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Norwegian Centre for Transport Research

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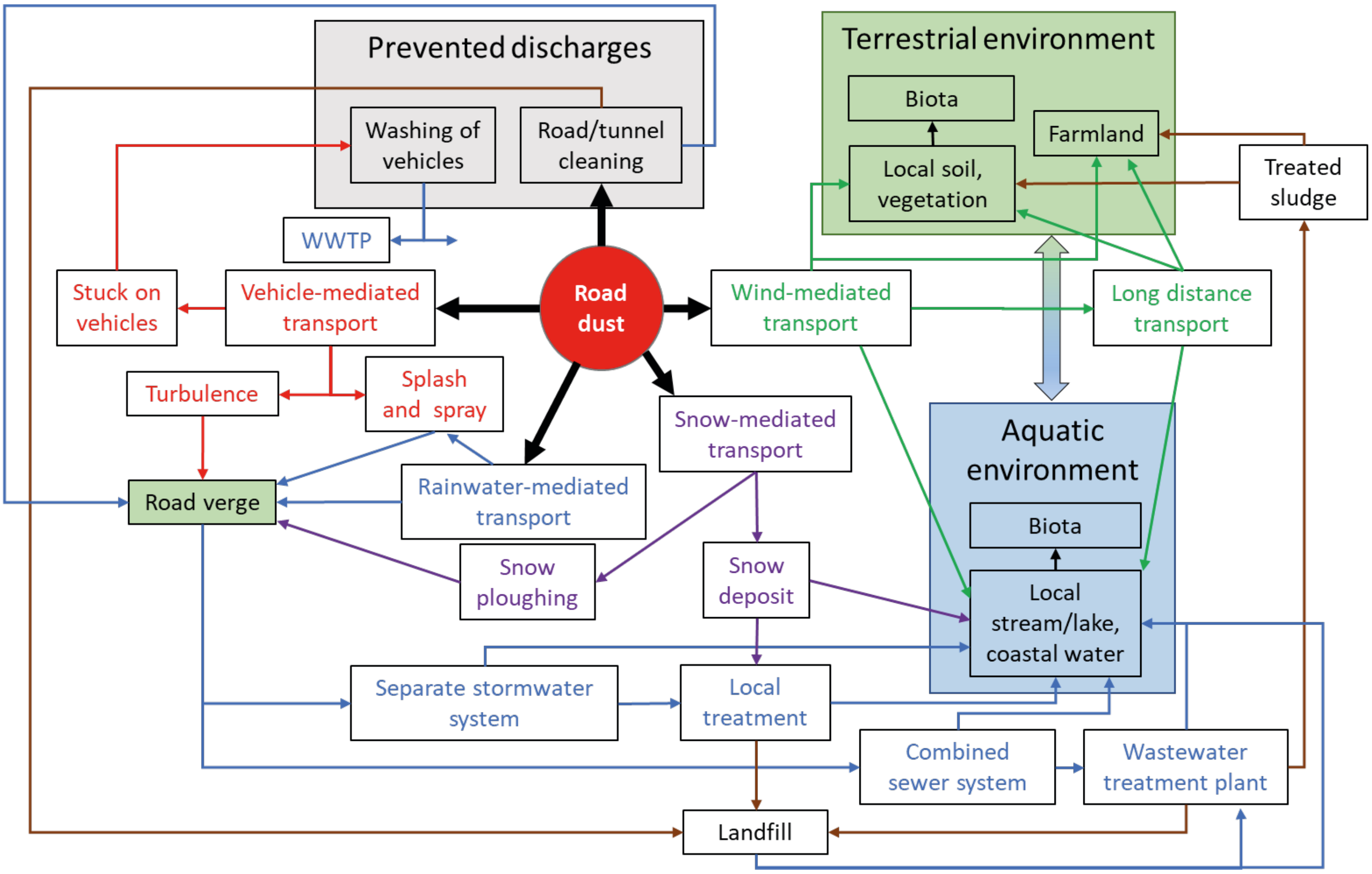
Microplastics in road dust – characteristics, pathways and measures



Norwegian Institute for Water Research

REPORT

Main Office
Gaustadalléen 21
NO-0349 Oslo, Norway
Phone (47) 22 18 51 00
Telefax (47) 22 18 52 00
Internet: www.niva.no

NIVA Region South
Jon Lilletuns vei 3
NO-4879 Grimstad, Norway
Phone (47) 22 18 51 00
Telefax (47) 37 04 45 13

NIVA Region East
Sandvikaveien 59
NO-2312 Ottestad, Norway
Phone (47) 22 18 51 00
Telefax (47) 62 57 66 53

NIVA Region West
Thormøhlensgate 53 D
NO-5006 Bergen Norway
Phone (47) 22 18 51 00
Telefax (47) 55 31 22 14

NIVA Denmark
Ørestads Boulevard 73
DK-2300 Copenhagen
Phone (45) 8896 9670

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Author(s) Christian Vogelsang, Amy L. Lusher, Mona E. Dadkhah, Ingrid Sundvor, Muhammad Umar, Sissel B. Ranneklev, David Eidsvoll and Sondre Meland	Topic group Environmental contaminants - freshwater	Distribution Open
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Summary

The expected main contributors to road dust-associated microplastic particles (RAMP) are rubber compounds in tyre treads, polymers used to strengthen the bitumen used in road pavement and thermoplastic elastomers used in road marking paints, where the former appears to dominate. The major fraction of RAMP is expected to be found in the runoff from the road and road verge generated during rainfall events. However, even if domestic wastewater treatment plants (WWTPs) are expected to be main recipients of road runoff in urban areas, their presence in the influents or effluents (neither treated water nor sludge) have not been undisputedly documented. There is generally a complete lack of actual evidence to support the extent to which RAMP are removed by existing treatment facilities, and to what degree they are present in road runoff entering these facilities. In addition, the release of tunnel wash water is probably a major point source of RAMP. The estimated treatment efficiencies referred to in this report is based on total suspended solids (TSS) as a proxy for RAMP as well as reported particle size distributions and densities. Sedimentation is expected to be the most important mechanism for the removal of the larger size fractions if sufficient settling time is provided (traditional Norwegian gully pots do not). The report discusses the expected efficiencies of existing treatment solutions, include the roadside treatment plants, gully pots and WWTPs receiving stormwater runoff from urban areas. It also discusses other potential treatment solutions that may be applied, both along the national road network in light of the revised version of handbook N200 by the National Public Roads Administration and in urban areas with limited available space for treatment solutions.

Four keywords	Fire emneord
1. Microplastics	1. Mikroplast
2. Road dust	2. Veistøv
3. Sustainable drainage systems	3. Naturbaserte renseløsninger
4. Compact treatment solutions	4. Kompakte renseløsninger

This report is quality assured in accordance with NIVA's quality system and approved by:

Christian Vogelsang
Project Manager

Bert van Bavel
Research Manager

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Microplastics in road dust – characteristics, pathways and measures

Preface

Norwegian Institute for Water Research (NIVA) and Institute of Transport Economics (TØI) have conducted this study on behalf of the Norwegian Environment Agency. The contract was signed August 8 2017 and the startup meeting was held on August 23. A workshop with invited national and Scandinavian experts and stakeholders was held in the premises of the Norwegian Environment Agency at Helsfyr, Oslo on September 25 to create an arena for ideas and exchange of knowledge around key topics with the aim to ensure a good knowledge base and that all important factors were to be considered in the further project work. Minutes from the workshop including a list of all participants is attached as Appendix O at the end of the report. All participants are acknowledged for their valuable contributions. We are grateful to the Norwegian Environment Agency for giving us the opportunity to prepare this report and particularly Trine-Lise Torgersen for valuable feedbacks throughout the project period and for a good and pleasant cooperation.

Good readings!

Oslo, 29.1.2018

Christian Vogelsang

Table of contents

Abbreviations

>35C	n-alkanes with more than 3 carbon atoms
24MoBT	2-(4-morpholinyl) benzothiazole
A	Removal efficiency of the first treatment step (%)
AADT	Annual average daily traffic
$A_{c,g}$	Catchment area of the gully pot (ha)
A_g	Cross section of the gully pot (m^2)
α	Correction factor included to take the expected turbulence in the gully pot during rain events into account
AM	Acryl-monomer
B	Removal efficiency of the second treatment step (%)
BMP	Best Management Practices
BR	Butadiene rubber
BT	Benzothiazole
C_{eff}	effluent concentration (mg/l)
C_i	Pollutant concentration in sample *i* (mg/l)
C_0	Inlet concentration (mg/l)
CSO	Combined sewer overflow
CVC	Credit Valley Conservation
D	Duration of the storm (hours)
d_{50}	Median particle mass (volumetric size distribution) (µm)
d_a	Aerodynamic diameter
D_{all}	Travelled distance on roads with all types of bitumen
$D_{i,j}$	Annual travelled distance for all vehicles of category *i* for driving category *j* (million vehicle km)
D_{PMB}	Total travelled distance on PMB roads
$D_{PMB,i}$	Annual travelled distance for all vehicles on roads with pavements containing PMB in the road wear layer in area i (million vehicle km)
d_s	Particle's Stokes diameter or effective diameter (m)
E_{mp}	Estimated annual emissions microplastics
ε	The trap efficiency (-)
$E_{T,r,t}$	Total emissions along the road stretch *r* over a given time period *t* (mg)
E_T	Estimated annual emissions of tread
E_T	Total national annual emissions of tread particles (tonnes)
$E_{TW,PM2.5}$	Amount of tyre wear generated as $PM_{2.5}$
$E_{TW,PM10}$	Amount of tyre wear generated as PM_{10}
EC	European Commission
ECHA	European Chemicals Agency
EF	Emission factors
$EF_{i,j}$	Specific tread emission factor for vehicles in category *i* for the relevant type of driving *j* (mg/vim)
$EF_{i,j}$	Specific emission factor (mg/vkm) for vehicles in category *i* for the relevant type of driving *j*
EF_{ST}	Specific studded tyre road emission factor
EI_{30}	Rainfall Erosivity Index
EMC	Event Mean Concentration
$E_{RW,SBS}$	Annual release of SBS in road wear
EVA	Ethylene vinyl acetate

$f_{PM2.5}$	Fraction of the total PM <2.5 µm
f_{PM10}	Fraction of the total PM <10 µm
f_{PMB}	PMB correction factor; fraction of PMB-roads to all roads (≥3,000 AADT)
$f_{SBS,i}$	SBS weight-fraction of the road wear in area i (-)
$f_{ST,i}$	Fraction of cars using studded tyres in area i (-)
FT-IR	Fourier Transform – Infrared
FWD	Four-wheel drive
$f_{w,i}$	Faction of the year considered winter and period for using studded tyres in area i (-)
g	Acceleration of gravity (9,81 m/s^2)
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
HOBT	2-hydroxybenzothiazole
I_6	6-minute rainfall intensity
I_c	Critical rain intensity for the gully pot (L/s·ha)
IDF	Rainfall Intensity-duration-frequency
ISO	International Standardisation Organisation
L_{all}	Total length of roads
LOH	Lokal overvannshåndtering
L_r	Length of the particular road stretch r (km)
μ	Dynamic viscosities (N s/m^2)
n	Number samples collected
NaCl	Sodium chloride
NaI	Sodium iodide
NCBA	N-cyclohexyl-2-benzothiazolamine
NIVA	Norsk Institutt for Vannforskning; Norwegian Institute for Water Research
NJCAT	New Jersey Corporation for Advanced Technology
NPRA	Norwegian Public Road Administration
NR	Natural rubber
$N_{r,i,t}$	Number of vehicles in category i that have travelled the particular road stretch r during the given time period t
P	Total pollutant load during an event
PA	Polyamide
PAHs	Polycyclic aromatic hydrocarbons
PBR	Polybutadiene rubber
PBTs	persistent, bioaccumulative and toxic substances
PCBs	polychlorinated biphenyls
PM	Particulate matter
PM_{10}	Particulate matter with size <10 µm
$PM_{2.5}$	Particulate matter with size <2.5 µm
$PM_{10\text{-}300}$	Particulate matter with size between 10 µm and 350 µm
PMB	Polymer modified bitumen
PSD	Particle size distribution
Q	Flow rate into the gully pot (m^3/s)
Q_{dim}	Dimensioning surface load
Q_m	Maximum runoff capacity that the gully pot can handle (L/s)
Q_{maxdim}	Maximum dimensioning load
R	total TSS removal efficiency (%)
RAMP	Road dust-associated microplastic particles = TWP + RWP$_{PMB}$ + RWP$_{RM}$
RDI	Rainfall Detachment Index
φ	Runoff coefficient for the catchment (-), typically set to 0.9 for paved roads
ρ_s	Density of the particle (kg/m^3)
ρ_w	Density of the surrounding water (1000 kg/m^3)

RP	Road particles
RP_{PMB}	Larger fragments or shreds from PMB-pavement
RP_{RM}	Larger fragments or shreds from road markings
RWP_{PMB}	Road wear particles with polymer modified bitumen
RWP_{RM}	Road wear particles with thermoplastic elastomers from road markings
SBR	Styrene-butadiene rubber
SBS	Styrene butadiene styrene
SEM	Scanning electron microscopy
SIS	Styrene-isoprene-styrene
SSB	Statistisk sentralbyrå (Statistics Norway)
SuDS	Sustainable Drainage Systems
t	Residence time in the pond
t_c	Concentration time; the time it takes rainwater to run from one end of the catchment to the other
TP	Tread particles
TRCA	Toronto and Region Conservation Authority
TSS	Total suspended solids
TWP	Tread wear particles
TWP_H	Tread wear particles from heavy vehicles
TWP_P	Tread wear particles from passenger cars
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UV	Ultraviolet
VEAS	Vestfjorden avløpsselskap
v	Total runoff volume during the event
ν	Kinematic viscosity (m^2/s)
V	Dry weather volume
v_{dim}	dimensioning runoff volume
V_i	Settling velocity of particle *i* with diameter d_i (m/s)
v_i	Volume of road runoff corresponding to sample *i* (m^3)
vkm	Vehicle kilometre
V_p	Settling velocity of discrete particles in water with laminar flow (m/s)
WFD	Water Framework Directive
WWTP	Wastewater treatment plant
ZnO_X	Zinc oxides

Extended summary

This report is divided in two parts:

In **part I** – **Characteristics & pathways**, we discuss the presence and characteristics of microplastic particles in road dust, how and where they are spreading and accumulating after release, and what we can expect to find in road runoff during rainfall events.

