris from riparian vegetation is a large source of organic matter, particularly to headwater streams (Dosskey et al. 2010). Streams with a large portion of adjacent riparian vegetation may be an object for accumulation of plant debris when the channel gets narrower. Aggrading channels can cause a raise of the water surface level (Dosskey et al. 2010).

Helcoski et al. (2019) presented a lower abundancy of microplastics in a wetland area in Washington with dense vegetation compared to the channel edge and proved that stem density and plant cover had a significant negative relationship with the total number of microplastics. Helcosci at al. (2019) found high abundancy of microplastics in the channel edge habitat, which could mean that vegetation may be effective at trapping suspended particles. In constructed water treatment wetlands, dense emergent vegetation is found to have removal rates of 90-97% for suspended solid particles (Convey et al., 2002). According to Seixas et al. (2019) is organic matter such as wood influencing the channel morphology by creating basins in the longitudinal profile, which trap sediments and may affect the stream power.

2.4.4. Stream characteristics

Stream geomorphology is the interaction between streams and the surrounding landscape. When water flows in a channel erosion of sediments from the outer stream banks occurs, and as well deposit of sediments in the inner banks. This creates a meandering shape of the stream (Grip & Rodhe, 2009).

Headwater streams can be divided into three basic flow classes; perennial or permanent, intermittent, and ephemeral (Fritz et al., 2013). The flow depends on seasonal changes, but perennial streams do not experience drought, intermittent streams might be dry during the dry season and are less predictable. Ephemeral streams are always above the groundwater table and only react on precipitation or snowmelt (Fritz et al., 2013).

The stream properties affect the transport processes. The hydraulic radius is described by the ratio of the cross-sectional area compared to the wetted perimeter. The wetted perimeter is the bed cross-sectional length of the bed load in contact with the water. The lower hydraulic radius, the more friction forces affect the bedload and cause turbulence. This bedload can be covered with sedimented hyporheic organic matter and is called the hyporheic zone. A headwater stream generally consists of different sections with different properties of the hyporheic zone and different hydraulic radius (Grip & Rodhe, 2009).

2.4.5. Weather

Since water is the major transportation medium of particles, the water balance in the channel, see *Equation 3.2* is of high importance. A schematic depiction of the water balance is presented in Figure 2.10.

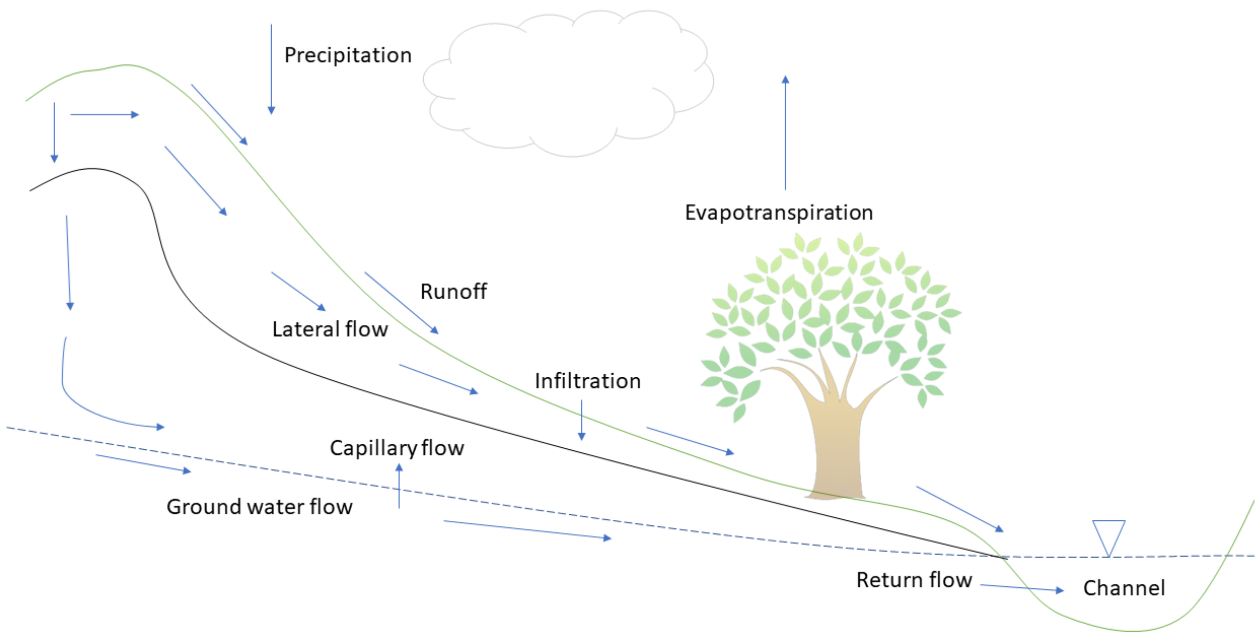

Figure 2.10. Water balance in the watershed area of a perennial stream, with the processes used in the water balance equation, described in Section 3.3. Based on information from Grip and Rodhe (2009).

Precipitation intensity plays a large role for the fate and transport of microplastics. A heavy rainfall flushes more particles off the road down to ditches and nature. Heavy rainfalls also generate high flows in watercourses which entails in a higher flow energy and a longer transport for a particle before settling (Andersson-Sköld et al., 2020). A precipitation of at least 2 mm/day is essential to mobilize the particles (Bäckström et al., 2006; Unice et al. 2019).

Brodie (2007) presented that particles start to accumulate on the road roughly two hours after the start of a small rain event (0.5-2mm/h). When the rain intensity exceeds the Rainfall Detachment

Index (RDI) threshold, particles start to move with the water. This might cause a peak in particle concentration in the first flush of precipitation water. RDI is dependent on how well the road retrain water and particles, which means dependence of the incline and road micro and macro structures (see Section 2.4.1). Brodie presented an exponential relationship for the particle load washed from a surface, presented in *Equation 2.7*.

$$L = L_0(1 - e^{-kX}) \qquad \textit{Equation 2.7}$$

- *L = Particle load washed from the surface [g]*
- *L_0 = Particle load on the surface available for washoff at the start of the rainfall [g]*
- *k = Proportionality constant (0.125 used for road surface by Brodie (2007))*
- *X = Rainfall parameter [mm/h]*

For a rain event longer than five hours, no clear relationship between the precipitation intensity and number of particles transported from the road has been found (Brodie, 2007). Unice et al. (2019) used a linear relationship with threshold value of 2 mm/day where a rate of 0 % particles were washed off, to 100 % of the particles washed off at a rain intensity of 5 mm/day or more.

In warm and sunny weather, the water loss due to evaporation is greater than in cool and cloudy weather (Grip & Rodhe, 2009). However, on rain occasions, the rain clouds block the sun and the air temperature often drops, why the evaporation is considered negligible during rain occasions.

Snow at the roadside might store particles. When melting, snow can bring larger water flows and hence entail a longer transport for the particles. Additionally, it causes a higher concentration in the water to the stream in similarities with what occurs in a first flush (Andersson-Sköld et al., 2020).

Wind transportation may affect the number of particles accumulated on the road surface. The transport distance is dependent on wind speed, particle size, and local topographic features. Tread wear particles up to 30 µm have been noticed to be airborne, but particles > 10 µm are not likely to be airborne for too long (Cadle & Williams, 1978). Tread rubber content along roadside was in the same study measured to 80 % within 5 m from the road, transported by either wind, splash or runoff water. Vogelsang et al (2018) means that only 7 % of the total mass of all particles are assumed to be in the size < 30 µm, why the long-distance wind transport is relatively small on a location with normal wind conditions. In agreement with the previous study, Bjekås and Lindmark (1994) assume that only 5 % of the tyre wear particles are airborne, which is supported by Baensch-Baltruchshat et al. (2020). Particles in the sizes 1-10 µm can reside in the air from minutes to hours and move from 100 m to 50 km (Kole et al., 2017). Panko et al. (2013) means that maximum of 10 % of the total weight is reduced by wind transport.

Broeke et al. (2008) assumed that 6 mg/vkm were released as airborne particles (PM_{10}), but none would end up in the road runoff. However, due to typically wet conditions in Gothenburg, more airborne particles are assumed to be deposited to the ground, and Vogelsang et al. (2019) set assumingly 25% of that for the larger particles in the PM_{10} range. Even though the airborne mass transport in wet conditions is assumed to be less than airborne mass transport in dry conditions, solution in small waterdrops in spray and splash is a transport path to be included (Vogelsang et al., 2019).

2.4.6. Stream power

Stream power (Ω) [W/m] represents the rate of energy dissipation per unit downstream due to friction and work at the stream bed banks (De Rosa et al., 2019). The formula is given in *Equation 2.8*.

$$\Omega = \rho\ g\ Q\ S \qquad \textit{Equation 2.8}$$

- *ρ = Density of water [kg/m^3]*
- *g = Gravitational acceleration [m/s^2]*
- *Q = Flow discharge [m^3/s]*
- *S = Local channel slope [-]*

Since the discharge is strongly weather dependent, simplifications must be made why the bankfull discharge traditionally is used in the calculation. The power of the flash flood affects the potential for sedimentation due to the shortened residence time (Unice et al., 2019).

With the use of Geographic Information Systems (GIS) and local geographical data, a local stream power value can be determined, with a cell size governed by the DEM resolution. Hence, when analysing small streams, the DEM resolution is strongly decisive for the outcome.

3. Methodology

To study road related microplastic fate in natural areas, several scenarios for the case study area were set up in a mass balance compartment model to capture the span of spreading in space and time. To obtain the flow conditions, simulations in the GIS based Soil and Water Assessment Tool (SWAT) were made, with additional analyses of stream power made in GIS, complemented with field studies. The factors affecting the spread were then analysed separately from a baseline scenario to distinguish the effect on the outgoing concentration of microplastics.

3.1. Study area

The studied stream is the largest stream in a small watershed of approximately 0.75 km^2, and the stream stretches through the watershed, crosses highway E20 in the upstream part, and discharges in Säveån downstream. The studied part of the stream is downstream from E20 and stretches 1200 m with an elevation difference of about 80 m, see *Figure 3.1*. The flow in the stream is highly weather dependent and can vary from dry to about 100 L/s. The case study area was chosen based on accessibility for field visits, and no other research has previously been done in the area.