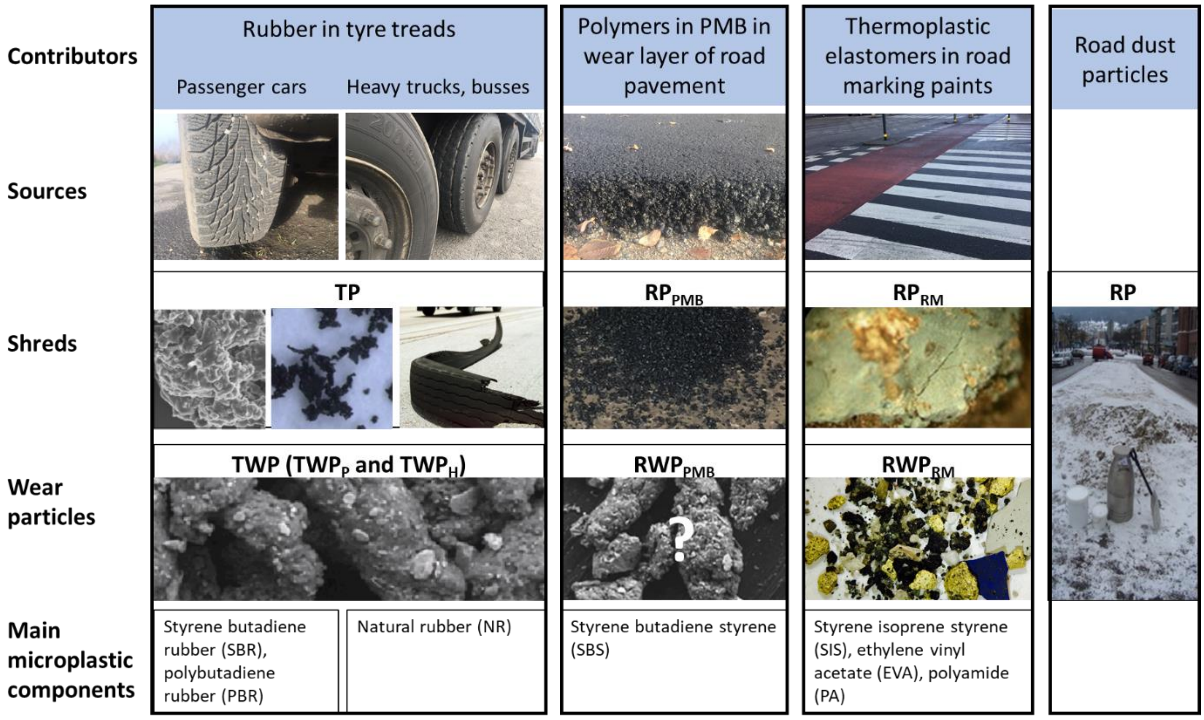
In **part II – Treatment solutions**, we discuss the efficiency of existing treatment solutions in removing microplastic-containing road runoff particles. These include the existing roadside treatment plants, gully pots and wastewater treatment plants (WWTPs) receiving stormwater runoff from urban areas. We also discuss other potential treatment solutions that may be applied, both along the national road network in relation to the revised version of handbook N200 by the National Public Roads Administration (Statens Vegvesen 2017) and in urban areas with limited available space for treatment solutions.

In the following summary our findings are presented in three extensive tables. Current knowledge status, as we interpret it, on each subtopic is indicated by the following colour coding:

🟩	Fairly good; no particular focus needed
🟨	Existing, but lacking important knowledge or non-existing
🟧	Almost or completely non-existing and believed essential to know

PART I – CHARACTERISTICS & PATHWAYS

Rubber in tyre treads, polymers added to strengthen the bitumen used in road pavement and thermoplastic elastomers in road marking paints are believed to be the main contributors to microplastic particles in road dust. The below figure summarises the sources and notation used to distinguish between larger shreds and wear particles from the different sources.



Road dust-associated microplastic particles; RAMP = TWP + RW$_{PRM}$ + RWP$_{PMB}$

The following table summarises the main characteristic features of the different types of RAMP.

<table>
<tr><th>Characteristics</th><th colspan="2">TWP</th><th colspan="2">RWP_{PMB}</th><th colspan="2">RWP_{RM}</th></tr>
<tr><td>Amounts</td><td>7,080-9,600 tonnes of rubber/year</td><td>🟩</td><td>28 tonnes of SBS/year</td><td>🟧</td><td>90-180 tonnes of thermoplastic elastomers/year</td><td>🟧</td></tr>
<tr><td>Size range</td><td><table><tr><th>Size bin</th><th>Volume%</th></tr><tr><td>50-350 µm</td><td>85</td></tr><tr><td>30-50 µm</td><td>8</td></tr><tr><td>10-30 µm</td><td>2</td></tr><tr><td>2.5-10 µm</td><td>4</td></tr><tr><td><2.5 µm</td><td>1</td></tr></table></td><td>🟨</td><td>Possibly as TWP, but limited information</td><td>🟨</td><td>Possibly within 50-4000 µm, but highly uncertain, particularly in lower size range</td><td>🟧</td></tr>
<tr><td>Density</td><td>1.7-2.1 g/cm^3, up to 2.5 g/cm^3</td><td>🟨</td><td>Possibly as TWP, but limited information</td><td>🟨</td><td>>1.2 g/cm^3</td><td>🟧</td></tr>
<tr><td>Shape and colour</td><td>Dark, sausage-shaped with rough surfaces</td><td>🟨</td><td>Probably as TWP</td><td>🟨</td><td>Limited reports, but coloured and apparently roundish with rough surfaces</td><td>🟧</td></tr>
<tr><td>Surface charge</td><td>Not reported</td><td>🟧</td><td>Not reported</td><td>🟧</td><td>Not reported</td><td>🟧</td></tr>
<tr><td>Biodegradability</td><td>Indication that SBR residual is slowly biodegradable</td><td>🟧</td><td>Not reported, probably limited</td><td>🟧</td><td>Not reported, probably limited</td><td>🟧</td></tr>
</table>

The following table summarises key findings within selected topics related to the presence and characteristics of RAMP in road dust, their local spreading and accumulation after release, and concentrations in road runoff during rainfall events.

Topic	Key findings	
Tread wear particles	*Contents:* The tread typically makes up approximately 40% of the TWP and constitute in the range of 1-5% of the RP. However, during the winter season the tread fraction of the road dust will be reduced (<1%) with drastically increased abrasion of road surfaces due to studded tyres. It is generally believed that the smallest fraction of TWP have been underestimated, due to challenges in analytical quantification.	🟨
	Quantification methodology: The rubber embedded in the TWP will not be visually identified using traditional methods, hence, chemical analyses of tyre tread components such as the SBR polymer and zinc (or organic zinc) may be used. FT-IR and spectral analysis may be an alternative, but needs to be further verified.	🟨
	Annual emissions: The estimated annual emissions of microplastics through the abrasion of tyre rubber on Norwegian roads are in the range of 4,300-5,700 tonnes or 17,700-24,000 tonnes as TWP.	🟩
	Road-specific emissions: Dependent on a wide range of factors with AADT, type of vehicle and driving pattern as probably the most important.	🟨
Polymer modified bitumen wear particles	*Characteristics*: There is limited specific information on the characteristics of PMB wear particles. Since they primarily are generated by studded tyres, they may differ considerably in composition compared to typical TWP generated by non-studded tyres.	🟧
	Annual emissions: The total annual releases of SBS in road wear caused by studded tyres were estimated to be approximately 28 tonnes	🟧

Topic	**Key findings**	
Road marking wear particles	*Characteristics*: There appears to be very limited documentation regarding the presence of microplastic particles from road marking paints in the environment	🟧
	Annual emissions: Very limited quantitative data exist. First estimates indicate annual releases of thermoplastic elastomers in the range of 90-320 tonnes in Norway.	🟧
Other sources	*Macroplastics littering*: Could be an important secondary B source to microplastics in road dust	🟧
Local spatial distribution of wear particles	*Deposition*: Rain or snowfall will drastically increase the deposition of airborne particles on the road or road verge.	🟩
	Spatial distribution: There is an exponential decline in TWP concentration with distance from the road, with typically 80% of TWP found within 5 m from the road.	🟩
	Variability: Since the weather is such an important factor for the local distribution, the spreading may drastically vary from day to day and with season.	🟩
Transport mechanisms for wear particles	*Wind-generated*: The loss of tyre wear particles due to wind is probably relatively small unless in a particularly windy location.	🟩
	Water-generated: Depending on the intensity and duration of the rainfall, the micro-structure, slope and general condition of the pavement and particle characteristics such as size, density and stickiness, rain and melt water will contribute to washing wear particles embedded on the road off and into the road verge. Small sized particles are more easily trapped in the microstructures of the road. Splash and spray by cars also contribute.	🟨
	Retention in road structures: In the Netherlands, 95% of all TWP deposited on roads with very open asphalt (ZOAB) are claimed to be permanently embedded in the small cavities in the road.	🟨
	Retention in verge: The verge is normally not considered a treatment step itself in Norway, some wear particles can be expected to be retained by the soil and vegetation within the verge, depending on the properties of the soil and the vegetation.	🟩
	Urban areas: Due to the complexity of the underground networks of the separate stormwater collection system and the combined sewer system, the actual transport pathway for the road runoff is not known for many areas.	🟨
	Road cleaning: Road cleaning is a rather efficient way of removing the larger sized particulates (>100-125 µm), but has limited effect on the amounts of airborne particles	🟩
	Vehicle-mediated: Particles may adhere to anywhere on the vehicle.	🟨
	Snow-mediated: Snow can accumulate pollutants, which are released during snow melt.	🟩
Accumulation and losses of wear particles	The time between rain events or road cleaning events is a key factor for the accumulation of large wear particles on the road and verge. The intensity and/or duration of the rain event or the type of the applied road cleaning determines how efficiently the deposited particles are removed.	🟨
	Concentrations in verge soil: Observed peak concentrations of TWP in the range of 0.6-117 g/kg dw.	🟨
	Concentrations in road runoff: Observed peak concentrations of TWP in the range of 0.3-197 mg/l. TSS concentrations in road runoff varies in the range from 50-200 mg/l and up 5000 mg/l in extreme cases with traffic density as an important determining factor.	🟨

Topic	Key findings	
	Transport vs degradation: TWP is more likely to be transported by runoff or wind erosion than being degraded (if in soil).	🟧
Tracking of microplastics in wear particles	Extractable organic zinc, the rubber polymer SBR, the benzothiazole 24MoBT and n-alkanes with more than 35 carbons are promising markers for tread particles in environmental compartments.	🟩
	The SBS polymer may be a potential marker for PMB wear particles in the environment.	🟧

PART II – TREATMENT SOLUTIONS

The following table summarises key findings within selected topics related to the expected efficiency of existing and potential treatment solutions in removing RAMP from road runoff along the national road network and in urban areas with limited available space for treatment solutions, as well as potential solutions for treating tunnel wash water.

Topics	Key findings	
Treatment – where and what	A large part of the ca. 247 km (ca. 352 km by 2029) of the national road network with an AADT >30,000 is located within urban areas.	🟩
	Sedimentation will be the primary mechanism for the removal of RAMP, while filtration, and possibly adsorption, will be important if additional treatment is needed.	🟩
	There is generally a complete lack of actual evidence to support the extent to which RAMP will be removed, and to what degree they are present in road runoff entering the existing facilities	🟧
Treatment solutions for highway runoff	Only wet ponds/basins/tanks are compliant with the step 1 treatment solution requirements presented in the revised version of the NPRA's Handbook N200.	🟩
	If the wet pond is well planned, and constructed according to those plans, as well as properly maintained, an annual average TSS removal above 80% is achievable.	🟧
	However, many of the existing wet ponds in Norway are in poor shape and malfunctioning, either due to poor building quality or poor, or even neglected, operation and maintenance. Hence, there may be a mismatch between expected treatment performance and what is actually performed on site.	🟨
	Wet ponds have proven to be effective and cost efficient measures in terms of protecting water bodies from polluted road runoff.	🟩
	A broad spectre of treatment solutions based on infiltration in native soil or filtration through engineered soil fulfil the listed functional requirements for treatment step 2.	🟩
	A common cause for low infiltration rate is compaction triggered during the construction work with the basin. To avoid this, lightest machinery possible should be used.	🟩
	If dimensioned properly, the expected removal efficiencies of infiltration basins are approximately 80-95%, while up to 100% can be achieved by soakaways. Sand filters are expected to achieve similar removal efficiencies as infiltration basins. However, the storage capacity of the infiltration pond will be decisive for the actual removal. It should be noted that any TSS that leaves the infiltration basin with the groundwater is usually not taken into account.	🟨
	Infiltration is rarely used in Norway today, and reports indicate poor functioning (poor infiltration rate).	🟨

Topics	Key findings	
	If compaction during construction is avoided and proper pre-treatment is provided by a preceding wet pond, the infiltration step should achieve good additional removal of TSS, giving a combined removal efficiency for both treatment steps in the order of 96% for TSS.	🟨
	During winter, the use of infiltration basins is challenging because frozen soils can significantly reduce, or stop, the rate of infiltration, making it function more as wet pond. The overflow may then be treated in a closed filtration system such as a soakaway.	🟩
Stormwater management principles in urban areas	Treatment solutions in urban areas are typically challenged by limited natural attenuation of surface runoff and limited space available for treatment units. These challenges may be met by, possibly combining, four alternative measures; A) by reducing the need for treatment, B) by preventing low-polluted stormwater from entering the combined sewer where possible, combined with increased local and/or centralised detention capacity to prevent CSOs, and increase the capacity for centralised treatment, C) by applying nature-based solutions (SuDS) to retain and prevent runoff on the surface, and where needed and possible, treat the runoff by infiltration in native soil as close to the source area as possible, and D) by applying local sub-surface technical treatment units with low footprint requirements.	🟨
	Where possible, SuDS should be a first choice for retention and detention, as they are rather low cost solutions and their operational performance and need for maintenance is rather easy to monitor. But proprietary treatment systems may be appropriate and cost efficient, both for pre-treatment (e.g. vortex separators) and for post-treatment (e.g. filtration devices and ballasted flocculation), where additional treatment is needed and infiltration not recommended.	🟨
	Treatment may be limited to manage the first flush from road structures in confined spaces in urban areas.	🟩
Retention in gully pots	Gully pots may retain a minor fraction of TWP larger than approximately 50 µm, but with current design criteria the volumetric loading of the gully pots will often be exceeded resulting in poor retention of TWP.	🟨
	Particles less than 50 µm may be discharged into the sewer system/recipient.	🟨
WWTPs: Influent	There are no direct measurements of TWP in WWTPs, but they are undoubtedly entering WWTPs through the combined sewer systems. Due to the potentially highly infrequently runoff from roads and verges, timing of the sampling campaign is probably key to be able to collect TWP, at least in the influent. However, it could also be that the TWP are easily lost using current methodologies for sampling, sample preparation and analysis.	🟧
	The roughly estimated (and partially speculative) annual loads of road-associated microplastics to Norwegian WWTPs amounts to 1020-1350 tonnes of tread rubber, 7 tonnes of polymers from PMB and 21-76 tonnes of polymers road marking paints.	🟧
WWTPs: Removal by primary treatment	Very limited removal can be expected by the first mechanical treatment steps, typically consisting of a coarse grid, sand and grease trap and filter screens, though fine screens with pore size of approximately 0.1 mm may remove up to approximately 40% of TWP.	🟧
	A large fraction (possibly 85%) of the TWP will probably be removed by the primary settler, but the settling may be negatively impacted by the expected high volumetric loading when the bulk of the TWP arrive at the WWTP.	🟧

Topics	Key findings	
WWTPs: Removal by chemical treatment	There is no documentation of how TWP are impacted by chemical precipitation, but TWP settle well anyway and the settler after coagulation is usually designed with a longer settling period than the primary sedimentation tank without precipitation.	🟨
WWTPs: Removal by biological wastewater treatment	Biodegradation is not expected to be an important removal mechanism in WWTPs, but the secondary settler in activated sludge processes will probably be an efficient barrier.	🟨
WWTPs: Effluent polishing	Rapid sand filtration is probably the most used (but not common) polishing step at Norwegian WWTPs. Particles >10 µm are usually well removed.	🟨
WWTPs: Sludge treatment	No documentation has been found on fate in sludge treatment. Limited biodegradation can be expected, but fragmentation of the particles may be an issue, particularly during lime stabilisation.	🟧
Sustainable drainage systems	Dry swales, infiltration chambers, perforated pipe systems and soakaways are appropriate for treating runoff from roads with up to medium traffic density. Filter strips are recommended pre-treatment for the other SuDS components and provide additional treatment.	🟩
	The system's capacity to store and infiltrate runoff before the next stormwater event determines the treatment effect. If dimensioned and maintained properly, a TSS removal of 75-80% should be achievable for infiltration SuDS. winter conditions are challenging as the top soil may freeze. However, perforated pipe systems and soakaways will provide good infiltration if the infiltration zone is situated below the freeze zone.	🟨
Compact technical treatment units	Centripetal force-enhanced settling units (i.e. vortex separators), gravitational settling units (i.e. closed wet basins and lamella basins), chemically enhanced settling units (i.e. ballasted flocculation) and filtration units (i.e. cartridge filters and media filters) may all be applied to treat highly polluted road runoff.	🟩
	It is important that the proprietary systems are designed so that flows from larger rainfall events can be managed by the units without significant resuspension of sediments or other pollutants. Any runoff that is bypassed will not be treated and should be taken into account in the overall pollution budget.	🟩
	Many of the claims that are provided by the manufacturers are based on laboratory testing under controlled conditions, showing very good TSS removal. It is important that the manufacturer of a device provide evidence to support any performance claims.	🟩
	Vortex separators may be an efficient method to remove the coarser (>150 µm) fraction of TWP. The actual result is highly dependent on the influent and structural details of the unit. If dimensioned properly, closed wet basins may provide similar removal efficiencies for first flush treatment as observed with wet ponds (ca. 80% TSS removal). The lamella settler improves the settling and a smaller sedimentation tank could also be used. Ballasted flocculation may provide very high removal efficiencies (up to 90% TSS). Filter units typically show above 80% removal of TSS when tested under laboratory controlled conditions, but field reports indicate somewhat lower removal efficiencies (ca. 60%).	🟧
	Proprietary treatment systems will require routine maintenance to ensure continuing operation to design performance standards. The manufacturers should provide detailed specifications and frequencies for the required	🟩

Topics	**Key findings**	
	maintenance activities. Access to the device for maintenance purposes is important and should play a role in siting.	🟩
Treating tunnel wash water	All tunnels (ca. 1100) are routinely washed and concentrations of contaminants (most probably also TWP) in tunnel wash water are high. If the tunnel wash water is treated, technical sedimentation basins and/or wet ponds are usually used, but this is done in very few tunnels in Norway. In the future, more advanced treatment such as chemical precipitation, membrane filtration and adsorption with organic and inorganic adsorbents may be used for the most heavily polluted tunnel wash waters. Most investigations performed on the latter treatment processes on tunnel wash water have been carried out at laboratory scale. More or less complete removal of TSS has been obtained when combining wet basins with chemical precipitation or (subsequent) filtration.	🟩

Utvidet sammendrag

Tittel: Mikroplast i veistøv – karakteristika, veier til miljøet og tiltak
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Rapporten er delt i to deler:

I **del I – Egenskaper og spredning** diskuterer vi tilstedeværelsen og egenskapene til mikroplastpartiklene som finnes i vegstøv, hvordan og hvor de sprer seg og akkumuleres umiddelbart etter at de er frigitt, og hva vi kan forvente å finne i veiavrenningen under nedbørshendelser.

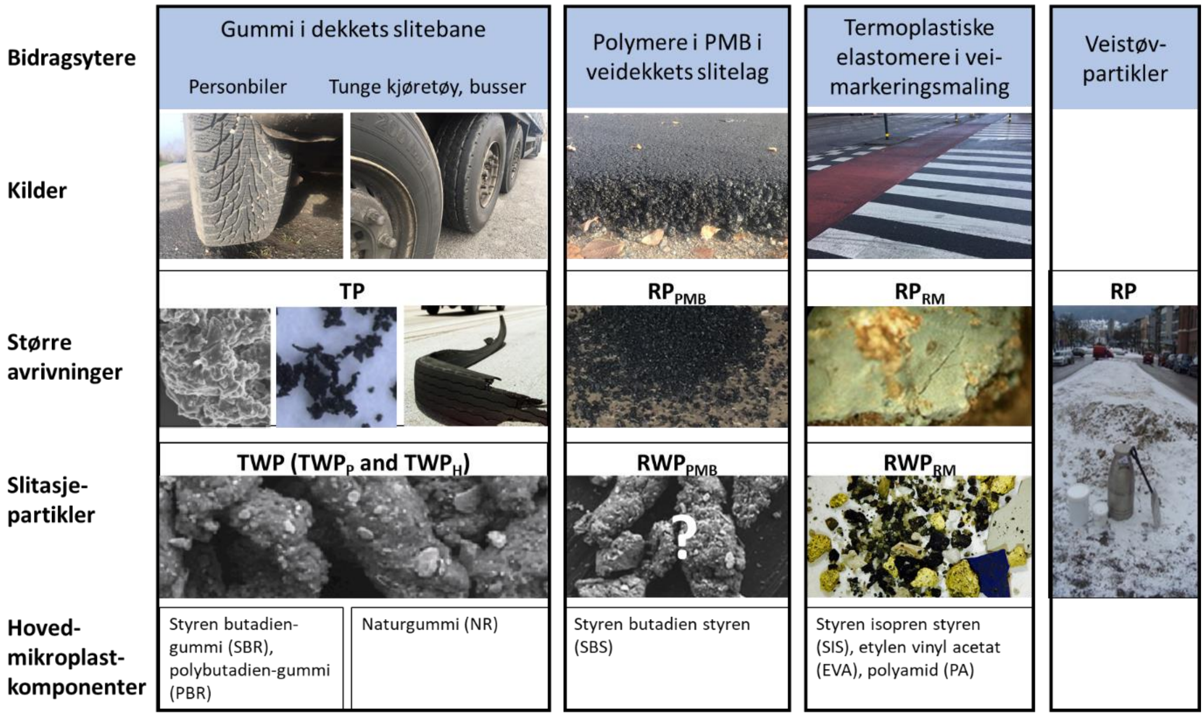
I **del II – Renseløsninger** diskuterer vi effektiviteten til eksisterende renseløsninger i å fjerne mikroplastpartikler fra veivannet. Disse inkluderer eksisterende renseanlegg langs hovedveiene, sandfang og avløpsrenseanlegg som mottar avløpsvann fra byområder. Vi diskuterer også andre mulige behandlingsløsninger som kan brukes både langs nasjonalveinettet, med bakgrunn i kommende nye krav gitt i den reviderte versjonen av håndbok N200 til Statens Vegvesen, eller i byområder med begrenset ledig plass til behandlingsløsninger.

I det følgende sammendrag er våre funn presentert i tre fortløpende tabeller. Nåværende kunnskapsnivå, slik vi tolker det, på hvert underemne er indikert med følgende fargekoding:

🟩 Relativt bra; spesielt fokus ikke nødvendig
🟨 Noe, men mangler viktig kunnskap, eller ikke-eksisterende
🟧 Nesten ikke-eksisterende og viktig å vite

DEL I – EGENSKAPER OG SPREDNING

Gummidekkets slitebane, polymere tilsatt for å styrke bitumen i vegdekkets slitelag og termoplastiske elastomere i veimarkeringsmaling er antatt å utgjøre den største andelen av mikroplast i vegstøv. Figuren under oppsummerer kilder og notasjoner brukt i rapporten til å skille mellom større avrivninger og slitasjepartikler fra de ulike kildene.



Veistøv-assosierte mikroplastpartikles; RAMP = TWP + RW$_{PRM}$ + RWP$_{PMB}$

Tabellen under oppsummerer de viktigste karakteristiske egenskapene til de ulike typene RAMP.

Karakteristika	TWP		RWP$_{RM}$		RWP$_{PMB}$	
Amounts	7,080-9,600 tonnes rubber/year	🟩	28 tonnes SBS/year	🟧	90-180 tonnes thermoplastic elastomers/year	🟨
Størrelsesområde	**Størrelse** – **Volum%** 50-350 µm – 85 30-50 µm – 8 10-30 µm – 2 2.5-10 µm – 4 <2.5 µm – 1	🟨	Muligvis innenfor 50-4000 µm, men usikkert, spesielt i nedre størrelsesområde	🟧	Muligvis som TWP, men begrenset med informasjon	🟨
Tetthet	1.7-2.1 g/cm^3, opptil 2.5 g/cm^3	🟨	>1.2 g/cm^3	🟧	Muligvis som TWP, men begrenset med informasjon	🟨
Form og farge	Mørk, pølseformet med ru overflater	🟨	Få rapporter, men fargede og tilsynelatende relativt runde med ru overflater	🟧	Sannsynligvis som TWP	🟨
Overflateladning	Ikke rapportert	🟧	Ikke rapportert	🟧	Ikke rapportert	🟧
Biologisk nedbrytbarhet	Indikasjoner at SBR-rest er langsomt nedbrytbart	🟧	Ikke rapportert, sannsynligvis begrenset	🟧	Ikke rapportert, sannsynligvis begrenset	🟧

Følgende tabell oppsummerer hovedfunn innenfor utvalgte tema relatert til forekomsten av, og egenskapene til, RAMP i veistøv, deres lokale spredning og akkumulering etter at de er dannet, og konsentrasjoner i veiavrenningen under nedbørshendelser.

Tema	Hovedfunn	
Dekkslitasje-partikler	*Innhold:* Materiale fra dekket utgjør typisk ca. 40% av TWP og ca. 1-5% av RP. I løpet av vintersesongen vil dekkslitasjens andel av veistøvet reduseres (til <1%) på grunn av drastisk økt veislitasje på veiflater forårsaket av piggdekk. Det er generelt antatt at den minste størrelsesfraksjonen av TWP er noe underestimert på grunn av utfordringer ved analytisk kvantifisering.	🟨
	Kvantifiseringsmetode: Gummifraksjonen i TWP vil sannsynligvis ikke bli visuelt identifisert ved hjelp av tradisjonelle metoder, men det er mulig å kjøre kjemiske analyser av TP-markører, som SBR og sink (eller organisk sink). FT-IR og spektralanalyse kan være et alternativ, men metodikken bør verifiseres ytterligere.	🟨
	Årlige utslipp: De estimerte årlige utslippene av mikroplast som dekkgummi på norske veier ligger i størrelsesorden 4.300-5.700 tonn eller 17.700-24.000 tonn som TWP.	🟩
	Vei-spesifikke utslipp: Avhengig av et bredt spekter av faktorer hvor ÅDT, type kjøretøy og kjøremønster sannsynligvis er de viktigste.	🟨
Polymer-modifisert bitumen-slitasje-partikler	*Egenskaper*: Det er begrenset med spesifikk informasjon om egenskapene til PMB-slitasjepartikler. Siden de hovedsakelig genereres av piggdekk, vil deres sammensetning sannsynligvis kunne være svært ulik typisk TWP generert uten piggdekk.	🟧
	Årlige utslipp: Det totale årlige utslippet av SBS på grunn av veislitasje forårsaket av piggdekk ble anslått til ca. 28 tonn.	🟧
Veimarkerings-slitasjepartikler	*Egenskaper*: Det ser ut til å være svært begrenset med dokumentasjon om forekomsten av mikroplastiskpartikler fra veimarkeringsmaling i miljøet.	🟧
	Årlige utslipp: Det finnes svært begrenset med kvantitative data. Et første estimat antyder et årlig utslipp av termoplastiske elastomere i veimakeringsmaling på i størrelsesorden 90-320 tonn i Norge.	🟧
Andre kilder	*Makroplastforsøpling*: Kan være en viktig sekundær B-kilde til mikroplast i veistøv.	🟧
Lokal spredning av slitasjepartikler	*Avsetning*: Regn eller snøfall vil drastisk øke avsetningen av luftbårne partikler på vei eller i veigrøft.	🟩
	Romlig fordeling: Det er en eksponentiell nedgang i TWP-konsentrasjonen med avstand fra veien, hvor typisk 80% av TWP blir funnet innenfor 5 meter fra veikanten.	🟩
	Variabilitet: Siden været er en så viktig faktor for lokal distribusjon, kan spredningen variere drastisk fra dag til dag og med sesong.	🟩
Transport-mekanismer for slitasjepartikler	*Vind-generert*: Tapet av dekkslitasjepartikler på grunn av vind er sannsynligvis relativt lite, med mindre området er spesielt vindutsatt.	🟩
	Vann-generert: Regn og smeltevann vil bidra til å vaske slitasjepartikler i veibanen ut i veigrøften. Effektiviteten vil være avhengig av intensiteten og varigheten av nedbøren, mikrostrukturen, helningen og den generelle tilstanden til veidekket, samt partiklenes størrelse, tetthet og klebrighet. Små partikler blir lettere fanget i mikrostrukturer i veidekket. Sprut fra biler kan også gi et vesentlig bidrag.	🟨
	Tilbakeholdelse i veidekkets struktur: I Nederland hevdes det at ca. 95% av all TWP på veier med svært åpen asfaltstruktur (ZOAB) blir permanent lagret i de små porene i veien.	🟨

Tema	Hovedfunn	
	Tilbakeholdelse i veigrøft: Veigrøften anses normalt ikke som et behandlingstrinn i seg selv i Norge. Slitasjepartikler kan forventes å tilbakeholdes av jord og vegetasjon i veigrøften, avhengig av egenskapene til de stedlige løsmassene og vegetasjonen.	🟩
	Urbane områder: På grunn av kompleksiteten i det underjordiske nettet av separate overvannledninger og fellesavløpsledninger, er det mange steder ukjent til hvilken type ledningsnett veiavrenningen går.	🟨
	Veivasking: Veivasking er en ganske effektiv måte å fjerne større partikler (> 100-125 µm), men har begrenset effekt på mengdene luftbårne partikler.	🟩
	Kjøretøy-mediert: Partikler kan klebe seg fast hvor som helst på kjøretøyet.	🟨
	Snø-mediert: Snø kan akkumulere forurensninger, som frigis ved snøsmelting.	🟩
Akkumulering og tap av slitasje-partikler	Lengden på tidsrommet mellom regnhendelser eller veivasking har stor betydning for akkumuleringen av store slitasjepartikler på veien og i veigrøften i. Intensiteten og/eller varigheten av regnhendelsen eller av hvilken type vaskemetode som benyttes bestemmer hvor stor andel av de avsatte parkilene som blir fjernet.	🟨
	Konsentrasjoner i veigrøftjord: Observerte maks-konsentrasjoner av TWP i området 0,6-117 g/kg tørrvekt.	🟨
	Konsentrasjoner i veiavrenning: Observerte maks-konsentrasjoner av TWP i området 0,3-197 mg/l. TSS-konsentrasjoner i veiavrenning varierer typisk i området 50-200 mg/l og opp til 5000 mg/l i ekstreme tilfeller med trafikkmengde som en viktig avgjørende faktor.	🟨
	Transport vs nedbrytning: Det er mer sannsynlig at TWP blir transportert bort fra veigrøften med vann eller vind enn at den brytes ned (hvis TWP ligger i jord).	🟧
Sporing av mikroplast i slitasjepartikler	Ekstraherbar organisk zink, gummipolymeren SBR, benzotiazolen 24MoBT og n-alkaner med mer enn 35 karboner er lovende markører for dekkslitasjepartikler i miljøet.	🟩
	SBS-polymeren kan være en potensiell markør for PMB-slitasjepartikler I miljøet.	🟧

DEL II – RENSELØSNINGER

Følgende tabell oppsummerer hovedfunn innenfor utvalgte tema relatert til forventet renseeffekt av eksisterende og potensielle behandlingsløsninger for fjerning av RAMP fra veiavrenning langs det nasjonale veinett og i byområder med begrenset ledig plass til behandlingsløsninger, samt mulige løsninger for behandling av tunnelvaskvann.