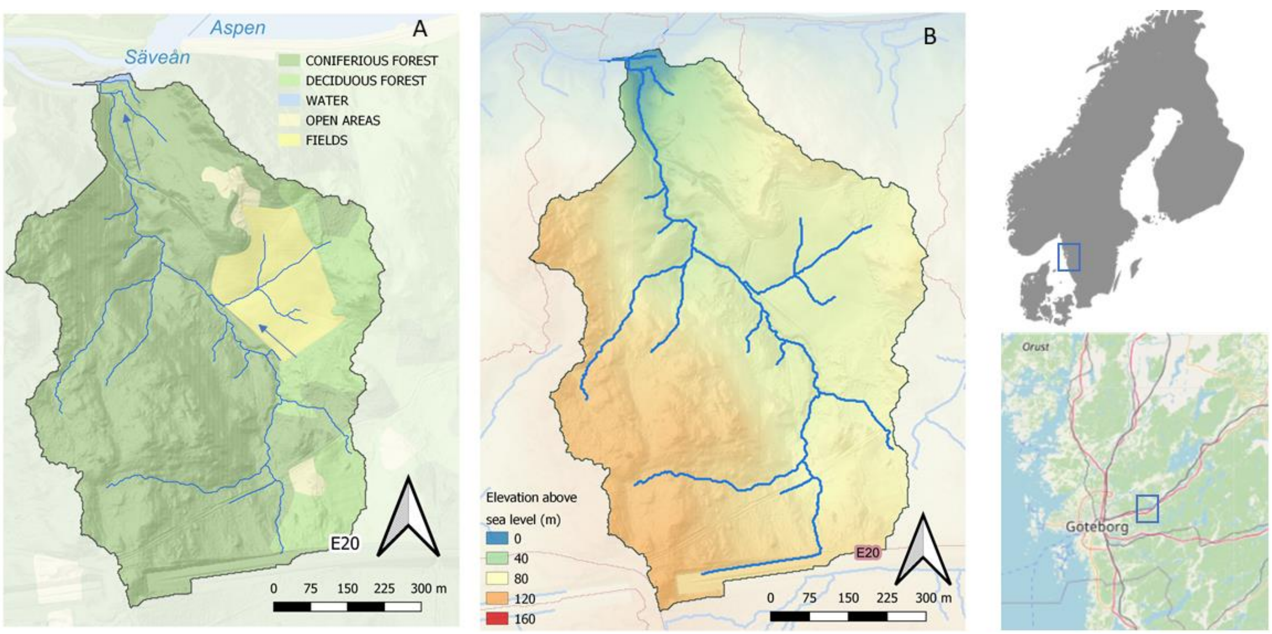

Figure 3.1. An overview of the study area is presented in A, with the runoff area to the stream marked with a thin black line. The direction of the flow is marked with blue arrows. In B, the elevation above sea level is presented in a coloured scale. (OpenStreetMap Contributors, 2020). The upper part of the watershed is not covered by the map since the microplastic particles are assumed to travel downstream.

A slope profile of the stream was obtained with the free software QGIS's plugin Terrain Profile Tool, presented in *Figure 3.2*. Both the profile and the incline of the stream channel are presented.

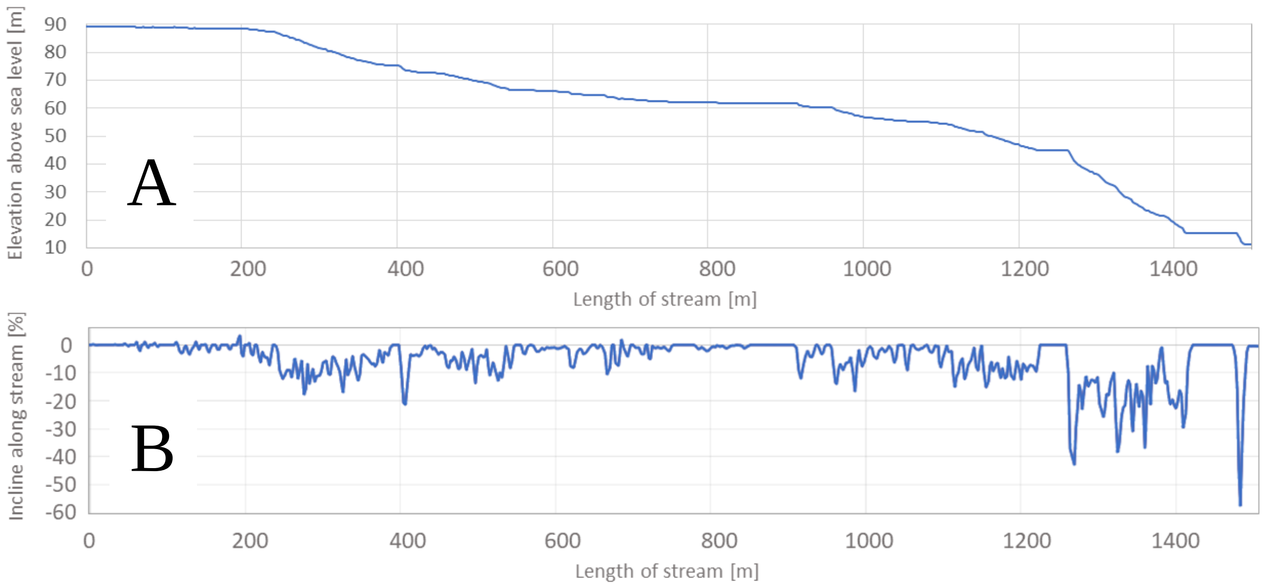

Figure 3.2. In A, the elevation of the stream channel is presented, with start in the ditch on the northern side of the highway. B presents the incline along the ditch and the stream. Both graphs are produced with the free software QGIS based on LIDAR-elevation data.

The soil type in the watershed is mainly rock, while where the stream flows, the soil type is sandy moraine, glacial clay, glacial deposits, and rock (SGU, 2020), presented in *Figure 3.3*. The soil type where the road is built is sandy moraine, which as stated by Fagerström and Wiesel (1972) has a hydraulic conductivity of 10^{-6} to 10^{-8} m/s. Small magazines, like thin layers of moraine on rock, as well as soil types with low porosity, react fast on precipitation or drought (Geological Survey of Sweden, 2020).

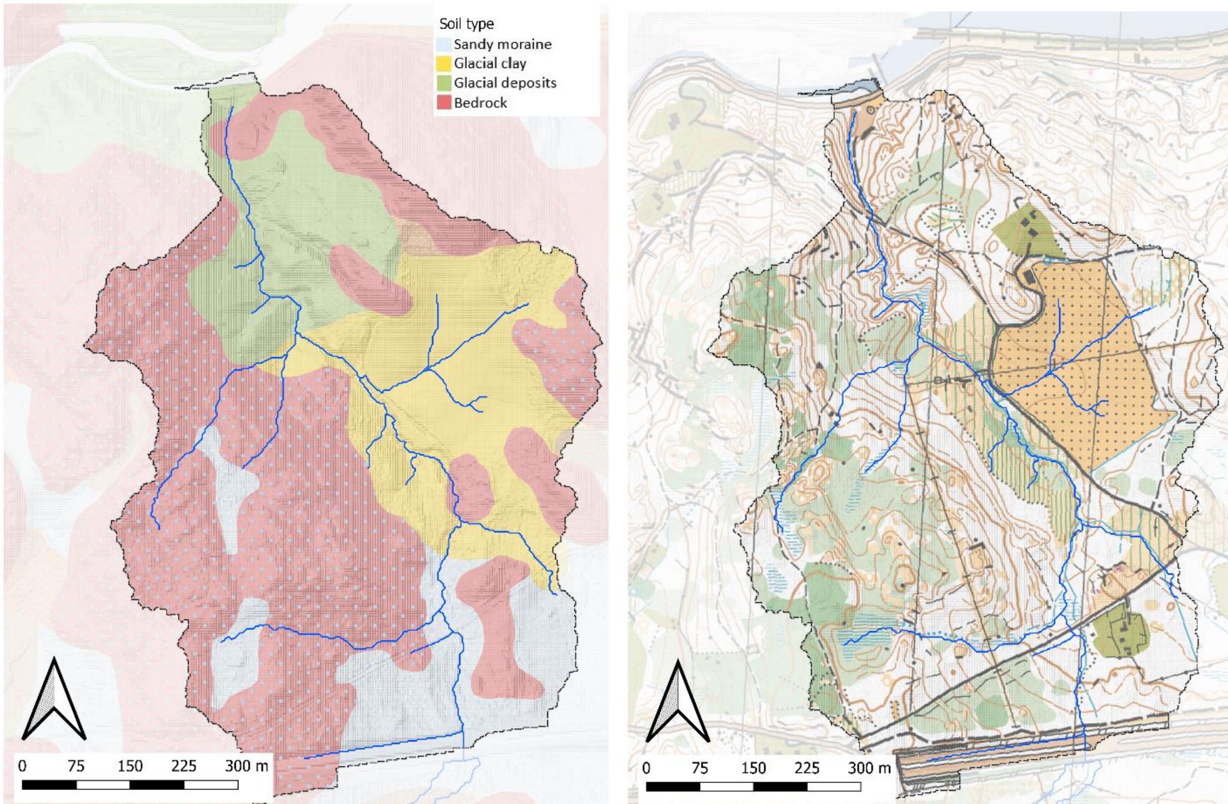

Figure 3.3. The soil type in the area is shown in the left picture. The area consists of mainly rock, but where the stream flows the soil type is sandy moraine, clay and glacial deposits. The map was made using data from the Geological Survey of Sweden (2020). Soil type map covers Jonsered Östra. In the right picture an orienteering map over the area is presented, showing features such as smaller gravel roads, farmlands and anthropogenic features.

E20 is a two laned highway stretching between Gothenburg and Örebro in Sweden and was built in 1964. The area of the road covered by the watershed, as estimated with the hydrological analysis tool in GIS stretches 315 m along the road, and due to the transverse slope of the road water drains away from the central part of the road. No stormwater pipes are documented to be installed in the area, but a culvert is carrying the water under the highway from the southern part of the watershed. An estimation was made that all water from the northern two files along the 315 m stretch are within the runoff area of the studied stream, as well as the southern lanes but via the culvert under the road. This was emphasized with studies of the cross section of the road, shown in *Figure 3.4*Figure 3.4. The transverse slope is calculated to appr. 2.1 %, and the mean alongside slope is close to 0 %. By assuming each lane to have a width of 3 m, and the outward shoulder to have a width of 2 m, the paved area within the watershed was estimated to have an impervious surface area of 5040 m^2. The verge sloping down to the ditch is covering a width of 2 m on each side which gives a verge area of 1260 m^2, which is 25 % of the impervious area.