Tema	Hovedfunn	
Rensing – hvor og hva	En stor andel av de 247 km (ca. 352 km i 2029) av det nasjonale veinettet, som har en ÅDT >30,000 og hvor rensing av veiavrenningen er påkrevd, befinner seg i urbane områder.	🟩
	Sedimentasjon vil være den viktigste mekanismen for fjerning av RAMP, mens filtrering, og muligens adsorpsjon, vil være viktig dersom ytterligere behandling er nødvendig.	🟩
	Det er generelt en fullstendig mangel på understøttende dokumentasjon på i hvilken grad RAMP vil bli fjernet, og i hvilken grad de er tilstede i veivannet som kommer inn til eksisterende renseanlegg.	🟧

Renseløsninger for avrenning fra hovedveier	Kun våte overvannsbassenger (naturbaserte eller teknisk utformede) er i samsvar med kravene til trinn 1-renseløsninger i henhold til den reviderte versjonen av Statens vegvesens håndbok N200.	🟩
	Hvis det våte overvannsbassenget er godt planlagt, og konstruert i henhold til disse planene, samt riktig vedlikeholdt, er det mulig å oppnå en årsgjennomsnittlig TSS-fjerning på over 80%.	🟧
	Imidlertid er mange av de eksisterende våte overvannsbassengene i Norge i dårlig forfatning og med funksjonsfeil, enten på grunn av dårlig byggekvalitet eller dårlig/forsømt drift og vedlikehold. Derfor kan det være et misforhold mellom forventet og faktisk renseeffekt.	🟨
	Våte overvannsbassenger har vist seg å være virkningsfulle og kostnadseffektive tiltak når det gjelder å beskytte vannlegemer fra forurenset avrenning.	🟩
	Et bredt spekter av renseløsninger basert på infiltrasjon i stedlige løsmasser eller filtrering gjennom konstruert jord oppfyller de funksjonelle kravene til trinn 2-renseløsninger.	🟩
	En vanlig årsak til lav infiltrasjonshastighet er kompaktering av løsmassene under byggearbeidet med bassenget. For å unngå dette bør det brukes så lette maskiner som mulig.	🟩
	Hvis åpne infiltrasjonsbasseng er dimensjonert korrekt, kan man forvente en TSS-fjerning på ca. 80-95%, mens opptil 100% kan oppnås med lukkede infiltrasjonsbasseng (perkolasjonsbasseng). Sandfiltre kan forventes å oppnå tilsvarende TSS-fjerning som åpne infiltreringsbassenger. Lagringskapasiteten i infiltreringsdammen vil være avgjørende for den faktiske renseeffekten. Det bør bemerkes at eventuell TSS som når grunnvannet under infiltrasjonsbassenget vanligvis ikke er tatt med i betraktningen.	🟨
	Infiltrasjon brukes sjelden i Norge i dag, og rapporter indikerer dårlig funksjon (lav infiltrasjonshastighet).	🟨
	Hvis kompaktering under byggefasen unngås og et vått overvannsbasseng inngår som forbehandling, bør infiltrasjonstrinnet kunne gi en tilleggsfjerning av TSS som samlet sett vil kunne bli på i størrelsesorden 96%.	🟨
	Om vinteren er bruk av infiltreringsbassenger utfordrende fordi tele i bakken kan redusere eller helt stoppe infiltrasjonen, slik at det fungerer mer som et vått overvannsbasseng. Overløpet kan da bli behandlet i et lukket infiltreringssystem.	🟩
Overvanns-håndterings-prinsipper i urbane områder	Renseløsninger i byområder utfordres typisk av begrenset naturlig demping av overflateavrenningen og av begrenset tilgjengelig areal. Disse utfordringene kan møtes med fire alternative tiltak, gjerne i kombinasjon; A) ved å redusere behovet for behandling, B) ved å hindre at lite forurenset overvann når fellesavløpsnettet, kombinert med økt lagringskapasitet lokalt og/eller sentralisert for å hindre overløp på fellesnettet, og øke kapasiteten for sentralisert behandling, C) ved å bruke natur-baserte løsninger for å holde tilbake og begrense avrenning over bakken, og hvor det er nødvendig og mulig, behandle avrenningen ved infiltrasjon i stedlige løsmasser så nær kildeområdet som mulig, og D) ved å benytte kompakte tekniske renseenheter med begrenset arealkrav plassert under overflaten lokalt.	🟨
	Hvor mulig, bør naturbaserte metoder være et førstevalg for tilbakeholdelse og lagring, da de gjerne har relativt lave investerings- og driftskostnader og det er relativt enkelt å overvåke deres operasjonelle ytelse og behov for vedlikehold. Men kommersielle behandlingssystemer kan være hensiktsmessige og kostnadseffektive, både for forbehandling (for eksempel	🟨

	hvirveloverløp) og for etterbehandling (for eksempel ulike filtreringsløsninger og ballastert flokkulering), der ytterligere behandling er nødvendig og infiltrasjon ikke kan anbefales.	🟨
	I byområder med begrenset plass kan behandlingen begrenses til å håndtere kun 'first flush'-avrenningen.	🟩
Tilbakeholdelse i sandfang	Sandfang kan holde tilbake en mindre andel av TWP større enn ca. 50 µm, men med dagens designkriterier vil den volumetriske belastingen av sandfangene ofte overskrides, noe som resulterer i dårlig tilbakeholdelse av TWP.	🟨
	Partikler mindre enn ca. 50 µm vil ende opp i det kombinerte avløpssystemet eller i resipienten.	🟨
Avløps-renseanlegg: Innløp	Vi har ikke funnet noen direkte målinger av TWP på avløpsrenseanlegg, men de vil uten tvil finnes i det innkommende avløpsvannet i områder med fellesavløpssystem. På grunn av den potensielt svært sporadiske avrenningen fra veier og veigrøfter er timingen av prøvetakingskampanjen sannsynligvis nøkkelen til å kunne samle TWP, i hvert fall i innløpet. Det kan imidlertid også være at TWP ikke blir fanget opp eller går tapt ved bruk av nåværende metodikker for prøvetaking, prøveutarbeidelse og analyse.	🟧
	Et grovt (og delvis spekulativt) estimat av mengden RAMP som årlig kommer inn til norske avløpsrenseanlegg antyder følgende; 1020-1350 tonn gummi fra bildekk, 7 tonn polymere fra PMB og 21-76 tonn polymere fra veimarkeringsmaling.	🟧
Avløps-renseanlegg: Fjerning med primærrensing	Meget begrenset fjerning kan forventes med de første mekaniske behandlingstrinnene, som vanligvis består av grovsiling, sand- og fettfang og eventuelt finsiling, selv om mikrosiler med porestørrelse ned mot 0,1 mm kan fjerne opptil ca. 40% av TWP.	🟧
	En stor andel (muligvis 85%) av TWP vil sannsynligvis bli fjernet på det primære sedimentasjonstrinnet, men sedimenteringen kan bli negativt påvirket av den forventede høye volumetriske belastningen når hovedmengden TWP kommer inn til renseanlegget.	🟧
Avløps-renseanlegg: Fjerning med kjemisk felling	Det finnes ingen dokumentasjon av hvordan TWP påvirkes av kjemisk felling, men TWP sedimenterer uansett godt og sedimenteringsbasseng etter kjemisk felling dimensjoneres gjerne med en lengre sedimenteringsperiode enn sedimentasjonsbasseng uten kjemisk felling.	🟨
Avløps-renseanlegg: Fjerning med biologisk behandling	Biologisk nedbrytning forventes ikke å være en viktig fjerningsmekanisme på avløpsrenseanlegg, men sedimentasjonsbasset som separerer ut bioslam i aktivslamprosesser vil trolig være en effektiv barriere.	🟨
Avløps-renseanlegg: Polering av utslipp	Hurtig sandfiltrering er sannsynligvis mest brukt (men ikke vanlig) ved norske avløpsrenseanlegg. Partikler >10 µm blir normalt godt fjernet.	🟨
WWTPs: Slam-behandling	Ikke noe dokumentasjon ble funnet om skjebne ved slambehandling. begrenset biologisk nedbrytning kan forventes, men fragmentering av partiklene kan skje, spesielt ved kalkstabilisering.	🟧
Lokal overvanns-håndtering (LOH) med	Tørre filtergrøfter, infiltrasjonskamre, perforerte rørsystemer og lukkede infiltrasjonsbasseng (perkolasjonsbasseng) er egnet for behandling av avrenning fra veier med moderat trafikktetthet. Filterstrimler anbefales som forbehandling for andre LOH-komponenter og gir ytterligere fjerning.	🟩

naturbaserte løsninger	Systemets kapasitet til å lagre og infiltrere avrenning før neste avrenningshendelse bestemmer renseeffekten. Hvis systemet er riktig dimensjonert og vedlikeholdt, burde en årsgjennomsnittlig TSS-fjerning på 75-80% være mulig for infiltrasjonsløsninger. Vinterforhold er en utfordring, siden det øverste jordlaget kan fryse. Men perforerte rørsystemer og lukkede infiltrasjonsbasseng vil gi god infiltrasjon hvis infiltrasjonssonen ligger under frysesonen.	🟨
Kompakte tekniske renseløsninger	Tekniske renseløsninger basert på sedimentering (f.eks. lukket sedimenteringsbasseng med eller uten lameller), sentrifugalkraft-forsterket sedimentering (f.eks. hvirveloverløp), fellings-forsterket sedimentering (f.eks. ballastert flokkulering) og filtrering (f.eks. patronfiltre og mediefiltre) kan alle benyttes til å behandle sterkt forurenset veiavrenning.	🟩
	Det er viktig at renseenhetene er utformet slik at avrenning fra større nedbørshendelser kan håndteres av enhetene uten betydelig resuspensjon av sedimenter eller andre forurensende stoffer. Eventuell avrenning som ledes utenom rensesystemet vil ikke bli behandlet og bør tas med i betraktningen i det totale forurensningsbudsjettet.	🟩
	Mange av påstandene knyttet til renseeffekt som gis av produsentene er basert på laboratorietesting under kontrollerte forhold, og viser meget god TSS-fjerning. Det er viktig at produsenten av en enhet viser dokumentasjon som støtter eventuelle ytelseskrav.	🟩
	Hvirveloverløp kan være en effektiv metode for å fjerne den grovere (> 150 µm) andelen av TWP. Det faktiske renseresultatet er sterkt avhengig av innkommende vannmengde og detaljer ved enhetens design. Hvis riktig dimensjonert, kan lukkede sedimentasjonsbasseng gi tilsvarende fjerning for first flush som observert for åpne sedimentasjonsbasseng (ca. 80% TSS-fjerning). Lameller forbedrer sedimenteringen, og gjør at sedimentasjonsbassenget kan gjøres mindre. Ballastert flokkulering kan gi svært god fjerning (opptil 90% av TSS). Filterenheter gir vanligvis over 80% fjerning av TSS når de testes under laboratoriekontrollerte forhold, men feltrapporter indikerer noe lavere fjerning (ca. 60%).	🟧
	De tekniske renseløsningene krever rutinemessig vedlikehold for å sikre kontinuerlig drift og renseresultat tilsvarende det de er designet for. Produsentene bør oppgi detaljerte spesifikasjoner og frekvens for nødvendig vedlikehold. Tilgang til enheten for vedlikehold er viktig og bør spille en rolle ved valg av plassering.	🟩
Rensing av tunnel-vaskevann	Alle tunneler (ca. 1100) vaskes regelmessig og konsentrasjonene av forurensninger (mest sannsynlig også TWP) i tunnelvaskevann er høye. Hvis tunnelvaskevann blir renset, gjøres dette normalt med våte overvannsbassenger (naturbaserte eller teknisk utformede). Men per i dag renses vaskevannet kun fra et fåtall norske tunneler. I framtiden vil kanskje de mest forurensede tunnelvaskevannene bli renset med mer avanserte rensemetoder slik som kjemisk felling, membranfiltrering og adsorpsjon med organiske og uorganiske adsorbenter. De fleste gjennomførte undersøkelsene av de sistnevnte renseprosessene er har blitt gjort i laboratorieskala. Mer eller mindre full fjerning av TSS har blitt oppnådd med en kombinasjon av våte overvannsbassenger og kjemisk felling eller (etterfølgende) filtrering.	🟩

1 Introduction

1.1 Overview

For decades now, road verges and their surroundings are being polluted by particles and a long range of hazardous substances from road traffic (Lagerwerff and Specht 1970, Bækken 1993), including rubber from tyre treads (Syversen 1989) (see **Figure 1.1**). In recent years, with increasing focus on macro- and microplastics contamination of the environment[1], other sources of microplastics to road dust such as road marking paint and polymer modified bitumen (PMB) in asphalt pavement have received some attention (Sundt et al. 2014, Lassen et al. 2015). Little is known about the latter two, but when rubber treads are present in road dust, they are typically included in dark, sausage-shaped conglomerates with rough surfaces and a large degree of mineral particles that increases their density (~1.7-2.1 g/cm^3). Hence they do not confirm to the description of common plastics; light, shiny, smooth and often coloured particles. Therefore, tread wear particles will probably show a different environmental distribution than traditional microplastics.

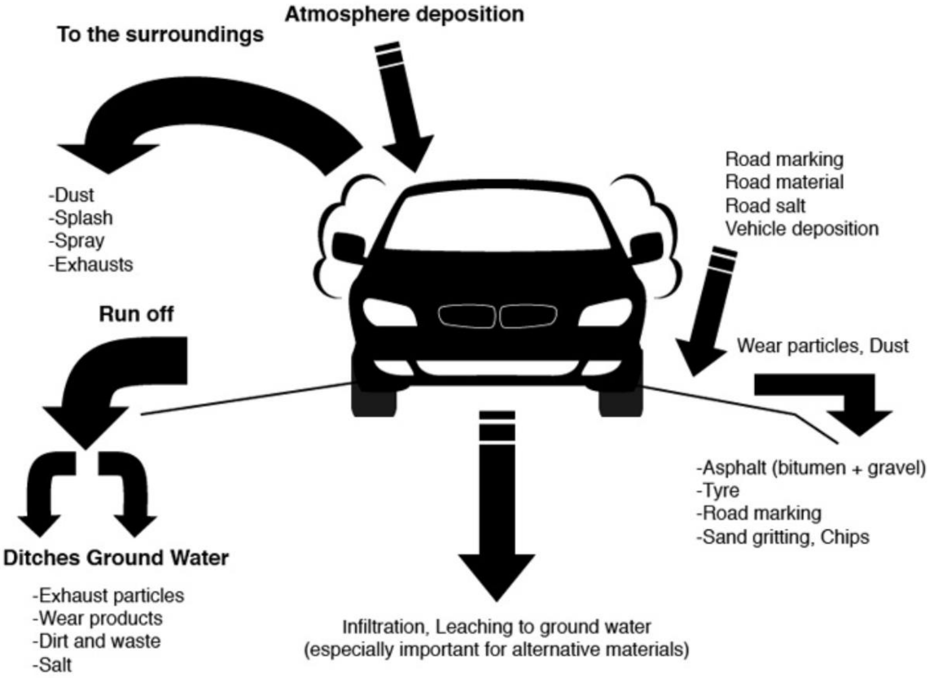


Figure 1.1 *Sources of traffic-derived pollutants (www.roadex.org)*

As pollutants are accumulating in road verges and surrounding areas, they are also, at least partially, transported away with road runoff during rain events. Most road runoff in Norway end up in the aquatic environment without any applied treatment, but runoff from extremely polluted roads (i.e. AADT > ~8,000-10,000) are treated, primarily in sedimentation ponds. Road runoff in urban areas may be discharged to the combined sewer system and thereby (if not retained in gully pots or discharged through sewer overflow) end up in the domestic wastewater treatment plants.

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[1] Initially marine environment, but recently focus has shifted to freshwater and terrestrial environments.

The first part of this report describes different characteristics of road-associated microplastic particles (RAMP) and their pathways to aquatic and terrestrial environments. The second part uses these characteristics and pathways to assess the expected fate and removal of particles by different treatment solutions and processes that may be applied in Norway.

1.2 The need to limit discharges of road-associated microplastics to aquatic and terrestrial environments

There are, as yet, no specific requirements regarding the removal of microplastics of any kind from (waste)water before discharge to the receiving environment. However, with the implementation of the Water Framework Directive (WFD) in the Norwegian Water Regulation (Vannforskriften[2]) all discharges to aquatic recipients need to take the vulnerability of the recipient into account. The actual need for treatment is, however, not addressed in this report.

Traditional synthetic and semisynthetic microplastics can have negative consequences on the environment. They can contaminate terrestrial aquatic and freshwater environments and their presence may present problems for biota that also inhabit these areas. Organisms can interact with microplastics through adhesion, absorption and ingestion and laboratory experiments have shown negatives effects on feeding, the immune system, growth, energy levels, fecundity and reproduction (see review such as GESAMP 2016). Concerns surrounding microplastic effects on biota have led to several laboratory exposure and toxicological studies which have confirmed that a diverse array of organisms, across trophic levels, can ingest microplastics (GESAMP 2016). These studies have enabled monitoring of the uptake and distribution of microplastic within whole organisms as well as excised tissues, e.g. gills, intestinal tract and liver. Laboratory studies have identified some potential effects of microplastic exposure including: increased immune response, decreased food consumption, weight loss, energy depletion, decreased growth rate, decreased fecundity and impacts on subsequent generations. Microplastics may be associated with hazardous chemicals, such as those that are incorporated into the polymer matrix during manufacture and also those that are sorbed from the environment, such as PBTs (persistent, bioaccumulative and toxic substances), which includes polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs).

Rubber tyre tread, which has started to be included as a “microplastic” may have similar consequences as microplastics. However, the complex chemical make-up, density and different environmental distribution may require rubber particles to be classified as a different environmental pollutant. Not enough information is available about the impact of road derived anthropogenic particles could be having on marine organisms, in fact there is no information on the consequences if they are consumed by biota. Further laboratory exposure experiments are required.

As there is still not enough information on the effects of tyre dust to organisms it will be vital to monitor its import and release, as well as develop suitable tools to limit the discharges into the environment. Laboratory experiments are needed now to monitor distribution and interaction with organisms to truly understand potential environmental consequences.

The current and expected requirements regarding treatment of road runoff and tunnel wash water are described in **Appendix A**, as well as a short discussion regarding domestic wastewater treatment plants as a common recipient of road runoff.

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[2] https://lovdata.no/dokument/SF/forskrift/2006-12-15-1446

PART I – CHARACTERISTICS & PATHWAYS

2 Microplastics in road dust

2.1 Definition of microplastics

Microplastics are, as the term suggest, plastics of microscopic size. However, both the definition of “plastics” and “microscopic size” has been disputed. **Plastics**, in general, are solid man-made materials consisting of polymers that have their carbon backbone derived from fossil (petroleum and petroleum by-products) or biological sources. A wide range of plastic materials exist with functional properties depending on the mix of polymers[3] and additives used, though all are regarded as being relatively persistent in the environment. Until recently the commonly used interpretation of **micro-size** related to microplastic particles has been <5 mm in maximum diameter to include pellets. However, with the updated definition by GESAMP (2015), we will adhere to the following size definitions in this report:

- *Macroplastics*: >25 mm
- *Mesoplastics*: 1-25 mm
- *Microplastics*[4]: 0.1-1000 µm
- *Nanoplastics*: <0.1 µm

It is also common to distinguish between primary and secondary microplastics; the former being manufactured to be used in the micro scale, while the latter now being further divided in two segments:

- *Secondary A*: Microplastics that break down through use (e.g. particles when first released from tyres or road marking paint)
- *Secondary B*: Microplastics that break down once disposed of in the environment (further abraded and fragmented particles due to e.g. frictional forces from passing traffic)

In **Table 2.1** key elements of the microplastics definition used in this report are summarised.

Table 2.1 Elements of the microplastics definition used in this report.

Element	**Provisional criteria**		**Reference**
Composition	Synthetic or natural polymer-based crafted materials		ISO (2013), ECHA (2012)
Physical state	A substance that is not a liquid or a gas		UNECE (2014)
Size	0.001-1000 µm		GESAMP (2015)
Solubility	<1 mg/l		ECHA (2014)
Degradability	Compartment Marine water Fresh or estuarine water Marine sediment Fresh or estuarine sediment Soil	Half-life < 60 days < 40 days <180 days <120 days <120 days	EC (2007)

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[3] The polymers themselves may also be composed of different types of monomers with associated ligands.

[4] The upper limit of the microplastic size range was also agreed upon by UNESCO at a meeting in September 2017.

2.2 Sources for microplastics in road dust

The main sources for microplastics in road dust in Norway are the wear surface of car tyres (i.e. the tread), road pavement where polymer modified bitumen are used in the wear layer and road marking paints. See **Figure 2.1**. In addition to these, general macroplastics littering along roads could be an important secondary B source to microplastics in road dust. In urban centres, road dust may also contain plastics derived from a range of other sources, among them construction and building materials (e.g. paintings, foils, foams, cement composites etc.), air deposition and artificial turfs (rubber granules[5] and artificial grass fibres). However, none of these have been considered in this report.

Tyre tread

The tread is composed of a complex mixture of compounds in which different types of rubbers typically make up 40-60 %, and the remaining compounds are added to give the tread necessary hardness, wear resistance, durability, elasticity and stickiness. The rubber mix of tyres for passenger cars is typically a mix of styrene-butadiene rubber (SBR) and polybutadiene rubber (PBR), while natural rubber (NR) is the dominating rubber in tyre treads of heavy vehicles. Non-studded winter tyres of passenger cars need a softer rubber mix for proper grip, hence they typically have a somewhat higher PBR ratio than summer tyres. A more detailed description of the tread composition can be found in **Appendix B**.

Polymer modified bitumen

Bitumen is the “glue” in the wear and binder layers of asphalt pavement to keep the gravel together. Polymer modified bitumen (PMB) is also used to increase the strength, stability and adhesive properties of the pavement also under cold winter conditions (Jørgensen et al. 2016). The most commonly used polymer[6] in Norway is the thermoplastic elastomer Styrene Butadiene Styrene (SBS), because it retains most of its properties at low temperatures. Since 2008 there has been a marked increase in the use of PMB on the national roads with heavy traffic, resulting in less rutting because of improved resistance against deformation and wear and tear from studded tyres (Jørgensen et al. 2016). The typical SBS content in bitumen is approximately 5% (Statens vegvesen 2014B).

Road paint markings

Both thermoplastic markings and water-based polymer paints are used on Norwegian roads (Sundt et al. 2014). While the plastic polymer content of thermoplastic markings is as low as 1-5% due to high filler levels (Sundt et al. 2014), the acrylic polymer content of the polymer paints is much higher (e.g. 15-40% according to Lassen et al. 2015). The most commonly used polymers in road markings in Norway are styrene-isoprene-styrene (SIS), ethylene vinyl acetate (EVA), polyamide (PA) and polyacrylate[7] (Sundt et al. 2014).

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[5] Primarily from tyres.

[6] The polymers used in PMB are elastomers (natural rubber, polybutadiene), thermoplastics (polyethylene, polypropylene) and thermoplastic elastomers (ethylene vinyl acetate EVA, styrene butadiene styrene SBS) (Statens vegvesen 2016)

[7] Sundt et al. (2014) listed acryl monomer, which is the monomer of polyacrylate.

2.3 Composition, shape and density of microplastic wear particles in road dust

2.3.1 Particle notation used in the report

To keep track of the different types of particles referred to in the report, we have tried to summarise their context in which they appear in **Figure 2.1**. For particles derived from tyre treads we distinguish between pure tread particles (**TP**) that typically are carved out or shredded from car tyres and tread wear particles (**TWP**) that are generated while driving with passenger cars (**TWP$_{P}$**) and heavy vehicles (**TWP$_{H}$**). For wear particles derived from the road, we distinguish between those coming from road pavement where polymer modified bitumen (PMB) has been used in the wear layer (**RWP$_{PMB}$**) and those coming from road markings (**RWP$_{RM}$**). When we refer to all the above mentioned wear particles, we will use the abbreviation **RAMP** for Road dust-Associated Microplastic Particles. Road dust particles in general, which include also other sources such as break wear and exhaust emissions, are denoted with **RP**, while larger fragments or shreds from the PMB-pavement or road markings are denoted **RP$_{PMB}$** and **RP$_{RM}$**, respectively.

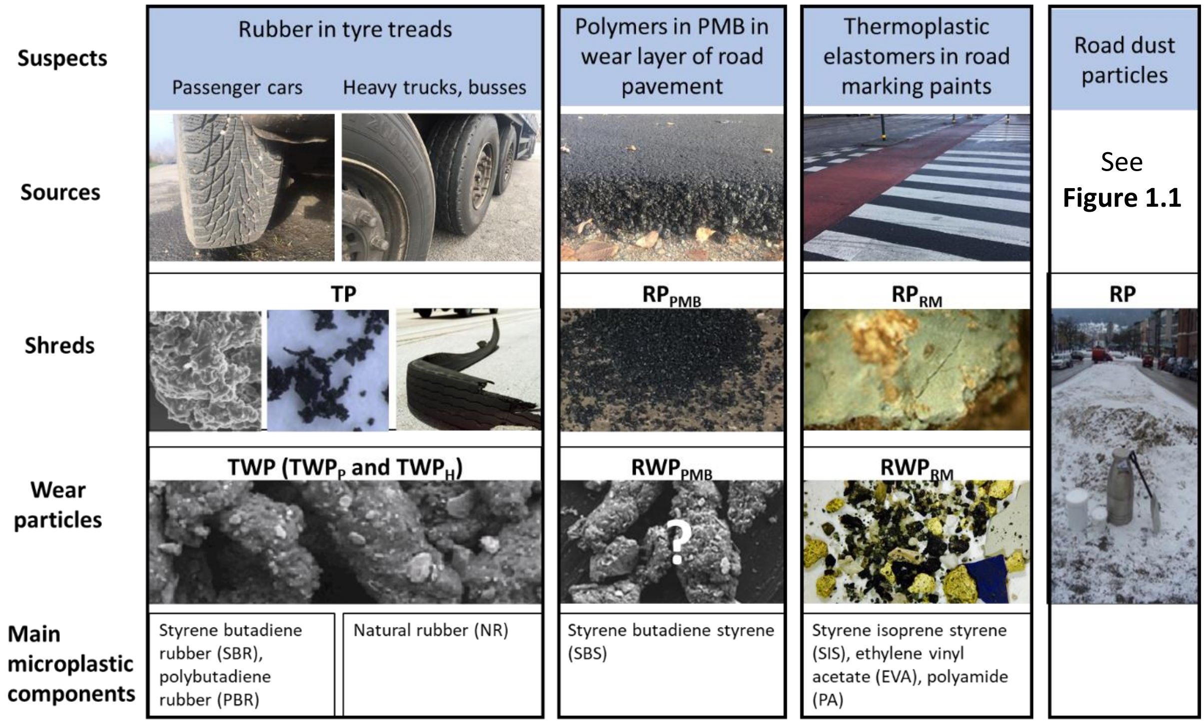

Figure 2.1 *Main suspects of microplastics in road dust, their sources and notation used to distinguish between larger shreds and wear particles from the different sources. Photos: Christian Vogelsang (all sources, RP$_{PMB}$), Luhana et al. (2004) (TP; SEM micrograph), Verschoor et al. (2016) (TWP), reprinted from Kreider et al. (2010) with permission from Elsevier (RWP$_{PMB}$), David Pettersen Eidsvoll (RWP$_{RM}$) and Sissel Brit Ranneklev (RP).*

2.3.2 Tread wear particles (TWP)

General content

Tread wear particles are generated during driving and are found as components in common road dust. Pure tread particles are seldom reported in road dust. Due to the shear forces and heat exerted on them when they are abraded, the TWP will typically contain a mix of tread and road surface materials (Kreider et al. 2010, Panko et al. 2013). However, most road dust particles will include additional material from other sources such as fuel, brakes and atmospheric deposition present in the surrounding environment. This is schematically shown in **Figure 2.2**. Reported contributions from tread to RP are typically in the range of around 1-5%, but ratios up to 10% have found (Grigoratos and Martini 2014). Calculations shown in **Appendix C**, based on measurements conducted by Kreider et al. (2010), indicate that the original tread material makes up approximately 40% of the TWP, and the original rubber material (i.e. microplastics) makes up approximately 8% of the total polymers of RP and approximately 2.4% of the total mass content of RP (tread constituted 5.2% of RP, hence in the high 1-5% range). To make the mass balance between tread and TWP increase, 22% of the rubber was assumed lost due to chemical degradation during the wear process. This is discussed in more detail in **Appendix C**.