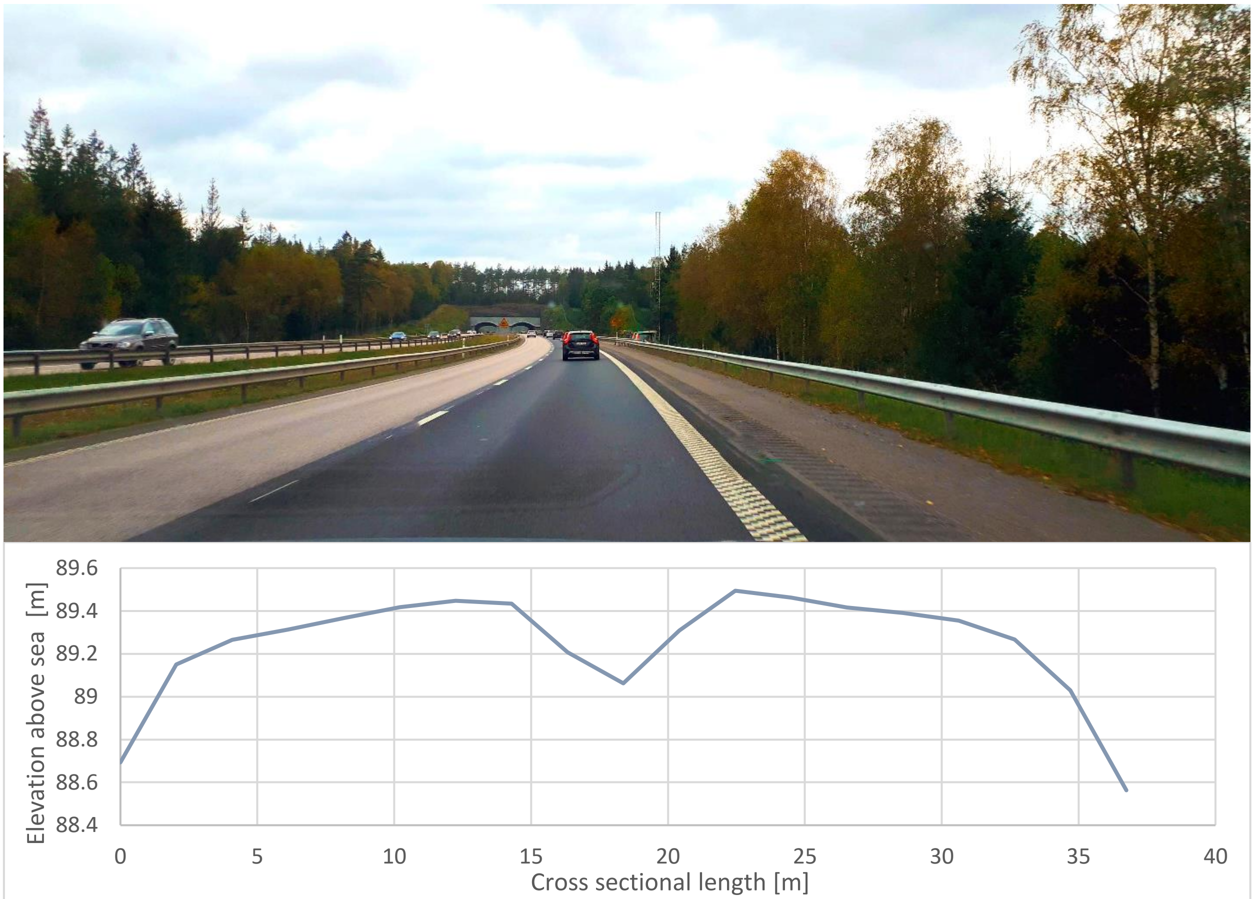

Figure 3.4. Top: overview picture of the case-study road stretch E20. Bottom: Profile of E20 and its transverse slope, from north to south. The graph was produced with the free software QGIS based on LIDAR-elevation data from Lantmäteriet (2020)

3.2. Microplastic emission estimate

The chosen calculation approach estimates the total emission of microplastic on the selected stretch of the highway, whereby traffic intensity is given in vehicles per day, multiplied by an emission rate given in grams per vehicle km. The road specific tread emission estimate was calculated with *Equation 3.1* from Vogelsang et al. (2019).

$$E_{r,t} = \sum\nolimits_{r,i} L_r \, N_{r,i,t} \, EF_i \qquad \textit{Equation 3.1}$$

- $E_{r,t}$ = *Total emissions along the road section length r during the time period t [g/day].*
- L_r = *Length of the road stretch r [m].*
- $N_{r,i,t}$ = *Number of vehicles in each category i during the time period t (from AADT data)*
- EF_i = *Rate of emission per vehicle in each category i [g/vkm].*

Except the effect of studded tyres, the factors affecting the emission rates, see Figure 2.1, were not considered to affect the emission rates in the different scenarios and were considered outside the scope of the study. This due to the high uncertainties in the existing studies of the emission rate. The effect of studded tyres was however used since it affects the rate substantially and can be considered as binary (either used or not used). Hence, an average value of the emission rate without the use of studded tyres was obtained by taking the average of the emission rate from several studies, see Appendix I, Summary of emission rates. These values were used in the calculation of the emitted mass, see *Table 3.1*. In the sensitivity analysis of the different factors, see Section 3.7, the average of the upper range value and the average of the lower range value was used to include the whole emission range.

In 2018 the annual average daily traffic in both directions of road section no. 7120017 in the Road Traffic Flow map was measured to a total number of 37 360 vehicles, where 3 370 (9%) of them were classed as heavy vehicles. The speed limit at the stretch was 100 km/h and the incline along the road was negligible (Trafikverket, 2020).

Table 3.1. Wear factors and estimated emission on the road stretch, based on emission rates from previous studies, see Appendix 1. The average value represents an average value of the studies which estimated a wear rate

	AADT, 2018, $N_{r,i,t}$ [v/day]	**Length, L_r [m]**	**Light vehicles (91%)**		**Heavy vehicles (9%)**		
			Wear factor, $EF_{i,j}$ [g/vkm]	Daily emission, $E_{T,r,t}$ [g]	Wear factor, $EF_{i,j}$ [g/vkm]	Daily emission, $E_{T,r,t}$ [g]	Total emission, $E_{T,r,t}$ [g]
Lowest	37360	315	0.058	621	0.35	374	995
Highest	37360	315	0.275	2941	1.04	1097	4038
Average	37360	315	0.097	1033	0.69	735	1770

3.3. Flow modelling

A dataset of the stream network and corresponding flows in the studied area was set up in the USDA-ARS developed Soil and Water Assessment Tool (SWAT) and validated with field studies. The incline of the road and nearby ditch was assembled by using the GIS-based plugin Terrain Profile Analysis Tool.

3.3.1. Soil and Water Assessment Tool

SWAT was developed to predict the consequences of land management practices on the hydrology, contaminant, and sediment transport, using the concept of hydrologic response units (HRUs) (Arnold et al., 1998). The runoff from each HRU is calculated separately from data about topography, soil properties, weather, and land use. Currently, no plugins for microplastic transport are available for SWAT, thus only the hydrological predictions in SWAT were be used. The runoff and simulated hydrologic cycle are based on the water balance equation, *Equation 3.2* from Arnold et al. (1998):

$$SW_t = SW_0 \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right) \qquad \textit{Equation 3.2}$$

- SW_t = *final soil water content*
- SW_0 = *initial soil water content*
- R_{day} = *amount of precipitation*
- Q_{surf} = *amount of surface runoff*
- E_a = *amount of evapotranspiration*
- W_{seep} = *amount of water entering the vadose zone from the soil profile*
- Q_{gw} = *amount of return flow*

The stream network was created with a D8-flow routing algorithm based on a 2x2m Digital Elevation Model-raster GRID 2+ (DEM) generated from LIDAR data. The mean error of the national Digital Elevation Model GRID 2+ for open hard surfaces is 0.05 m in elevation and 0.25 m in plan (Lantmäteriet, 2020).

The metrological conditions were based on historical daily precipitation, humidity, wind speed, solar radiation and temperature data from the two closest active metrological stations Göteborg A and Landvetter Flygplats by SMHI. Data with start in 2015 were used to warm up the model to then predict the flow for the years from 2017 to 2020. Further description of the SWAT procedure is presented in Appendix II.

3.3.2. Stream Power modelling

The Stream Power was modelled in QGIS with the DEM-raster as input. From the DEM-raster, the Stream Power Index (SPI) was in the raster calculator computed with the raster layers flow accumulation and slope. The flow accumulation layer was adapted to the cell size and the slope layer was converted from grades to radians, according to *Equation 3.3*.

$$SPI = (\alpha * cellsize) * \tan(\beta * \pi / 180) \qquad \textit{Equation 3.3}$$

- α = *Flow accumulation*
- β = *Slope*

3.4. Compartment Mass Balance Model

A compartment model is usually made to represent the transport of material in systems such as biological processes and chemical and ecological interactions (Laínez-Aguirre et al., 2014). The mass balance is by Chapra (1997) described in *Equation 3.4.*

$$Accumulation = loading - outflow - reaction - settling \qquad \textit{Equation 3.4}$$

A rough compartment model with the transport processes was set up to build a first estimation and a ground for future models of microplastics in small waterways, see conceptual model in *Figure 3.5*. The parts of the stream where the water speed was slow were assumed to be a place for particles to settle, thus the compartments were divided according to the elements affecting the water retention time in mind. The compartment division was mainly made based on field studies of the flow and the flow conditions, but the incline, depth of the stream channel and occurrence of obstructive debris were also considered, see Section 3.5.

The compartments were calculated separately with the software Excel by Microsoft, and inflow of water and concentration of microplastics were transferred downstream in the system. The reduction of microplastics was calculated with Hazen´s surface loading theory, where the surface loading speed was compared to the settling velocity of each particle class. A critical particle size for each inflow to a basin was calculated, where all particles larger than that size were assumed to be deposited. Since the water flow in the stream might be influenced by groundwater and surface water runoff from the whole watershed, different flow was used in a compartment downstream compared to the previous one, simulated by SWAT.

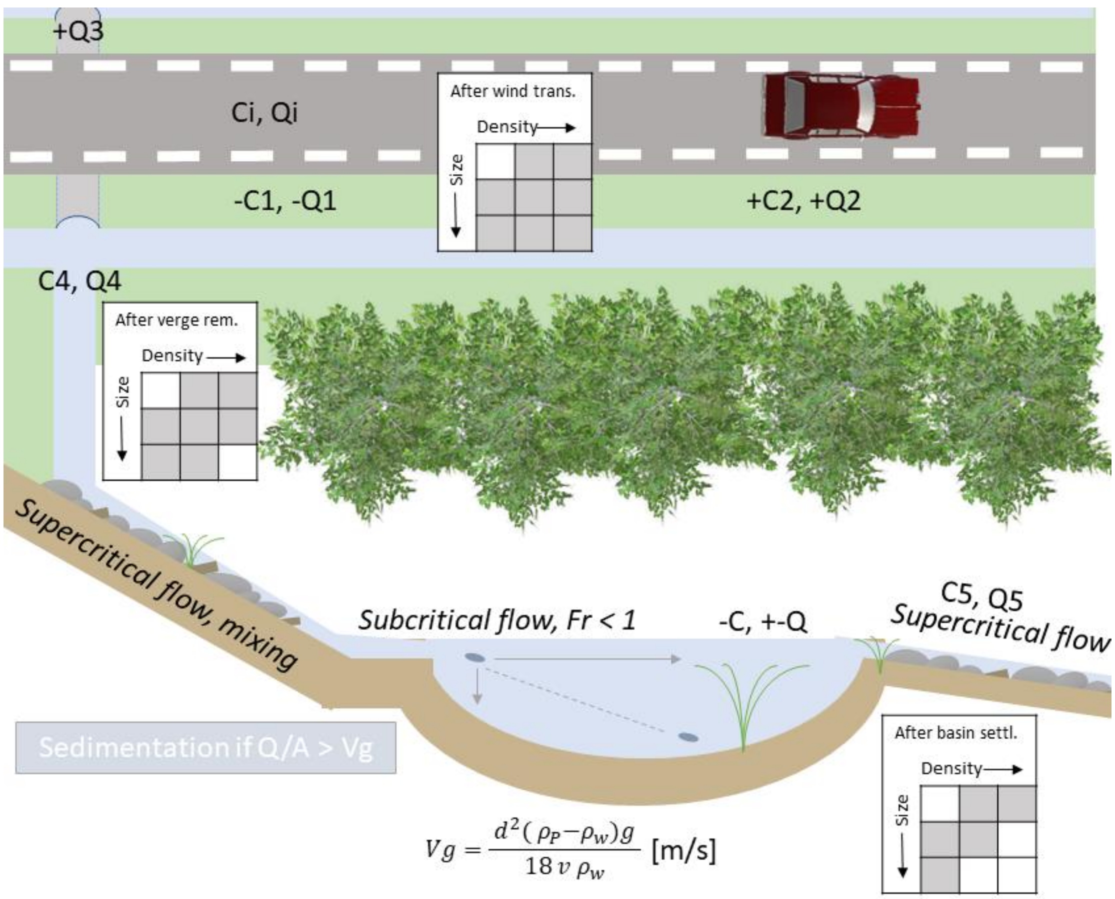

Figure 3.5. Schematic sketch of the compartment modelling procedure. The effect of the different transport processes is calculated within each compartment, to obtain a new concentration to be transferred to the next compartment. The flow simulation will provide the compartment model with the change in flow. The tables signify the particle size-density distribution where the grey squares represent the particles still in transport. C corresponds to the concentration, Q for the flow, Fr for Froude's number, A for surface area and Vg for the settling velocity.