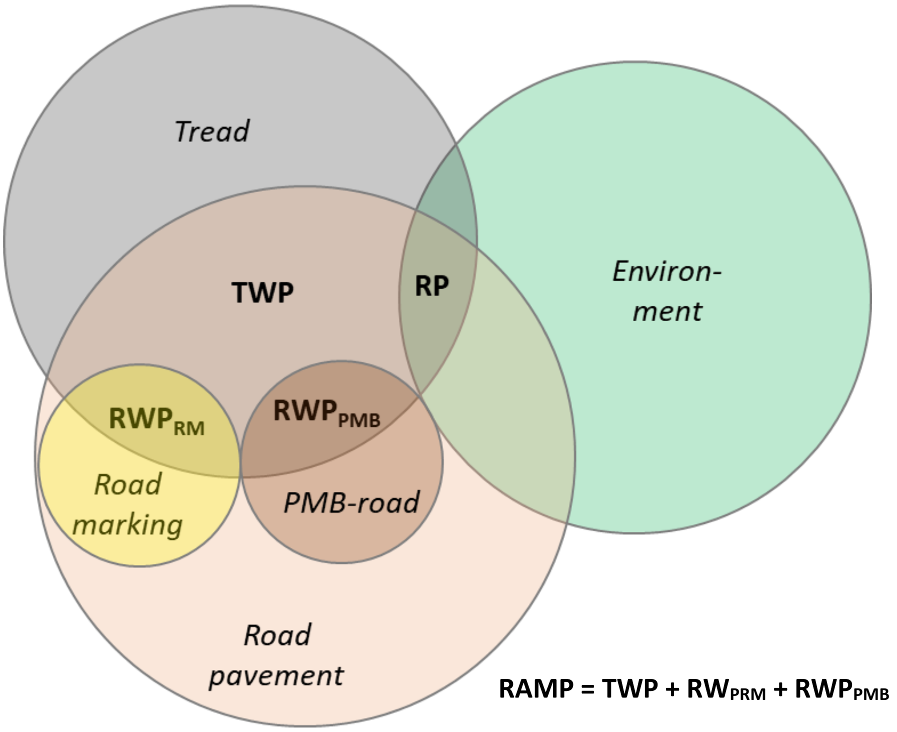

Figure 2.2 *Schematic illustration of contributors to road dust associated microplastic particles (RAMP).*

Shape

Tread wear particles are reported to be generally elongated (“sausage-shaped”) with rough surfaces, (Gunawardana et al., 2011, Kreider et al. 2010). Hence, they have very similar features as other typical road wear particles, though generally somewhat larger in size (Kreider et al. 2010). See **Figure 2.3**. See **Appendix C** for more details regarding shape similarities between TWP and RP.

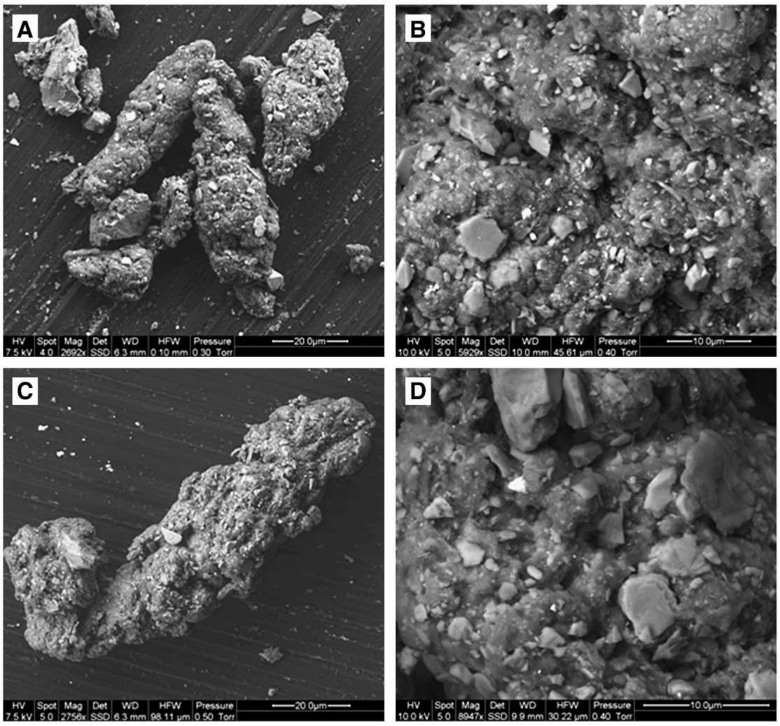

Figure 2.3 *Scanning electron microscope images of RP (A, B) and TWP (C, D). Scales are located below the photos. Mineral incrustations are evident in the photos of greater magnification (B, D). Reprinted from Kreider et al. (2010) with permission from Elsevier.*

Particle size distribution (PSD)

The main part of the tread wear is coarse particles or shreds >10 µm, but a substantial amount (ca. 1-10%) are airborne particles[8] (Grigoratos and Martini 2014). According to findings from Krieder et al. (2010) and Smolders and Degryse (2002), the average volume size of TWP are in the range of 65-85 µm. There is, however, very limited data available to indicate the variability in PSD. A typical size distribution of tread particles based on the findings of Krieder et al. (2010), including recommendation by Broeke et al. (2008) for the PM_{10} (<10 µm) and $PM_{2.5}$ (<2.5 µm) fractions, are shown in **Table 2.2**. This is discussed in more detail in **Appendix D**.

Table 2.2 *Typical size distribution of tread wear particles (Krieder et al. 2010 and Broeke et al. 2008)*

Size bin	Volume%
50-350 µm	85
30-50 µm	8
10-30 µm	2
2.5-10 µm	4
<2.5 µm	1

Particle densities

Because of the much higher mineral content of TWP and RP (typically 50-60%) compared to tread (ca. 16%), TWP and RP will have significantly higher densities than the tread. Reported densities for TWP and RP are typically in the range of 1.7-2.1 g/m3 (Kayhanian et al. 2012, Snilsberg 2008), but

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[8] Cadle and Williams (1978) showed that tyre wear particles up to 30 µm were airborne.

2.53 g/cm^3 has also been noted[9] (Grigoratos and Martini 2014), as compared to 1.15-1.18 g/cm^3 for pure tread (Statens vegvesen 2016, Banerjee et al. 2016, Dumne 2013). Some of the variability in the reported densities could be caused by variable concentrations of natural organic debris embedded in the particles, as suggested by Snilsberg (2008) and differences in road construction materials. This is discussed in more detail in **Appendix C**.

Contents of hazardous substances

As aromatic extender oils and sink oxides (ZnO_x) are added to tyre treads (see **Table B1** in **Appendix B**), elevated levels of these compounds may be found in TWP. Kreider et al. (2010) reported zinc levels of 9,000 ppm in tread and 3,000 ppm in TWP, which are in line with reported values of 3,000-10,000 ppm from other studies (Davis et al. 2001, Legret and Pagotto 1999, Pierson and Brachaczek 1974, Waddell and Evans 1996). This is also why zinc has been suggested used as a specific tracer for tyre wear (see discussion in **Section 2.5** regarding this). Kreider et al. (2010) also found that the total PAH content of the tread represented only 5% of the total PAH content of the RP, which corresponded well with previous studies estimating a low contribution of tyres to total PAHs in road dust and environmental media (Macias-Zamora et al. 2002, Takada et al. 1990, Zakaria et al. 2002). It should be noted that the TWP in the studies conducted by Kreider et al. (2010) were generated under controlled conditions without any influence from other sources. A summary of reported hazardous substances associated with TWP are summarised in **Appendix E**.

2.3.3 Polymer-modified bitumen wear particles (RWP_{PMB})

PMB wear particles are most probably found as composites of the above described tread wear particles (see **Figure 2.2**). Hence, PMB wear particles would have more or less the same shapes, size distributions and densities. However, since the absolute dominating part of the PMB wear are caused by studded tyres during the winter season, the fraction of tread in these particles may be significantly lower compared with typical TWP generated during the summer season (roughly 1/5; see **Section 2.7**). Moreover, due to the increased durability and stickiness of the PMB also at low temperatures, the PMB wear particles may differ from other asphalt wear particles. It must be noted that these are just speculations, as there is limited information on the characteristics of PMB wear particles in this regard.

2.3.4 Road marking wear particles (RWP_{RM})

We have found no studies reporting wear particles from road marking paints (RWP_M) in the environment, but Horton et al. (2016) reported findings of larger fragments (2-4 mm) of road marking in sediment samples from the River Thames. However, researchers at Norwegian Institute for Water Research has isolated what we believe are road marking wear particles from road dust collected along roads in the Oslo area. See **Figure 2.4**. A wide range of particle sizes has been identified, typically varying in the range of 50-2000 µm, however this size range is very uncertain, particularly in the lower end. The actual origin of the particles has not yet been verified by analysis. A simple settling test has indicated that their density is >1.2 g/cm^3 as they do not float in a saturated NaCl solution.

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[9] Verschoor et al. (2016) refer to a density of 1.2-1.3 g/cm^3 for tread wear particles, which seems to be unrealistically low.

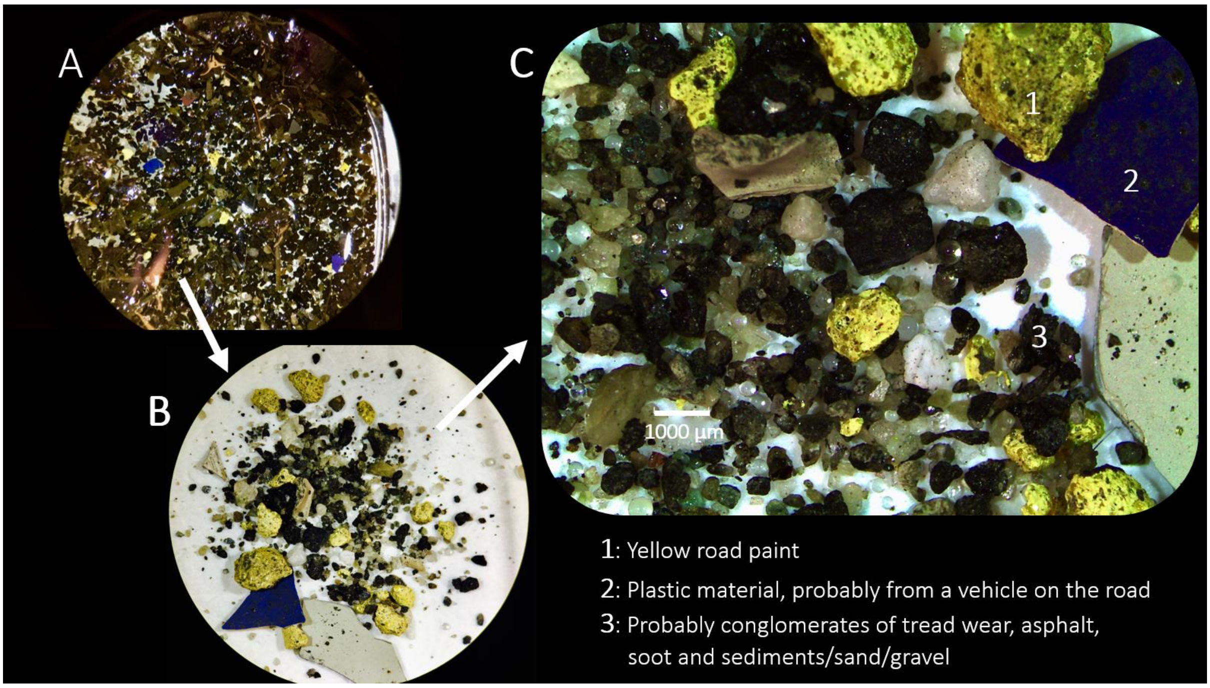

Figure 2.4 *Wear particles of road marking collected from road dust in March 2017 in the Microtyre project. A: The original collected particulates before any separation; B: A collection of micro-, meso- and macro-plastic particles after clean-up; C: Close-up of a section of B). Credit: David Pettersen Eidsvoll, NIVA.*

2.4 Analytical challenges related to tread wear

2.4.1 Collection of tread wear

Various techniques have been used to collect particles from tyre wear and other non-exhaust sources, either under real-world test conditions or in the laboratory using specialised testing machines. The different sampling methods and inherent challenges are discussed in **Appendix F**.

2.4.2 Identification and quantification of rubber from tyre wear

Commonly applied methodologies for the identification of microplastics are based on visual identification using a stereo microscope of the plastics as they tend to stand out from the rest of the particulates as shiny, smooth and "plastic-like". Rubber does not have these characteristics, and rubber embedded in tyre wear particles are nearly impossible to detect visually. Hence, relying solely on visual identification is inappropriate methodology. Thus, Fourier Transform – Infrared (FT-IR) spectroscopy combined with microscopy has become increasingly popular to identify and quantify microplastics in environmental samples. Vollertsen and Hansen (2016) argues that such a methodology should be able to properly identify and quantify the SBR rubber from tyre treads if an adequate spectral analysis[10] of all present chemical bonds is performed for each particle. In verification tests with real tyre treads, they obtained about 100% recovery rates despite concerns regarding potential interference from the carbon black filler in the tread material and possible detrimental changes in the chemical structure of the SBR rubber during sample preparation caused

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[10] They note that the reflection mode is only applicable to particles >80 µm, while the transmission mode (ATR mode) is required for smaller particles to acquire better IR spectra.

by oxidation (by H_2O_2 + catalyst[11]) and ultrasonic treatment. However, whether the methodology is adequate to identify and quantify the SBR rubber in real TWP with more impurities and where at least a part of the rubber is thermally degraded (Fauser 1999) is still under investigation (see **Appendix B**).

Another option, which has been relatively extensively applied, is to conduct chemical analyses of tyre tread components such as the SBR polymer and zinc (or organic zinc). Since these are also highly relevant for tracking tread wear in different environmental compartments, this is discussed in more detail in the next section, **Section 2.5**. A drawback with such chemical analyses is that it is usually only applicable to gross samples and not to identify individual particles.