3.5. Field studies

First, the area adjacent to the highway was investigated. This means presence of sewage systems and their position if there are any. The length of the grass in the verge was also investigated.

Cartography of the water pathways was made on three occasions: first, on a rain event when the ground was expected to be saturated with water after several days with rain and second after a rain event after previous wet days and third, after some days with dry weather. The field work was initiated in the beginning of November 2020, and finished in beginning of December 2020. The objectives of the field work were to classify the aquatic environment in connection with the stormwater drainage from E20. The documentation was based on previous maps over the study area (mainly detailed maps used in the sport orienteering, see *Figure 3.2*) as well as a stream network created with QGIS.

The classification was based on the size of the sections with similar flow pattern. The flow pattern was divided into subcritical or supercritical flow, by visual judgement. To describe flow pattern, Froude's number can be used. Froude's number is a dimensionless number, which indicates if the flow is subcritical, $Fr < 1$ or supercritical, $Fr > 1$, see *Equation 3.4*

$$Fr = \frac{v}{\sqrt{g * \frac{A}{B}}} \qquad \textit{Equation 3.4}$$

- v =*measured average velocity over the cross section [m/s]*
- g = *gravitational acceleration [m/s²]*
- A = *flow cross section [m²]*
- B = *free surface width [m]*

To illustrate these flow patterns, wave propagation was used. Practically, a stick placed in the water was used, and the flow was classified as supercritical when no upstream waves were present, see *Figure 3.6.*

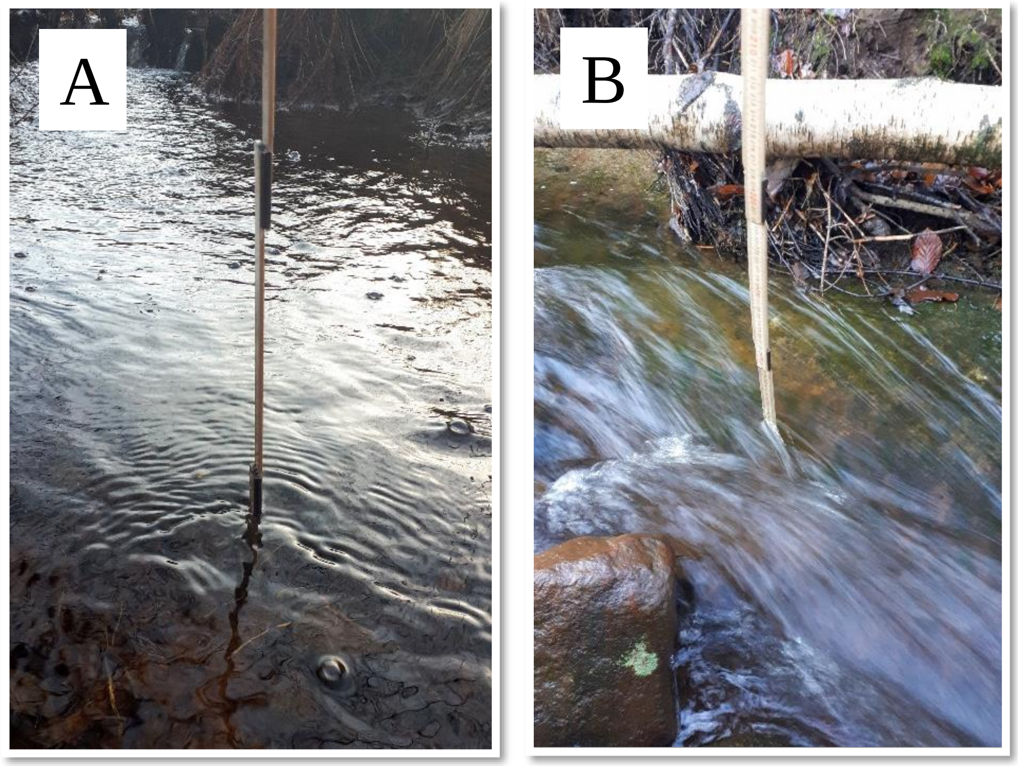

Figure 3.6. Example of measurements of Froude's number with a stick, where in A a typical subcritical flow is shown, and in B a section where the flow is supercritical is shown.

The flow and water speed were documented to validate the SWAT simulation. The flow, Q [m^3/s], was to be measured with a simple suitable method, either the volume-time method (low flow), see *Equation 3.5*, or by calculating the section area of the stream and measuring the speed of the water with an item of similar density as water (high flow), see *Equation 3.6*.

$$Q = \frac{V}{t} \qquad \textit{Equation 3.5}$$

- *V = volume [m^3]*
- *t = time step [s]*

$$Q = k * A_{mean} * v \qquad \textit{Equation 3.6}$$

- *k = constant to obtain a mean speed (0.5 for uneven bottom and fast flow, from Hydromatch (n.d.))*
- *A_{mean}= mean cross sectional area on the calculated stretch [m^2]*
- *v = measured surface velocity [m/s]*

The constant for uneven bottom was set to 0.5, based on data from Hydromatch (n.d.). When a culvert existed, the flow was measured as mentioned above, but without the constant for uneven bottom.

For the compartment division, information about the stream channel was documented with length, depth, and width of the basins with Froude's number equal to or less than 1. The bottom of the stream was documented, as well as occurrence of obstructive debris. The documentation was made by paper and pen, and photographs.

3.6. Simulated scenarios based on definite dates

The dates for each scenario were chosen to cover different kind of real scenarios, and to give a basis for the simulation of different seasonally affected factors, see Section 3.7.

The flow conditions were simulated for four different weather and season scenarios, named D1-D4, to highlight the seasonal differences compared to flow quantities. To capture different seasonal changes, two days in July, one after a wet week and one after a dry week, was simulated. The same selection was made for two scenarios during wintertime. The settling velocities were calculated using Stokes´ law (*Equation 2.3*). In the calculation, assumptions were made that there was fresh water, the water temperature was 4 °C respective 20 °C, and that the particles were spherical. The flow was taken from the SWAT simulation for the date of the specific scenario, and extracted for each basin position based on which sub-catchment the basin was located in.

The size distribution was recalculated to a modified distribution, based on the volume-size distribution by Kreider et al. (2010), but with regards to emission rates of the smaller particles PM_{10} and $PM_{2.5}$ found by Broeke et al. (2008), see Figure 3.7. These data were estimated to be a measure of the volume with zero porosity between the grains, and hence represent the size-mass distribution.

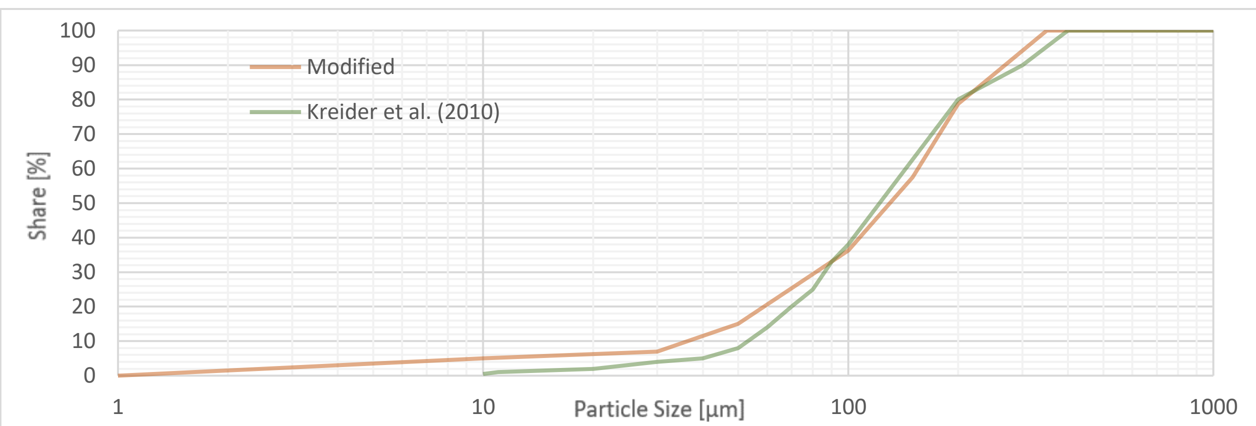

Figure 3.7. Cumulative size distribution used in the model, based on data from Kreider et al. (2010) but modified with recommended ratios of PM_{10} and $PM_{2.5}$ by Broeke et al. (2008). The modified data is compared to the original data from Kreider et al. (2010), however remade by the author smoothed over 18 data points.

The mass of the particles in each category (sorted by size and density) was calculated together with size bin data mentioned earlier, under assumptions that the particles were spherically shaped, and that all particles in the calculated scenario consisted of only three different densities: 1.7 g/cm^3, 1.9 g/cm^3 and 2.1 g/cm^3 which is in the typical density range by Snilsberg (2008). Each density was estimated to be distributed equally over the total emission of 1770 g during the season when no studded tyres are used. In the size-volume distribution, data from Vogelsang et al. (2019) based on Kreider et al. (2010) and Broeke et al. (2008) was used.

Based on the findings by Gustafsson et al. (2019), the microplastic particle generation was expected to be increased in the winter scenarios with 20 % and decreased in the summer scenarios with 20 % from the calculated average emission amount. The share of heavier particles was expected to increase during the colder scenarios due to the use of studded tyres. This share was estimated to 50 % mass of particles or particle aggregates with a density of 2.1 g/m^3.

The sampling made by Kreider et al. (2010) was made in the initial stage of the emission, and no transport processes had yet affected the emitted mass. The first transport process affecting the emitted mass was assumed to be wind transport and was in normal conditions estimated to remove 5-7 % of the total emitted mass. Due to the wet Nordic conditions and the fact that some particles deposit from the air phase to the ground on the road or in the verge, the removal was estimated to be 3.5 % of the total emitted mass, and only in the smallest size range, <10 µm but independent on the density. The splash and spray generated in wet conditions were assumed to land in the verge.

Some of the particles end up entrapped in pores in the paved area, which can be estimated with *Equation 2.6*. This require a rain intensity in an hourly scale, why a simplification for particle wash off from the road surface, by Unice et al. (2019) was used. The simplification estimates a relationship of 0 % of the particles were washed off at a precipitation intensity of 2 mm/day, and 100 % of the particles were washed off at a rain intensity of 5 mm/day or more, described in *Equation 3.7.*

$$x = \frac{y-2}{0.03} \qquad \textit{Equation 3.7}$$

- *x = share washed off [%]*
- *y = precipitation intensity [mm/day]*

When calculating the removal rates in the verge, the case study site shows high similarities with the study site in the study made by Bäckström et al. (2006), why removal rates from that study were used instead of the removal rates from other studies. As described in Section 2.4.2. , Bäckström et al. estimated the loss of particles to 15-20 % when the verge area constituted 50 % of the paved area. This relationship was expected to be linear, why a verge of 25 %, of the road area is reducing the particle amount with about 7.5-10 % of the total mass entering the system in normal conditions. The loss was assumed constitute of particles in the larger size bin, > 25 µm. This is less than in other studies mentioned in the literature study, although considering that this ditch was built as early as in the 1960's, the optimal blend of soil was probably not used. The hydraulic conductivity of the soil at the site is in the lower range (10^{-8} to 10^{-6} m/s) compared to the optimal rate (10^{-6} to 10^{-5} m/s), which indicates a lower treatment efficiency than expressed in studies on the treatment efficiency of swales.

However, for some events, Bäcktröm et al. (2006) showed contributing contaminant rates, strongly dependent on the incoming concentration of the stormwater. To obtain a realistic verge removal or contribution, the dates of the scenarios D1-D4 were compared to the removal rates and precipitation data in the events in the study by Bäckström to find a similarity with the measured removal rates and antecedent precipitation, which are shown in *Table 3.2*. However, with the linear relationship in mind, the reduction and addition were reduced with 50 %.

Table 3.2. Expected removal rates in the swale studied by Bäckström et al (2006), and corresponding expected removal rates in the case study verge

Event from Bäckström et al. (2006)	**1**	**2**	**3**	**7**	**10**	**11**	**12**
Date	2000-05-25	2000-05-26	2000-05-28	2000-06-13	2000-06-20	2000-06-22	2000-06-23
Swale runoff [m^3]	0.8	2.6	0.2	5.1	0.6	1	3.4
Reduction SS [%]	22	47	-129	35	-1	-82	-29
Precipitation [mm]	6.8	13.2	2.7	16.8	3.9	6.7	11.3
Antecedent days without rain (below 2mm/day)	28	0	1	9	0	0	0
Similar scenario	Scenario D4		Scenario D3	Scenario D2		Scenario D1	
Expected reduction in case study verge [%]	11	23.5	-64.5	17.5	-0.5	-41	-14.5

Since the water temperature affects water density and viscosity, the settling velocity in Stoke's law, *Equation 2.3,* is affected. A simplification was made that the temperature of the surface water temperature is 4 °C in winter and 20 °C in summer.

With the relationship between flow energy and sedimentation declared by Chapra (2006), an assumption was made that no or negligible sedimentation occurs when the stream power is high. The number of basins with subcritical flow along the stream was based on the two field visits, one at higher flow and one at lower flow. When the flow was simulated similarly in SWAT as at these field visit dates, the number of subcritical basins were predicted to be the same.

The same argument is as well valid for the surface size of the basins which can be expected to be the same as in either the field visit 2 or field visit 3 when the measurements were taken. When the ground is saturated with water, as often in wintertime or after several days with rain in summertime, the flow is assumed to be in the same order of magnitude as on the field visits. When the ground is dry, especially the shallower marsh areas, where the water flows out over a larger surface area, the water surface was assumed to be smaller.

Table 3.3. Scenarios based on a specific date during winter- or summer time, with description of the effect of the different factors

	Scenario D1	**Scenario D2**	**Scenario D3**	**Scenario D4**
Date	2020-07-06	2020-07-23	2020-11-22	2020-01-27
Flow (out) [m^3/s][a]	0.017	0.005	0.029	0.031
Precipitation [mm/day][b]	8.0	7.0	3.7	9.6
Antecedent number of days with precipitation below 2mm.[b]	0	8	0	8
MP generation compared to standard [%][c]	-20%	-20 %	+20 % and heavier particles	+20 % and heavier particles
Mass-density distribution	Equal over the three different densities	Equal over the three different densities	25 % with a density of 1.7 g/m^3 , 25% in 1.9 g/m^3 , and 50% in 2.1 g/m^3	25 % with a density of 1.7 g/m^3 , 25% in 1.9 g/m^3 , and 50% in 2.1 g/m^3
Wind removal [%]	3.5 %	3.5 %	3.5 %	3.5 %
Share of accumulated MP mass washed off from the road [%][d]	100 %	100 %	57 %	100 %
Verge removal [%] [e]	0 %	18 %	0 %	11 %
Verge contribution [%][e]	41 %	0 %	65 %	0%
Water temperature [°C]	20	20	4	4
Predicted number of basins with subcritical flow[f]	14	19	14	14
Reduced basin surface area[f]	No	Yes	No	No

[a] From SWAT
[b] SMHI (n.d)
[c] Gustafsson et al (2019)
[d] Unice et al. (2019)
[e] Bäckström et al. (2006)
[f] Field visit

3.7. Sensitivity analysis

To analyse the effect of each factor encountered in the studied scenarios in

Table 3.3, each factor was analysed separately, based on a baseline scenario. However, some factors are strongly connected, and were hence analysed in the same process. Some factors were given an average impact in the baseline scenario to study the effect of both high and low rates. These factors chosen were based on studies of the effect on the outcome in the specific date scenarios D1-D4. The flow was chosen from the two field visits when flow conditions were studied.

In all scenarios, except from the conditions described, precipitation of >5mm/day was assumed, as well as 0 days of antecedent dry days. The input data of the sensitivity analysis scenarios are shown in *Table 3.4.*

Table 3.4. Scenarios based on each factor or process. Each scenario proceeds from a baseline scenario

Processes		**Sc F1: Baseline**	**Sc F2: Effect of high flow**	**Sc F3: Effect of high wear rate**	**Sc. F4:Effect of low wear rate**	**Sc F5: Effect of studded tyres**	**Sc F6: Effect of verge contribution**	**Sc F7: Effect of verge removal**	**Sc F8: Effect of low temperature**
Flow [m^3/s] (out to Säveån)	Low, 0.0152	X		X	X	X	X	X	X
	High, 0.036		X						
Wear rate [g/vkm]	High			X					
	Average	X	X			X	X	X	X
	Low				X				
Studded tyres	No	X	X	X	X		X	X	X
	Yes					X			
Basins with subcritical flow	Few, 14		X						
	Many, 19	X		X	X	X	X	X	X
Verge effect	Removal, -0.23%							X	
	Zero effect	X	X	X	X	X			X
	Contribution, +15%						X		
Basin surface area	Small	X		X	X	X	X	X	X
	Large		X						
Temperature [°C]	High, 20	X	X	X	X	X	X	X	
	Low, 4								X

4. Results

In the following chapter, the results of the SWAT analysis, field work and compartment modelling are presented.

4.1. Field observations

The field observations during the three observation occasions at the field site are presented here.

4.1.1. Field observations 3rd of November

During the field trip to the case study area on 3rd of November 2020, flow measurements and observations of the flow conditions were made. The previous three days were wet with a precipitation above 10 mm/day, and the previous 14 days had no dry days and an average precipitation of 7.9 mm/day.

When the stream was meandering, the water speed was reduced and the supercritical flow became more subcritical. Banks of sediment were visible in the inner curve of the stream. Where the water flowed out in more shallow areas, the water speed dropped, and more sediment were visible. Also, a positive relationship between the incline and the turbulence was evident, see *Figure 4.1*.

Figure 4.1. Photographs taken during the field trip on 3rd of November. To the left: Subcritical flow in a shallower segment of the stream, where the slope is flatter. To the right: A segment of the stream where the flow is supercritical and the slope is steeper.

Due to the relatively high flow, the volume and time method (*Equation 3.4*) could not be used. Consequently, the flow in the stream was measured with the floating item method. The flow was measured at 9 points along the stream, where measurements were possible depending on access to the stream and a homogeneous bathymetry of the stream channel. The results of the flow, together with the SWAT simulations are presented in Figure 4.4.

4.1.2. Field observations 22nd of November

During the field trip to the case study area on 22nd of November 2020, flow measurements and observations of the flow conditions were made. It was apparent that the sediments were deposited in the inner curves of the meandering, see *Figure 4.2*. The low stream power was also corresponding to where the water was calmer.

Figure 4.2. Picture of the meandering of the stream during field observations, where the bank in the inner curve shows a deposition of sediments.

The flow was measured at 11 points along the stream. In addition, where the water flow was subcritical ($Fr < 1$), the water surface area was measured or assessed. Along the stream, 14 basins with subcritical flow were discernible.

4.1.3. Field observations 6th of December

During the field observations at the case study area on 6th of December 2020, flow measurements and observations of the flow conditions were made. It was made on a date when the antecedent precipitation was lower than before compared to the previous field observations, to observe the flow patterns during these conditions.

The flow was measured at two points along the stream. Where the water flow was subcritical ($Fr < 1$), the water surface area was measured or assessed. Along the stream, 19 basins with subcritical flow were discernible.

4.2. SWAT modelling

From the SWAT results, a time series over the whole simulation period was extracted, representing the flow out to Säveån with a daily timestep. Seasonal changes can be observed with a higher flow in the winter half year, and a lower flow during the summer half year, see *Figure 4.3*. The flow varies between almost dry to 140 L/s, with a normal winter flow of about 15 L/s.

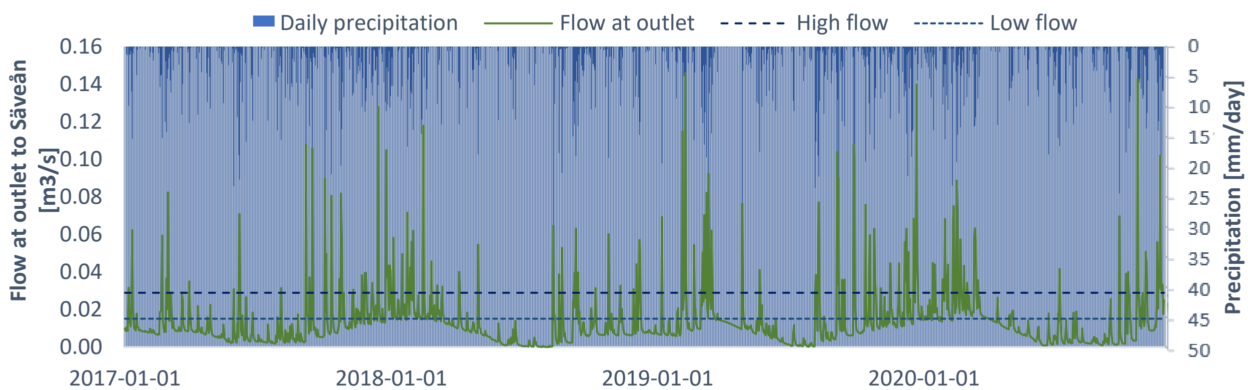

Figure 4.3. SWAT modelled discharge [m^3/s] from the stream out to Säveån (green), and corresponding daily precipitation (blue). Seasonal changes can be seen with a higher flow during the winter half-year, despite low precipitation, and a lower flow during the summer half-year. The low flow from the sensitivity analysis is shown with dashed line, while the high flow is shown with a dashed line with larger gaps.

The SWAT-simulated values were compared to the field measured values, see Figure 4.4, with a sensitivity range of errors in the manually measured flow.