2.5 Markers for RAMP

The difficulties in visual identification of TWP (see **Section 2.4.2**), and the inherent complexity of the many possible pathways of RAMP to the aquatic and terrestrial environments (see **Section 3.1**), warrants the use of a proper marker for particles. Several tyre components have been used as markers for tyre rubber in the environment (see **Table 2.3**). The most promising are extractable organic zinc (Fauser 1999), vinylcyclohexene[12] (Unice et al. 2012), the benzothiazole 24MoBT (Ni et al. 2008) and n-alkanes with more than 35 carbons (Rogge et al. 1993). In addition, carbon black is a potential marker for tread as 90% of the carbon black on a global scale is used in the rubber industry as a reinforcing filler in a variety of products, with tyres as the major application area (Gottschalk et al. 2015). However, the distinction between engineered and naturally occurring carbon black (e.g. from combustion sources) is in practice almost impossible. Zinc has previously been suggested as a tracer for tyre rubber in road dust as it is found in tyres at an order of magnitude higher than in break wear (Apeagyei et al. (2011), but the many other sources (see **Table 2.3**) make it inadequate as a tracer in other environmental compartments (Grigoratos and Martini 2014).

We have not looked into whether e.g. the SBS polymer in PMB pavements or any of the polymers in road marking paints would be proper markers for such wear particles in different environmental compartments.

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[11] SBR rubber is prone to be attacked by ozone during use (Erickson et al. 1959) and H_2O_2 + Fenton reagent has been used to treat wastewater from SBR production facilities (Zhang et al. 2012).

[12] Vinylcyclehexene is a marker for the sum of the rubber polymers styrene butadiene rubber (SBR) and butadiene rubber (BR). The use of a deuterated internal standard in the measurements is necessary to circumvent matrix effects (Unice et al. 2012).

Table 2.3 *Examples of markers applied for tracking tyre tread wear in the environment.*

Tracker		**Content in tyres**	**Concentration in tyre wear**	**Other road-relevant sources**	**Other non-road relevant sources**	**References**
Metals	Zinc	8.4-13.5 g/kg[13]	0.3-2.6%[14]	Break wear, automobile exhaust, lubricants, galvanized road furniture, metallic barriers	E.g. mine leaching, metal production, waste incineration, fossil fuel consumption, fertilizer production, cement production	Kreider et al. (2010), Smolders and Degryse (2002), Kennedy and Gadd (2000)
	Organic zinc	1.3 g/kg[15]	-	Engine lubricants	Scrap tyres	
Rubber[16]	SBR	12-18% (passenger cars tyres)	-	-	>70% of global consumption of SBR used in tyre manufacturing	Pierson and Brachaczek (1974), Cadle and Williams (1978, 1980), Lee et al. (1989), Saito (1989), Fauser (1999)
	NR	16-24% (truck tyres)	-	-	>75% of global consumption of SBR used in tyre manufacturing	Barbin and Rogers (1994)
Benzothiazoles[17]	24MoBT	Ca. 1%	3.8 mg/kg[18]	Antifreeze products	Pesticides, photosensitizers in photography, scrap tyres	Ni et al. 2008
	BT		24-171 mg/kg[19]	-	Many other urban sources[20]	Ni et al. 2008, Rogge et al. (1993)
	HOBT	-	1100 mg/kg	-	-	Ni et al. 2008
	NCBA	-	-	-	-	-
n-alkanes	>35C	10 g/kg[21]	2.3 g/kg	-	Probably few other urban sources	Rogge et al. (1993)

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[13] As summarized by Luhanna et al. (2004) and Councell (2004)

[14] Kreider et al. (2010), Smolders and Degryse (2002), Gadd and Kennedy (2000)

[15] Measured as extractable organic zinc by Fauser (1999) using atomic absorption spectrometry with a heated graphite tomiser.

[16] SBR: Styrene butadiene rubber; NR: Natural rubber.

[17] 24MoBT: (2-(4-morpholinyl)benzothiazole); BT: benzothiazole; HOBT: 2-hydroxybenzothiazole; NCBA: N-cyclohexyl-2-benzothiazolamine.

[18] Reddy and Quinn (1997)

[19] Reddy and Quinn (1997), Rogge et al. (1993), Kennedy and Gadd (2000)

[20] Ni et al. (2008)

[21] Concentrations in road dust were found to be 34 mg/kg.

2.6 Estimated releases of tread

2.6.1 Tread emission factors

The tread emission rate is dependent on factors such as tyre construction, composition and size, accumulated mileage, driving behaviour, vehicle type, vehicle settings and maintenance, road surface characteristics and weather. These factors are discussed in more details in **Appendix G**. A wide range of tread emission factors (EF) have been reported for different types of vehicles and conditions (Kole et al. 2017), reported as mg of particulate matter (PM) from the tread per travelled vehicle km (mg/vkm). Importantly, it has been shown that driving within urban areas, due to more acceleration and braking and more corners and bends, results in higher emission factors than driving within rural areas or on highways (Dannis 1974, Stalnaker et al. 1996, LeMaitre et al. 1998, Luhana et al. 2004). Although limited data existed to support the quantitative differentiation, Broeke et al. (2008) suggested a factor 2 for all vehicle categories (see **Appendix G** for details).

One of the currently most extensive sets of EFs has been developed by the Dutch Task Force Traffic and Transport, distinguishing between driving within urban areas, in rural areas and on highways for a number of vehicle categories (Broeke et al. 2008, Klein et al. 2017), as shown in **Table 2.4**. These EFs are used in the calculations of annual emissions in the Netherlands (Klein et al. 2017, Verschoor et al. 2016). There are a lot of traffic-related information available in the Norwegian Road Administration's on-line map service (https://www.vegvesen.no/vegkart/vegkart), however, it is not possible to make such a detailed differentiation between vehicle categories as the one used in the Netherlands.

Table 2.4 *Emission factors for tread during urban driving, rural driving and highway driving for different vehicle categories used in calculations of annual emission in the Netherlands (Klein et al. 2017).*

Vehicle category	All	Urban driving	Rural driving	Highway driving
	mg/vkm	mg/vkm	mg/vkm	mg/vkm
Passenger cars	100	132	85	104
Motorcycles	50	60	39	47
Mopeds	23	13	9	10
Delivery vans	140	159	102	125
Lorries	600	850	546	668
Trucks[22]	495	658	423	517
Busses	360	415	267	326

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[22] The term "road tractors" is used by Klein et al. (2017), while the term "trucks" is used in the RIVM Report of Verschoor et al. (2016).

2.6.2 Estimates of annual tread emissions in Norway

The EFs in **Table 2.4** can be used to estimate the annual particulate matter (PM) emissions of tread particles on Norwegian roads by multiplying them with the vehicle kilometres travelled by the respective vehicle categories and type of driving:

$$E_T = \sum_{i,j}(D_{i,j} \cdot EF_{i,j}) \qquad (1)$$

Where:

- E_T is the total national annual emissions of tread particles (tonnes)
- $D_{i,j}$ is the annual travelled distance for all vehicles of category *i* for driving category *j* (million vehicle km), and
- $EF_{i,j}$ is the specific tread emission factor for vehicles in category *i* for the relevant type of driving *j* (mg/vkm) (see **Table 2.4**).

The amount of tyre wear generated as PM_{10} ($E_{TW,PM10}$) and $PM_{2.5}$ ($E_{TW,PM2.5}$) can be calculated using the appropriate PM fraction factor:

$$E_{T,PM10} = f_{PM10} \cdot E_T \qquad (3)$$

$$E_{T,PM2.5} = f_{PM2.5} \cdot E_T \qquad (4)$$

Where:

- f_{PM10} is the fraction of the total PM <10 µm = 0.05 (see **Table 2.2**) and
- $f_{PM2.5}$ is the fraction of the total PM <2.5 µm = 0.01 (see **Table 2.2**)

The first annual tread emission estimate for Norway was conducted by Syversen (1989) and was calculated to 6000 tonnes. The latest estimate was 7,500 tonnes reported by Sundt et al. (2014), including the emissions of associated microplastics of 4,500 tonnes (assuming that the tread contained 60 % SBR). The emission factors and total annual vehicle distances they used in their calculations are summarised in **Table 2.5**. We have also included updated emission estimates in **Table 2.5** based on national statistics for 2016[23] and emission factors (all type of driving) from **Table 2.4**. Despite the significantly longer total travelled distance, the estimated emissions are within the same range of those found by Sundt et al. (2014) because of the significantly lower emission factors applied for heavy vehicles. Sundt et al. (2014) also calculated the emissions of tread and associated microplastics based on the total lifetime weight losses of tyres, which summarised to 9,600 tonnes of tread material and 5,700 tonnes of microplastics.

Assuming that tread make up approximately 40% of TWP, the total generation of TWP in Norway would amount to 17,700-24,000 tonnes. The tread fraction of TWP probably changes drastically in the winter season due to the use of studded tyres. Using a road wear factor of 7.5 g/vkm for passenger cars with studded tyres (see **Section 2.7**) and 140 mg/vkm for light vehicles with normal summer tyres as suggested by van der Gon et al. (2008), the tread would make up roughly 0.7% of TWP due to the estimated 54 times increase in road wear.

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[23] Data from KOSTRA at www.ssb.no/statistikkbanken - Tabell: 07302: Kjørelengder, etter kjøretøytype. Gjennomsnitt per kjøretøy.

Table 2.5 *Estimated annual emissions of tread (E_T) and microplastics (E_{mp}) due to tread wear on Norwegian roads.*

Study	**Vehicle category**	$D_{i,j}$	$EF_{i,j}$	E_T	E_{mp}
		million vkm	**mg/vkm**	**tonnes**	**tonnes**
Sundt et al. (2014)	Passenger cars	30,000[24]	132[25]	3,960	2,380
	Heavy vehicles	5,000	712[26]	3,560	2,140
	Total	**35,000**	**-**	**7,520**	**4,520**
This study	Personal cars	35,348	132	4,666	2,800
	Busses	570	360	205	123
	Small lorries (delivery vans)	7,307	140	1,023	614
	Large trucks (lorries)	1,978	600	1,187	712
	Total	**45,200**	**-**	**7,080**	**4,250**

2.6.3 Road specific tread emissions

It may be of interest to estimate the tread emissions along a particular stretch of road for a given period of time. This can be done using the following equation:

$$E_{T,r,t} = \sum_{r,i} L_r \cdot N_{r,i,t} \cdot EF_{i,j} \qquad (1)$$

Where:

- $E_{T,r,t}$ is the total tread emissions along the road stretch *r* over a given time period *t* (mg),
- L_r is the length of the particular road stretch *r* (km), and
- $N_{r,i,t}$ is the number of vehicles in category *i* (see **Table 2.4**) that have travelled the particular road stretch *r* during the given time period *t*.

$N_{r,i,t}$ may be calculated based on available AADT data[27].

This could be of particular interest if treatment of the road runoff is necessary (see **Part II** of the report). The estimated accumulated emissions of tread particles from the Skullerud junction in Oslo is shown in **Table 2.6**. A large highway (E6) passes through this junction and all runoff from the highway and surrounding area (3.4 ha) are collected and treated in the basins below the highway (see **Figure 2.5**). The estimated daily tread emissions are approximately 22 g or about 8.1 kg tread per year. Åstebøl and Coward 2005) estimated the total annual emissions of total suspended solids from the same area to be 3,788 kg per year (5,051 kg/km road·year), which indicate that the tread emissions constitute no more than 0.21 % of TSS.

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[24] Brunvoll et al. (2005)

[25] Russian emission factor prepared for the United Nations Economic Commission for Europe (UNECE) for passenger cars; 0.033 g/tyre·km x 4 tyres.

[26] Russian emission factor; 0.178 g/tyre·km x 4 tyres. Sundt et al. (2014) chose to use four wheels for the heavy transport, noting that many trucks do have more wheels, indicating that the Russian emission factor for heavy transport was considered possibly too high.

[27] In Norway this is available at www.vegvesen.no/vegkart.

Table 2.6 *Estimated daily emissions of tread particles from highway E6 passing through the Skullerud junction.*

Road stretch	AADT	Length	Passenger cars		Ratio long vehicles		Emissions
	v/day	km	Ratio	EF(mg/vkm)	Ratio	EF (mg/vkm)	g/day
North of junction	70,936	0.375	0.92	104	0.08	668	10.9
South of junction	64,670	0.375	0.88	104	0.12	668	11.4
Total	67,803	0.750	0.90	104	0.10	668	**22.3**

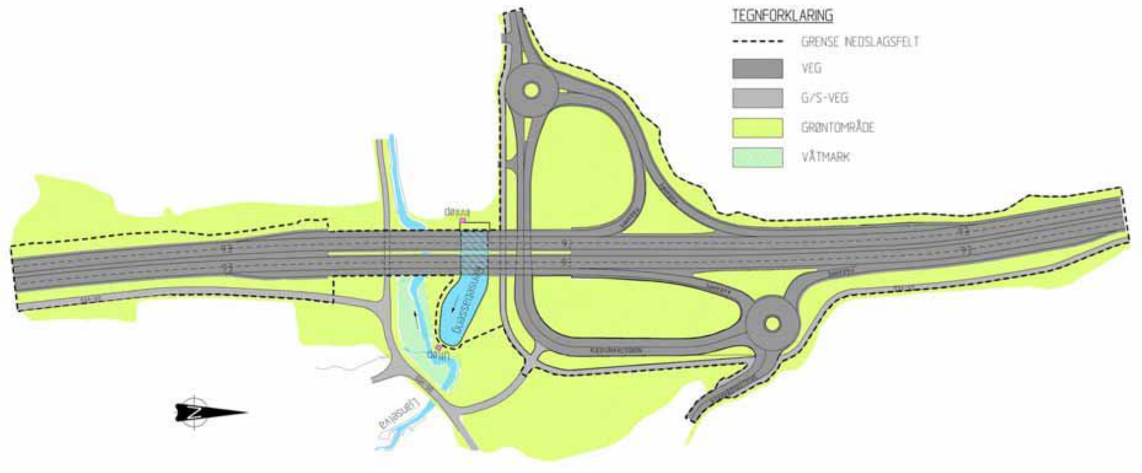

Figure 2.5 *The Skullerud junction and stormwater treatment basins below (a closed sludge basin of 68 m^2 and an open main basin of 910 m^2) (Åstebøl and Coward 2005).*

2.7 Estimated releases of PMB due to road wear

Approximately 5% of the 300,000 tonnes of bitumen and bitumen emulsions used in Norway per year are modified with polymers, primarily SBS[28]. The addition of SBS varies somewhat (3-10%), but on average this is approximately 5% of the weight of the bitumen (Aurstad et al. 2016). Hence, approximately 750 tonnes of SBS are applied on Norwegian roads per year. According to the Norwegian Road Administration map service (https://www.vegvesen.no/vegkart/) polymer modified bitumen (PMB) is applied to a total of 2,770 km of public roads.