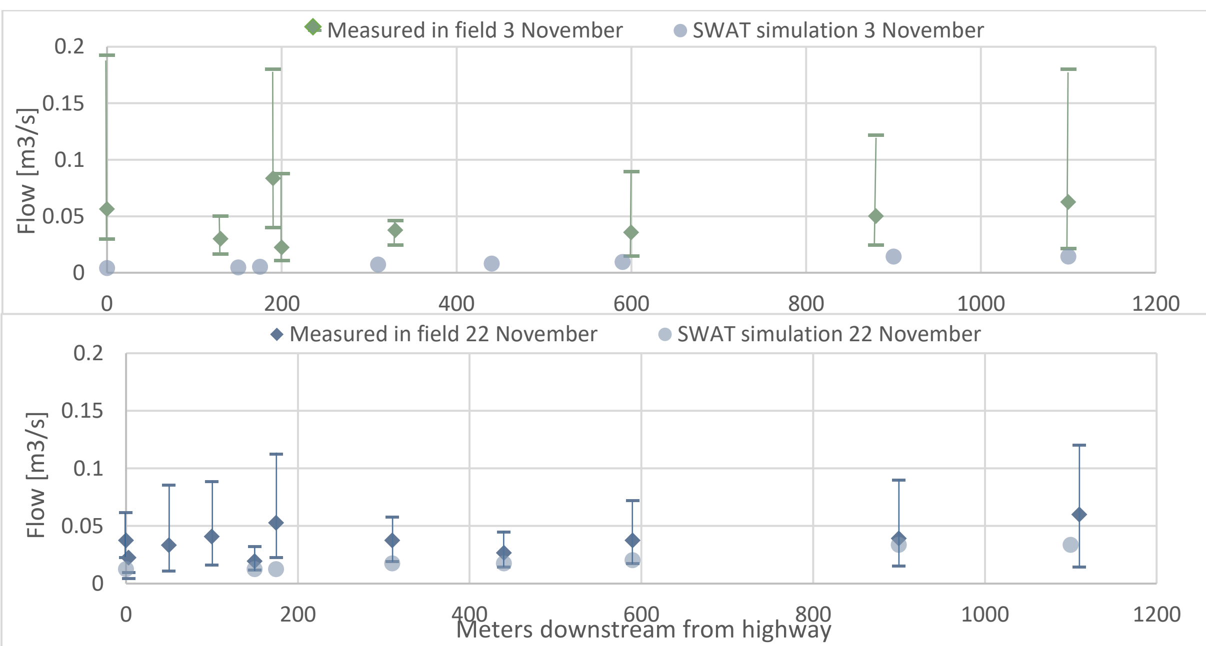

Figure 4.4. Flow at different measurement points along the stream compared to the SWAT modelled flow. The horizontal short lines are representing the sensitivity range of the field measured values based on possible measuring errors.

4.3. Stream power analysis

A model of the stream was created with the GIS Stream Power analysis and is presented in the *Figure 4.5.* The stream power presents where the erosion on the bed load is high, and hence where the energy of the flow is high versus low.

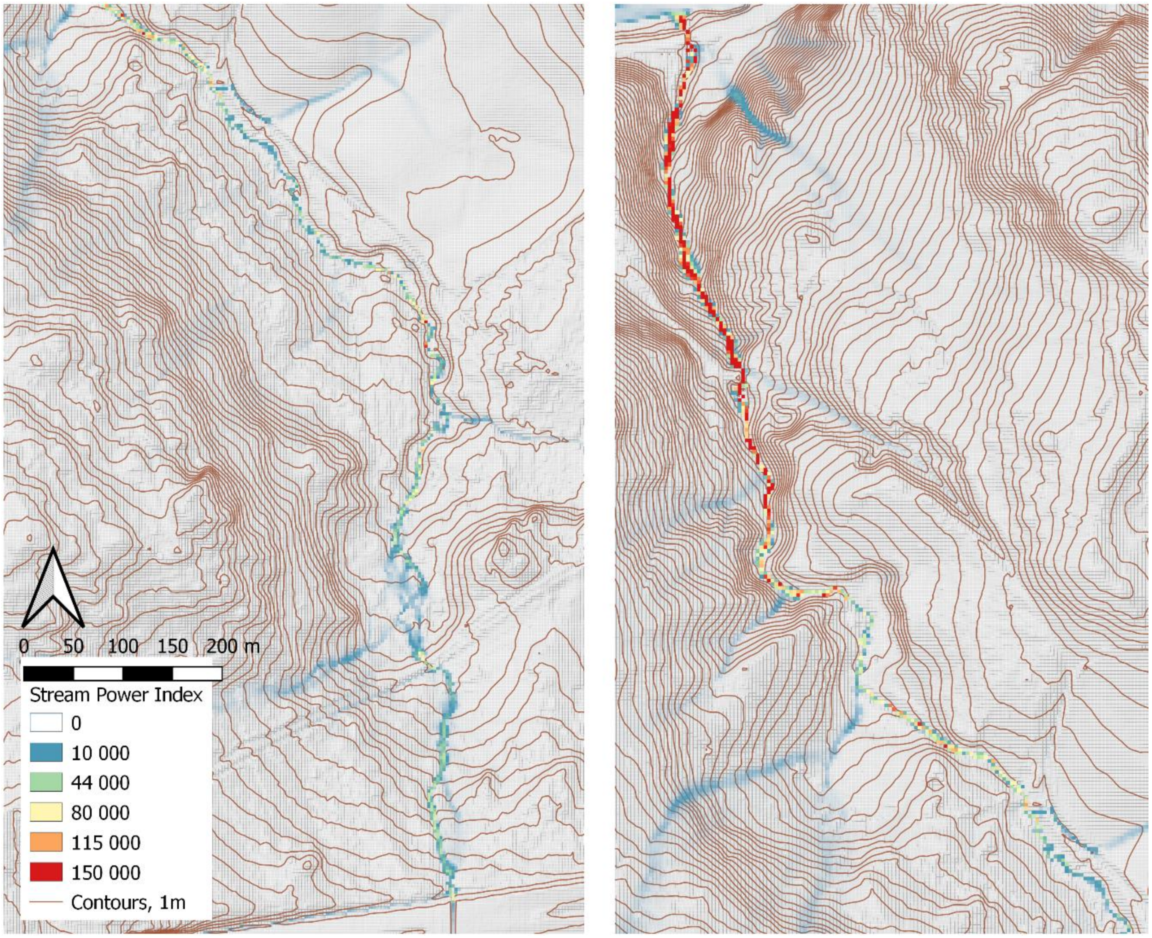

Figure 4.5. Stream Power Index in the catchment area downstream from the highway, with isolines showing the elevation with 1 m equidistance. Where the colours are towards the red, the stream power is high and settling is less probable to occur. To obtain a good resolution and visibility, the figure is separated with the upper part of the watershed in the left picture, and the lower part of the watershed in the right picture.

4.4. Scenarios

In this section, the results from the tested scenarios are presented, both the date-based D1-D4 scenarios, and the sensitivity analysis of the different factors F1-F8.

4.4.1. Scenarios D1-D4

The results of concentration and microplastic deposition in scenario D1-D4 are shown in *Figure 4.6.* The indata to the figures are presented in Appendix III.

Scenario D1 represented summertime and was simulated to represent realistic conditions during the 6th of July 2020 with a precipitation of 8 mm/day and an outflow to Säveån of 17 L/s. Due to no dry antecedent days, the emissions of only one day were accumulated and washed out. However, due to the low concentration in the road runoff, the verge was estimated to contribute with 41 % of the particle mass, accumulated there from previous runoff occasions, and the concentration out from the verge was 48 mg/L. The flow was estimated to be subcritical in 14 basins along the way. The results show the largest mass deposit in the first basin closest to the road, and a decrease of microplastic conentration downstream. The concentration out to Säveån was close to zero, 0.01 mg/L, since most of the particles were deposited in the basin close to the roas (Basin 1), but also in 5 and 8 deposition was dominant, and since the road accumulation time was only one day. The total emitted number of particles/L spaned between 1.5 * 10^{10} and 1.5 *10^{7}.

Scenario D2 also represented summer-time, the 23rd of July 2020, and with a similar precipitation as D1, but with 8 dry antecedent days. The flow out to Säveån was much lower than in D1, and the verge was estimated to reduce outgoing concentration of microplatsics with 18 % which gave a higher concentration out from the verge of 285 mg/L. Due to the lower flow, the number of basins was higher, but the basin surface area was lower. The modelled concentration leaving the stream and enterin Säveån was 0.04 mg/L, and higher than in D1. Although the higher number of basins, the microplastic particles settled only in two basins with a majority in Basin 1 and a small amount in Basin 8 as in D1. The total emitted number of particles/L spaned between 4.2 * 10^{11} and 4.2 *10^{8}.

Scenario D3 was silmulated to represent the same date as one of the field visits, the 22nd of November 2020, with a precipitation of 3.7 mm/day. Due to the low precipitation rate, only 57 % of the microplastic mass was assumed to be washed off from the road surface. The emissions were accumulated during only one day due to antecedent wet conditions. The flow out to Säveån was 0.029 m^3/s and studded tyres increased the mass accumulated on the road and affected the density distribution of the particles. The verge contributed with 65 %, which resulted in an outflow from the verge with a concentration of 150 mg/L. This scenario showed a low concentration out to Säveån of 0.01 mg/L, which together with D1 is the lowest concentration compared to the other scenarios. The most deposition ended up in the early basins with a majority in Basin 5. However, due to the relatively low mass emitted, the loading on the first basins were not that high as in other scenarios. The total emitted number of particles/L spaned between 1.4 * 10^{10} and 1.4 *10^{7}.

Scenario D4 represented 27th of January 2020 and had a similar flow as D3 but with 8 antecedent dry days and a precipitation of 9.6 mm/day. Studded tyres were used and the verge was estimated to remove 11 % of the largest particles which gave a concentration out from the verge of 339 mg/L. The result showed a concentration of 0.12 mg/L out to Säveån, but large removal in the first basins as well. This scenario also gave a large load to the early basins, but with a majority in the later ones of these (Basin 4 and 6, where Basin 6 have similar properties as a marsh), instead of Basin 1. This means that the concentration of microplastics is higher during a longer time compared to the other scenarios, and that the particles were deposited later in the system. The total emitted number of particles spaned between 1.2 * 10^{11} and 1.2 *10^{8}.

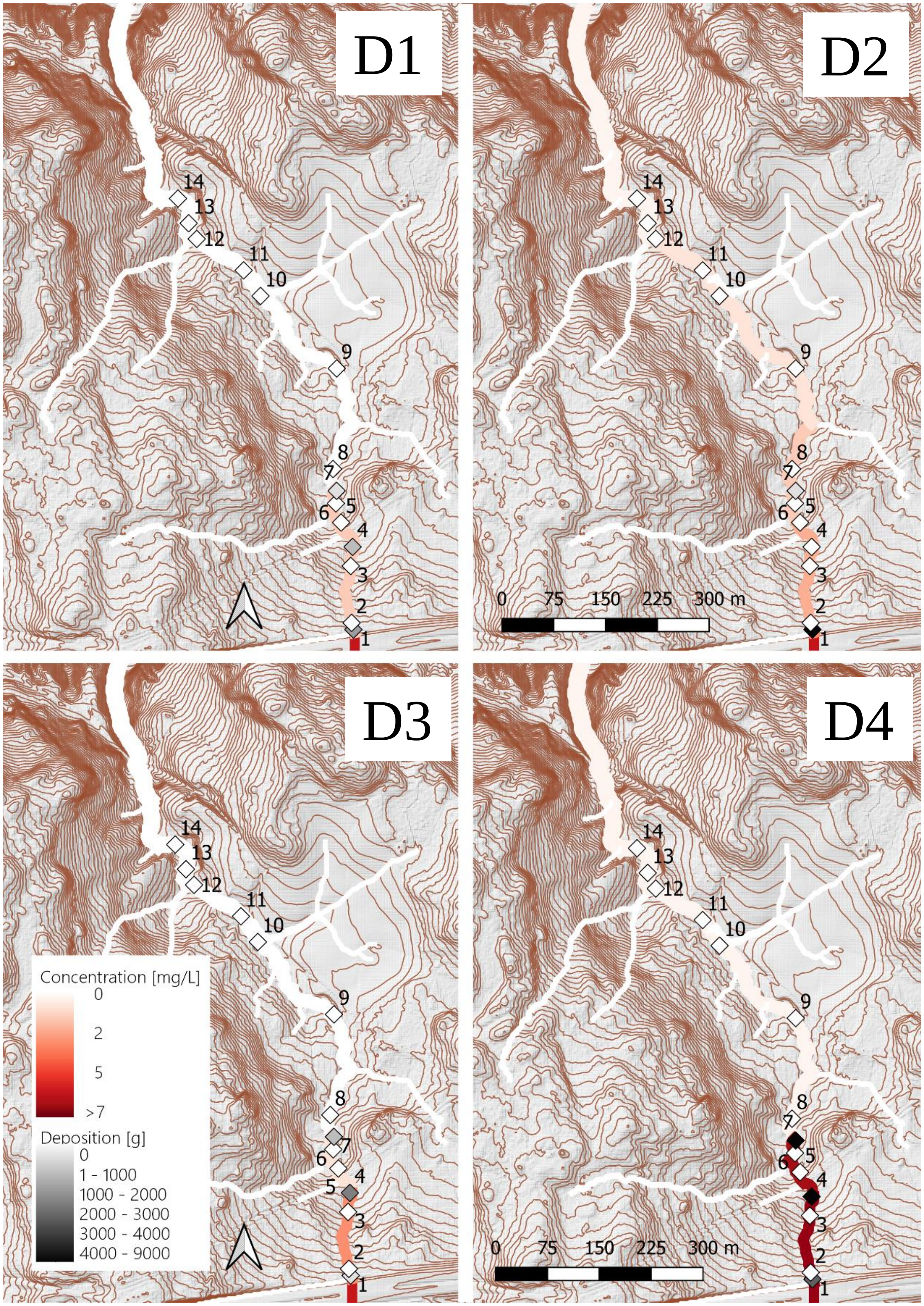

Figure 4.6. Coloured scale of the concentration of microplastic particles in the water at in scenarios D1-D4. The deposition over one day in the different subcritical basins is shown in the rombs. In the white squares, the flow is assumed to be subcritical, but no deposition occurs in the model. The map representation is based on Table IV.1 and Table IV.2 in Appendix III.

4.4.2. Sensitivity analysis, F1-F8

The results for the studied factors are expressed as the release of microplastics out to Säveån, see Figure 4.7 The baseline scenario is marked as a blue dashed line, and the scenarios releasing more than the baseline were F3 High wear rate, F5 Studded Tyres and F6 Verge contribution. The scenarios where the concentration was lower than in the baseline scenario were F2 Low flow, F4 Low wear rate and F7 Verge removal.

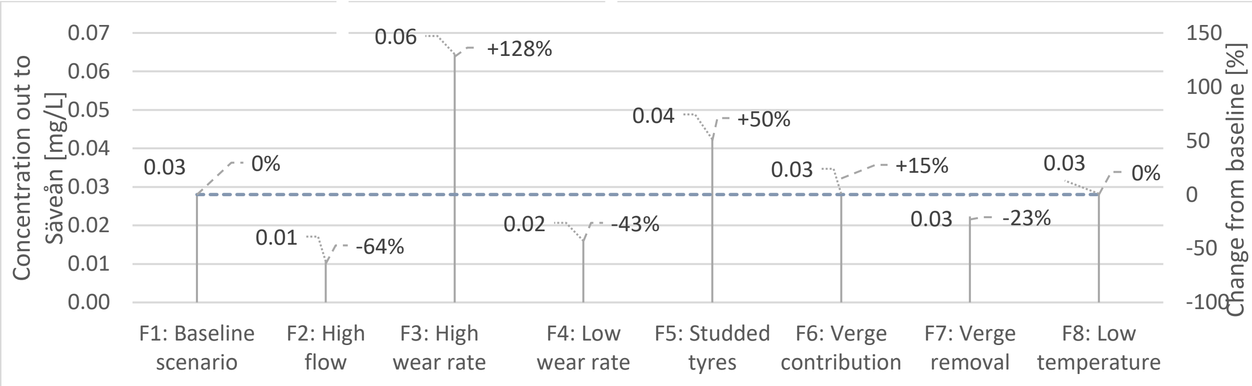

Figure 4.7. Representation of the amounts of microplastic particles entering Säveån, calculated from a baseline scenario with different factors changed. The left axis represents the concentration released to Säveån, and the right axis show the difference from the baseline scenario.

When studying the relative deposition in each basin shown in *Figure 4.8*, the largest deposition change from the baseline scenario was shown in scenario F3 High wear rate. Notable is that deposition in the later basins was much higher in F2 High flow. The scenario with the highest total deposition was scenario F3 High wear rate, followed by F5 Studded tyres. The scenario with lower temperature, F8 Low temperature, also showed high differences from the baseline scenario with a skewness towards deposition later in the system.

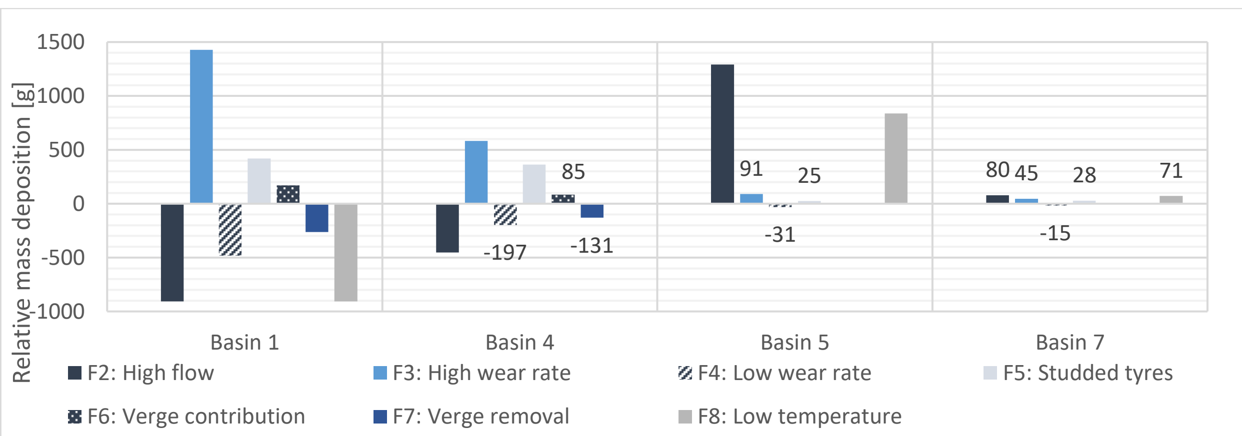

Figure 4.8. Relative mass deposition in each basin during the scenarios in the sensitivity analysis F1-F8, compared to the baseline scenario. Labels are set where the relative deposition is less than 200 to improve clarity.

5. Discussion

This section covers a discussion of the affecting factors for microplastic fate and transport from highway to stream outlet, how the choice of method, chosen parameters and other uncertainties affect the results. Finally, recommendations for further studies are presented.

5.1. Model performance and input data

To be able to fulfil the aim of the study within the limitations, many assumptions were made. Due to these assumptions, the model itself is not completely reliable, why the study is to be considered as a first step towards a method to map the microplastic fate and transport in the small stream environment.

The chosen modelling approach includes road entrapment, wind transport, verge removal and settling of particles in the water phase. Some factors had to be excluded due to modelling limitations, such as aggregation, dissolution, biofouling, degradation and resuspension. Aggregation, dissolution, biofouling and degradation were excluded based on the literature study, as the factors were estimated to have negligible effect on the fate and transport in a system with such a short retention time as a stream with high incline and a length of 1200m. The retention time is not stated during the different scenarios, why a tracer test could have been performed to state the retention time as short enough to exclude the previously mentioned parameters from the calculations.

Resuspension was as earlier mentioned excluded from the study since it is a complex process dependent on stream power and water velocity, which are reliant on the cross section on the stream. Due to the complexity of the modelling, resuspension was excluded from the scope of the study. Eder et al. (2014) means that resuspension in streams draining small watersheds accounts for up to 6% of the total sediment load, however dependent on the flow volume.

Comparing Hazen´s surface loading velocity to the particle settling velocity gives a binary outcome where all particles above the threshold diameter in a certain density are assumed to settle, and all particles under the threshold diameter are assumed to remain suspended. This may explain the large mass deposition in certain basins, and zero in other, similar basins downstream. This modelling approach requires an extensive and accurate size-mass distribution, which are rare in the field of road related microplastic particles. Thus, the result might be a bit skewed towards deposition early, and might underestimate the deposition and concentration along the stream. Concerning the size distribution, Kreider et al. (2010) means that particles can be as small as nm, which is outside the range of this study due to lack of size distribution data and measurement difficulties. This means however that smaller particles may be suspended in the system, but not detected by the chosen modelling approach. The smaller particles may not contribute substantially to an increased concentration or mass deposition, but will increase the number of particles, and pose a threat by being more available for smaller organisms to consume, supported by Windsor et al. (2018). The results of this study also show that the smaller the particle is, the more prone it is to be transported further in the system and reach sensitive areas far away from anthropogenic features.

One of the processes given the most space in the method was the sedimentation, which was simplified to only occur in the basins considered to have calmer flow. This since supercritical flow is more effective than subcritical flow to keep the sediments in suspension (Chapra, 1997). Stokes law presume laminar flow and no vertical mixing. In practice, the flow conditions are not always neither one nor the other but a scale from subcritical to supercritical, why the equation is a simplification. Also, different parts of a basin can have different flow conditions and settling may occur continuously in the whole stream, which was seen in the field observations of deposition in the inner curve of the meandering parts of the stream. To encounter this, more comprehensive studies of the flow conditions along the stream must be done, and further estimations of the percentage of deposited material in a certain flow condition are needed. Further assumptions made connected to the settling were that the particles were spherical, and that the subcritical basins had a rectangular bathymetry. These assumptions affect the results towards a slightly higher settling rate than settling of irregularly shaped particles. However, this is considered negligible due to the shallowness of the basins.

When modelling the flow, the values were generally higher in field than in SWAT. This could depend on the lack of measured data, which was limited to only one measure occasion per field trip day. With an average value from several measurement during the whole field trip day, the model could have been calibrated to better fit the field measured flow.

5.2. Microplastic fate and transport

The results from all scenarios, both date specific and in the sensitivity analysis, show that the basins in the beginning of the system, as close to the source as possible are highly crucial for the exposure to microplastic particles downstream. This is shown by a large deposition in especially Basin 1, 4 and 7. The microplastic particles that do not end up in the ocean end up in verges or in small stream basins close to the highway, and if the stream flows through a marsh, it is a typical deposition spot for microplastic particles. According to Ji (2017) and Helocoski et al (2010), as stated in the literature study, factors affecting the water velocity such as densely vegetated wetlands, shallow ditches and low incline were shown as crucial for particle deposition. This was demonstrated in the results with only the smallest particles transported through the marsh area in Basin 7.

The scenarios based on a specific date D1-D4 showed larger differences in both concentration and mass deposition compared to the scenarios based on each factor, F1-F8. This shows a high dependency of the outgoing concentration. Thus, the wear rate and the number of antecedent dry days, where the microplastic particles accumulate on the road, were highly crucial for the deposition and concentrations.

Results from the simulated scenarios show higher concentrations in the water in scenario D3 and D2, which represent the conditions in the summer and in the beginning of the winter, respectively. In these scenarios, almost all factors were different. However, in scenario D3, the mass deposition was more equally distributed over three basins, compared to D2 where the largest deposition occurred in the first basin. When studying the sensitivity analysis of these factors, the effect of studded tyres was shown to be the most affecting factor after a high wear rate. Compared to these, the verge contribution was not crucial. However, this was for a verge with similar size and properties. Since the verge was estimated to have a linear removal effect with increasing size, it is in general assumed to have a larger effect at a large size. This is also in line with previous studies which most showed a higher removal rate than the one used (Broeke et al. 2008; Unice et al. 2019). The study by Bäckström et al. (2006) was applied due to its similarities with the case study verge.

In water, a mean value of measured microplastic concentrations was summarised from four studies from 1974 to 2019 by Rødland (2019) to 100 mg/L in road runoff, 2.3 mg/L in sedimentation ponds and 1.6-36 mg/L in rivers. When comparing the modelled concentrations leaving the stream from scenario D1-D4, the results show significantly lower values (0.014-0.416 mg/L) compared to the values in rivers from Rødland (2019). This may indicate that streams containing microplastic released to rivers may not dramatically change the already occurring concentrations. It is however essential to note the difference between a small stream and a river, and not many studies have been analysing the effect of exposure of microplastics to species in small stream ecosystems and natural marshes.

The modelled concentrations (0.014-0.416 mg/L) released to Säveån are much lower than concentrations causing acute toxic effects for aquatic species (25- 100 000 mg/L) (Wagner et al. 2008). However, the model shows that the concentrations of scenario D4, 15 mg/L, are approaching alarming values in the first section of the stream. The exposure may vary over seasons and depending on weather conditions, since these high values are shown after a period of drought in winter conditions where studded tyres are used. The particles are then smaller and are more prone to be transported a longer way from the road and may deposit in more sensitive areas. The flow in the stream is also shown to be higher and more stable during wintertime, despite several antecedent dry days, compared to the summer scenarios.

The previously mentioned seasonal differences between the summer and winter half year were shown also in the sensitivity analysis. The use of studded tyres during winter is shown to increase the load of particles deposited to the basins along the stream, but due to the increased density not affecting the concentration out to Säveån remarkably. The scenario with lower temperature, F8, showed the same outgoing concentration as in the baseline scenario, but a skewed deposition towards the later basins, which may indicate a tendency to further transport in colder weather. However, when analysing the model in detail for this scenario, the previously mentioned error with the threshold diameter giving a binary outcome may be a reason for this deposition skewness.

Found by Gustafsson (2001), and presented in the literature study, the tyre wear rate was shown to be highly crucial for the released mass of microplastic particles. This was demonstrated in the results when a high wear rate was compared to the other factors in the sensitivity analysis. The wear rate was the factor affecting the total deposited mass of microplastic the most, but also the concentration out to Säveån. If including different size and density distribution studies in the wear rate, the wear factor might have been even more crucial.

When studying the stream power index compared to the field observations, the location of the subcritical basins corresponded to the locations of a low modelled stream power. These findings support the idea that stream power index could be used as a first rough step to identify subcritical basins and hence possible sinks for microplastic particles.

To reduce the contamination of natural areas in the vicinity of rural highways, focus should hence be directed towards a reduction in emissions. Street sweeping is used to reduce particle amounts in urban areas (Sartor & Gaboury, 1984), and could be used as a measure to reduce the outgoing concentrations also in rural areas. Since the verge is substantial, it can be formed to trap more particles. However, literature (Bäckström et al. 2006) state that the verge today primarily is a measure that mitigate the concentration peaks since when exposed to low concentrations it contributes to higher concentrations to highway adjacent streams. It can also be considered to collect the stormwater from roads and lead it to sedimentation ponds.

The studied stream has a high drop from the highest point to the lowest (an average incline of 7%), which gives a higher probability for a higher stream power index compared to a stream with less incline. Roads are often built in the lower landscapes and hence in the lower part of the watershed and are not crossed by headwater streams. However, wetlands are situated in the lower part of the watershed and are hence exposed to a large portion of road related microplastics. The stream capacity is lower in these water courses due to the lower gradient, and the pollution is hence settling in a closer area to the highway. Even though highways built through a watercourse in a slope might be rare in the Gothenburg area, the northern Sweden has a dramatic coastal landscape with larger roads built in the slopes facing towards the Baltic Sea.

5.3. Further research

Since the study is based on available studies on road related microplastic particles, more studies of microplastic generation, mass-size distribution and verge removal would increase the reliability of the concentration entering the stream system.

In this study, only four real date scenarios were simulated. For a better understanding, it would be interesting to compare the outcomes of this research with similar simulations for different dates with other hydrological conditions and environmental factors. With better data available, especially on particle size distribution and resuspension, more parameters included would increase the accuracy of the model.

To increase the understanding of road related microplastic exposure to the environment, further research of a larger area would be of value, where the possibility of using stream power as basin determining data instead of field visits could be further investigated. In addition, more measurements of microplastic occurrence, especially in small streams, would increase the possibility to put the modelled concentrations in relation to measured valued, and to calibrate the models that are used.

6. Conclusions

The modelling approach used in this thesis can be seen as a first step towards a better understanding of the microplastic particle fate and transport in small highway adjacent streams. The model shows that the exposure and deposition of microplastics in the stream are highest in the beginning of the stream, closest to the highway, and that the concentrations leaving the stream are not contributing to increase the microplastic concentrations in Säveån. The concentrations and deposition are peaking during the winter half year when studded tyres are used, and are most dependent on the factors concerning the wear rate. Also, the number of antecedent dry days is crucial for the concentration in the outgoing runoff water, and hence for the deposition in the stream. If the particles are in the smaller range, they are transported further and may deposit in basins further away in the system.

Knowing the concentrations and deposition of microplastics in the environment is essential to assess the scale of the problem, and to build a base for implementation of microplastic reduction measures. In addition, with an improving science field of tyre materials with a lower abrasion rate, and with good stormwater management also in rural areas, the world could take one step closer to the objective of a cleaner environment.

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Appendix I, Summary of emission rates

The calculation of normal emission rates was based on previous studies on the range of emission rate, and on previous studies estimating an emission rate. Other data could have been used, but to save resources and minimize sources of error, the data expressed in g/vkm was used.

Table I.1. Emission rates from seven different studies, calculated together to an average value. Tofind the sensitivity range, the highest and lowest value was extracted and calculated to an average value, used in the sensitivity analysis

	Light vehicles wear rate [g/vkm]			**Heavy vehicles wear rate [g/vkm]**		
Source	Lowest	Estimated	Highest	Lowest	Estimated	Highest
Bækken (1993)	0.100		0.360			
Rogge et al (1993)	0.024		0.360			
Hann et al. (2017)	0.050		0.104		0.67	
Boulter (2006)		0.1		0.189		1.403
Klein et al. (2017)		0.104		0.517		0.668
Sundt et al. (2014)		0.132			0.712	
Lindström and Rossipal (1987)		0.050			0.7	
Average	**0.058**	**0.097**	**0.275**	**0.353**	**0.694**	**1.0355**

Appendix II, SWAT method

In the following appendices, the SWAT-model build up method are described.

Appendix II.1. Data preparation

Data (soil, property and elevation) was downloaded from Lantmäteriet and SGU, via the SLU geodata extraction tool Zeus. The files were imported, the four elevation files were merged into one file, and the clipped to fit the same size as the soil- and property map. The Swedish names of all soil types and properties were changed to real letters, and predefined styles were loaded for a better graphical representation. Both files were rasterized based on the attribute number and hence converted into the file format .sdat. The DEM-layer was clipped with the Serval plugin, to represent the pipe under the highway.

Lookup tables were imported in the project-specific database, as well as created in a file with the format .csv. The codes were obtained from Bergion (2020) and full translate tables are presented in Table II.1 and II.2.

The weather data was gathered from SMHI, and all was to be inserted to SWAT in a daily timestep. The wind, solar and the humidity had to be converted to a daily timestep by taking the average of the 24 hours during that day. In the solar case, a conversion to $MJ/m^2/day$ had to be done by multiplying the w/m^2 value with 0.0864 (1 day=60s*60min*24h=86400s). The humidity data had to be converted to fraction, so divided by 100. The temperature was presented in min and max values for each day. The data was chosen to be stretching from 2015-01-01 to 2020-11-03.

Appendix II.2. SWAT simulation

SWAT was started and a threshold of 1 ha and 2500 number of cells was chosen when this best represented the stream network studied on the site. A snap threshold of 150 was chosen to obtain a proper amount of subbasins, here 42.

When creating HRU:s, the created raster files were used, combined with corresponding .csv lookup tables. Slope bands were set to between 0, 2, 4, 6, 8, 10, 12, 9999 %, which ended into 950 HRU:s

In SWAT editor was WGEN_User used as database, and the textfiles with station information were imported, which have connections to the corresponding weather data. NYskip was set to 3. SWAT was run and obtained data was imported into the program for analysis.

Table II.1. Translating table from Swedish soil names to SWAT codes

SOIL_ID	SWAT_CODE	SWE_NAME
1	BUCKSPORT	Mossetorv
5	BUCKSPORT	Kärrtorv
28	PILLSBURY	Postglacial finsand
31	PILLSBURY	Postglacial sand
33	PILLSBURY	Svallsediment, grus
40	PANTON	Glacial lera
43	PANTON	Glacial lera
50	HINCKLEY	Isälvssediment
75	BUCKSPORT	Torv
91	WATER	Vatten
95	SCARBORO	Sandig morän
200	FREDON	Fyllning
890	ROCK OUTCROP	Urberg

Table II.2. Translating table from Swedish landuse names to SWAT codes

LANDUSE_ID	SWAT_CODE	SWE_NAME
1	URHD	Bebyggelse
30	WWHT	Odlad åker
40	FRSD	Skog löv
51	RNGE	Öppen mark
56	FRSE	Skog barr
80	WATR	Vatten

Appendix III. Results scenario D1-D4

The follwing tables are the base of the result representations in Figure 4.6.

Table III.1. Concentration [mg/L] leaving each basin in Scenario D1-D4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Sc. 1	1.5	1.2	1.2	1.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sc. 2	3.0	1.9	1.9	1.9	1.9	1.6	1.6	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.5	0.5	0.4	0.4
Sc. 3	3.0	2.5	2.5	2.5	0.8	0.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sc. 4	15.2	12.8	12.8	12.8	7.1	6.6	6.6	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1

Table III.2. Microplastic particle deposition [g] in each basin in Scenario D1-D4

Basin no	Basin 1	Basin 5	Basin 8
Length from highway [m]	**0**	**140**	**210**
Sc. 1	1262	606	35
Sc. 2	9824	0	64
Sc. 3	244	1792	733
Sc. 4	2197	6341	7536

Table III.3. Comparison between the concentrations leaving and entering the stream, and the largest particle size leaving the stream out to Säveån. Based on minimum size and maximum size, the range of particle amount concentration is presented. MP stands for the number of particles

Scenario	Q out [m^3]	Concentration from verge [mg/L]	Concentration out to Säveån [mg/L]	Largest particle size leaving [µm]	Max particle concentration [MP/m^3]	Min particle concentration [MP/m^3]
1	0.021	48	0.01	6.8	1.46E+10	1.46E+07
2	0.007	285	0.42	5.9	4.22E+11	4.22E+08
3	0.038	150	0.01	11.2	1.36E+10	1.36E+07
4	0.036	339	0.12	11.5	1.43E+10	1.43E+07

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