The use of studded tyres is by far the most important cause of pavement wear, though a number of factors influence the specific wear factor; the weight and speed of the vehicle, the type, mass and numbers of spikes, wet or dry roads (increases at least two-fold when wet), road salting[29] and type of road pavement (Lundy et al. 1992). Also loose material on the road surface, e.g. traction sand may enhance the abrasive wear of the pavement and of the material itself (Kupiainen 2007). The studded-tyre specific road wear for passenger cars has decreased considerably the last decades due to the introduction of less abrasive spikes and more abrasion-resistant pavements (Aurstad et al. 2016) from 17.1 g/vkm in the 1970's via 11.6 g/vkm in 2002 (Amundsen and Roseth 2004) till the present 5-10 g/vkm (NVF 2013). We have used 7.5 g/vkm in the calculations for roads where PMB

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[28] Joralf Aurstad (Statens vegvesen Vegdirektoratet), personal communication.

[29] The use of salt increases the period with wet pavement and reduces the period with snow and ice cover that would otherwise reduce abrasion.

has been used. As the wear layer of the pavement typically contains approximately 5% PMB, the amount of SBS in the road wear is approximately 0.013 g/vkm.

Taking all public roads >3000 AADT into account and the limited use of studded tyres in the greater Oslo area and around Bergen, **the total annual releases of SBS in road wear caused by studded tyres were estimated to be approximately 28 tonnes**. The calculations and accompanying assumptions are shown in **Appendix H**.

2.8 Estimated releases of polymers from road marking

Wear of road markings has received considerably less attention than tyre wear and very limited quantitative data exist. As far as we are aware of there exists no other estimates of releases of polymers from road marking paints than the ones made by Sundt et al. (2014), Lassen et al. (2015) and Magnusson et al. (2016). The latter extrapolated their calculations based on the values presented by Sundt et al. (2014). Sundt et al. (2014) estimated the annual wear in Norway to be 320 tonnes based on the assumption that the annual consumption (see **Table 2.7**) reflects the annual abrasion, though being aware of that some markings are overpainted or removed. When doing similar estimations for Denmark, Lassen et a. (2015) estimated the abrasion factor to be 15-43%.

Table 2.7 *Annual use of thermoplastic elastomers in road marking paints in Norway in 2014 (Sundt et al. 2014).*

Chemical component	**Annual use**
Styrene-Isoprene-Styrene (SIS)	85 tonnes
Ethylene vinyl acetate (EVA)	66 tonnes
Polyamide (PA)	57 tonnes
Acrylate polymers[30]	112 tonnes
Total	**320 tonnes**

The road marking paint consumption was much the same in 2016 as in 2013, the year for which Sundt et al. (2014) performed their estimate[31]. As we have not been able to confirm or update the polymer consumption data (**Table 2.8**), we have used the 320 tonnes of polymer consumption as basis for the updated annual particle emission estimate for road marking losses caused by road wear (RWP_{RM}) and use the same assumptions as Lassen et al. (2015). The line of arguments, assumptions and calculated losses due to wear are summarised in **Table 2.8**. **The total annual emissions of thermoplastic elastomers were roughly estimated to be 90-180 tonnes**. These estimates should be interpreted as indicative at best and necessarily more correct than the earlier indicative estimates presented by Sundt et al. (2014).

We have no data on wear rate of road marking, however, the use of studded tyres will significantly impact the abrasion of road markings (Lundy et al. 1992), as well will the use of snowploughs in the wintertime.

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[30] Sundt et al. (2014) noted acryl monomer here. GEVECO, a main deliverer of road marking paints in Norway, uses the water-based paint marking AquaRoute. According to available MSDS for four different AquaRoute road paint formulas (http://vegmerkeren.no/dokumenter/hms_produktdatablad/), they all contain 15-40% acrylate polymer. Hence, the 1000 tonnes of paint marking used in 2016 would exceed the 112 tonnes estimate of acrylate polymer use.

[31] 12,476 tonnes of thermoplastic marking with 1-5% content of thermoplastic elastomers and 1,066 tonnes of paint marking were used in 2013. The applied volumes in 2016 were 12,207 tonnes thermoplastic marking and 1,000 tonnes paint marking according to numbers provided by GEVEKO Markings.

Table 2.8 *Arguments and assumptions used to estimate annual emissions of thermoplastic elastomers due to tear and wear of road marking in Norway. Red numbers indicate emissions.*

Arguments	**Assumptions**	**tonnes**
The difference between amount applied and remaining before repainting = loss	15-25% of all road marking paint applied annually for repainting	48-80
	30-50% of initial road marking paint worn off	14-40
The amount used for new road marking (new roads or rehabilitation of existing roads)	75-85% of all road marking paint applied annually	240-272
The difference between amount applied and remaining before pavement is removed (for reuse) = loss	30-50% of initial road marking paint worn off	72-136
The amount removed with pavement = not lost	Target for Norway: 80% reuse of bitumen (99.5% of bitumen in collected asphalt is recycled)	136-168
Total		**86-176**

3 Spatial distribution and pathways

3.1 Main pathways for microplastics in road dust to aquatic and terrestrial environments

Road-associated microplastic particles (RAMP) may end up in the aquatic or terrestrial environment. However, as illustrated in **Figure 3.1**, there are many potentially pathways, each of them governed by a set of transport and transformation processes. Since each of these processes are influenced by a wide range of factors with spatial and temporal variations depending on local conditions, the complete picture is extremely complex. In this chapter we will look at the main factors influencing the different transport processes.

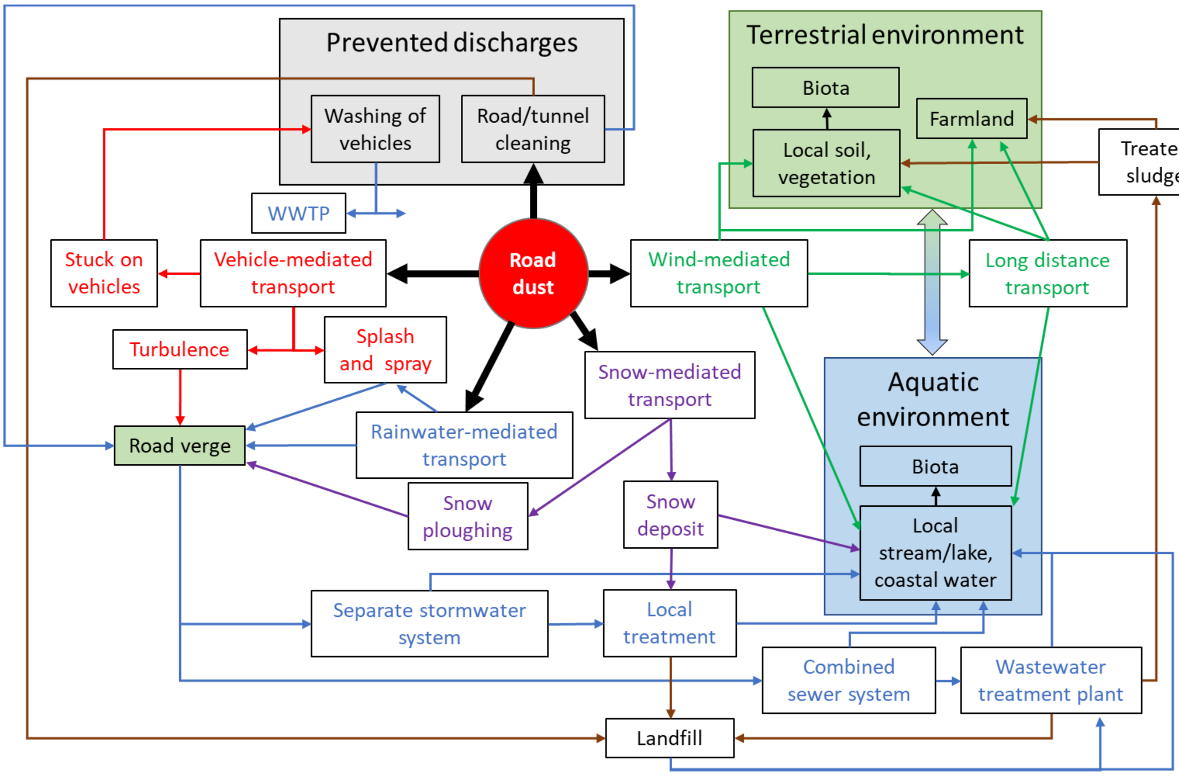

Figure 3.1 *Potential main pathways for microplastics in road dust to reach aquatic environments (blue background) and terrestrial environments (green background). Some pathways may prevent discharges to the environment even without direct treatment (grey background).*

Some of the transport pathways are via applied treatment processes. Roads in rural and peri-urban areas are equipped with ditches or verges outside the road shoulders. The primary role of the verge is to lead the road runoff away from the road. Depending on the road construction, local soil condition and local stormwater management needs, a part of the road runoff in the verge will infiltrate to groundwater locally and the excess will be directed to a local stream or lake (see **Figure 3.2**), or via an on-site treatment system if needed. The latter is the topic of **Chapter 5**. In urban areas dominated by impervious surfaces the need to quickly convey rainwater and snowmelt water out of areas where they can cause damage (e.g. flooded streets and basements), has traditionally led to the now common subterranean stormwater collection system with associated sewer network. Some of these lead to a local domestic wastewater treatment plant whereas others may end up in a nearby creek or lake. The available space for roadside treatment systems such as those typically used in rural areas are also limited in urban areas. These topics are discussed in **Chapter 6**.

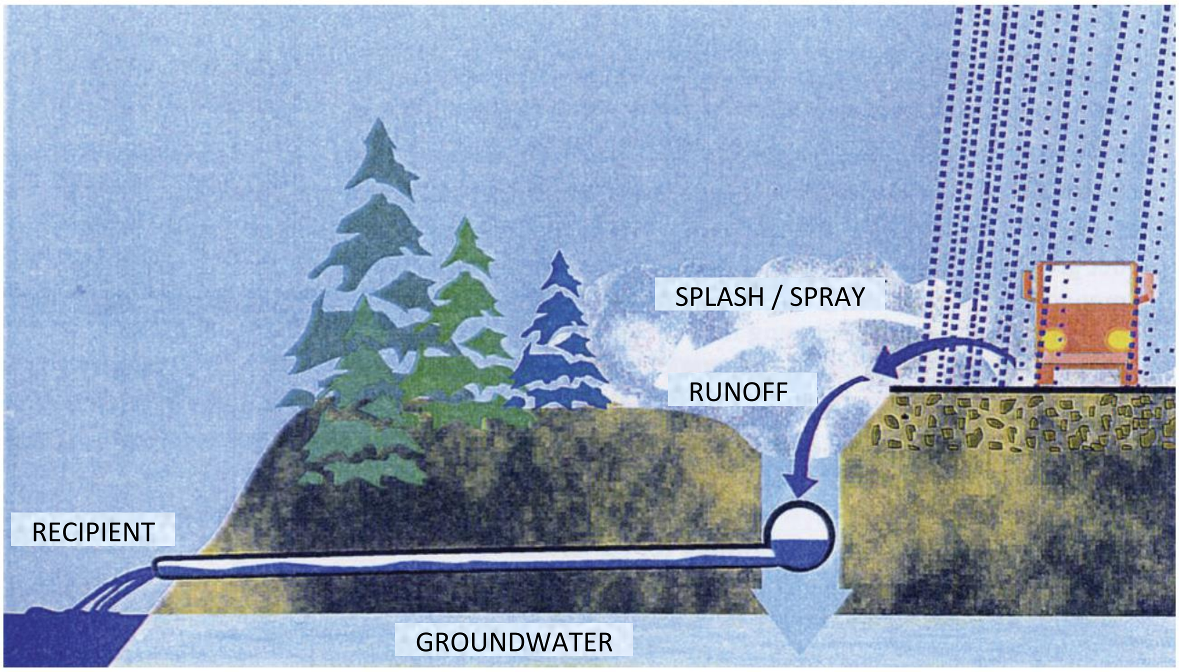

Figure 3.2 *Principle drawing illustrating runoff and spreading of pollutants from a road (translated from Åstebøl and Hvitved-Jacobsen 2014).*

3.2 Local accumulation and spatial distribution of wear particles

Wear particles from tread (TWP), road pavements with polymer modified bitumen PMB (RWP_{PMB}) and road markings (RWP_{RM}) will deposit on the road surface or in the area alongside the road or they will be transported further away by wind. TWP, based on tyre markers (see **Section 2.5**), have been found at highly variable concentrations alongside roads ranging from 0.6 to 117 g/kg dw (Pierson and Brachaczek 1974, Cadle and Williams, 1978, Spies et al.,1987, Fauser et al.,1999). Most of the wear particles are typically observed up to 5 meters from the road with an exponential decline with distance from the road, as illustrated in **Figure 3.3.** Cadle and Williams (1978) found approximately 80% of the tread wear within 5 m from the road. At approximately 30 m away from the road, the tread wear level was more or less completely diminished, which is in line with other reported studies (Fauser 1999, Saito 1989) and reported observations for most other road dust-associated contaminants (Amundsen and Roseth 2004).

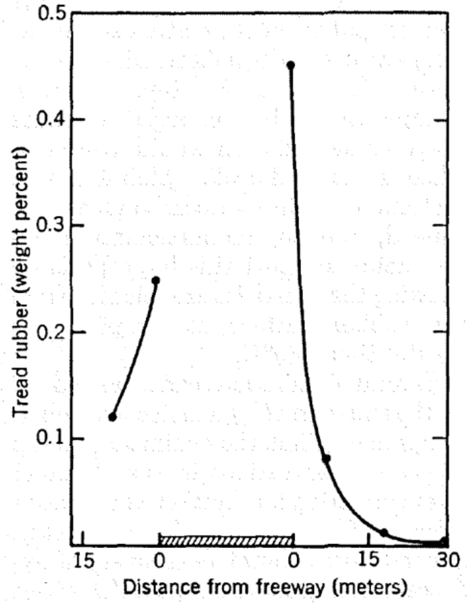

Figure 3.3 *Tread rubber content of soil in distance from the road (Cadle and Williams 1978).*

As indicated in **Figure 3.1** and illustrated in **Figure 3.4**, there are several processes contributing to the transportation of wear particles within the proximity of the road verge;

Dry weather resuspension and settling of coarse particles

Though wear particles are constantly generated by passing traffic, they are not accumulating on the road at the same rate. Passing vehicles and wind impact suspension and resuspension of settled particles on the road under dry conditions, which will bring (more of) the wear particles to the road verge (**Figure 3.4A-D**). Since smaller particles tend to accumulate more easily within microstructures of the pavement, they are usually not resuspended as much as larger particles. This is discussed in more detail in **Appendix I**.

Wind may contribute to long distance transport of airborne particles directly to both terrestrial and aquatic environments. The transported distance is dependent on both particle size, wind speed and local topographic features (including vegetation and buildings). Though tread wear particles up to 30 µm have been shown to be airborne (Cadle and Williams 1978), particles >10 µm are not likely to stay airborne for long. The behaviour of particles in the 1–10 µm range strongly depends on particle characteristics and local conditions. These particles can stay in the air for minutes to hours and typically travel distances varying from hundred meters to as much as 50 km (Kole et al. 2015).

As only around 7% of the tyre wear particles are assumed to be <30 µm in size (see **Table 2.2**), the long-distance transport loss of tyre wear particles due to wind is probably relatively small if not in a particularly windy location.

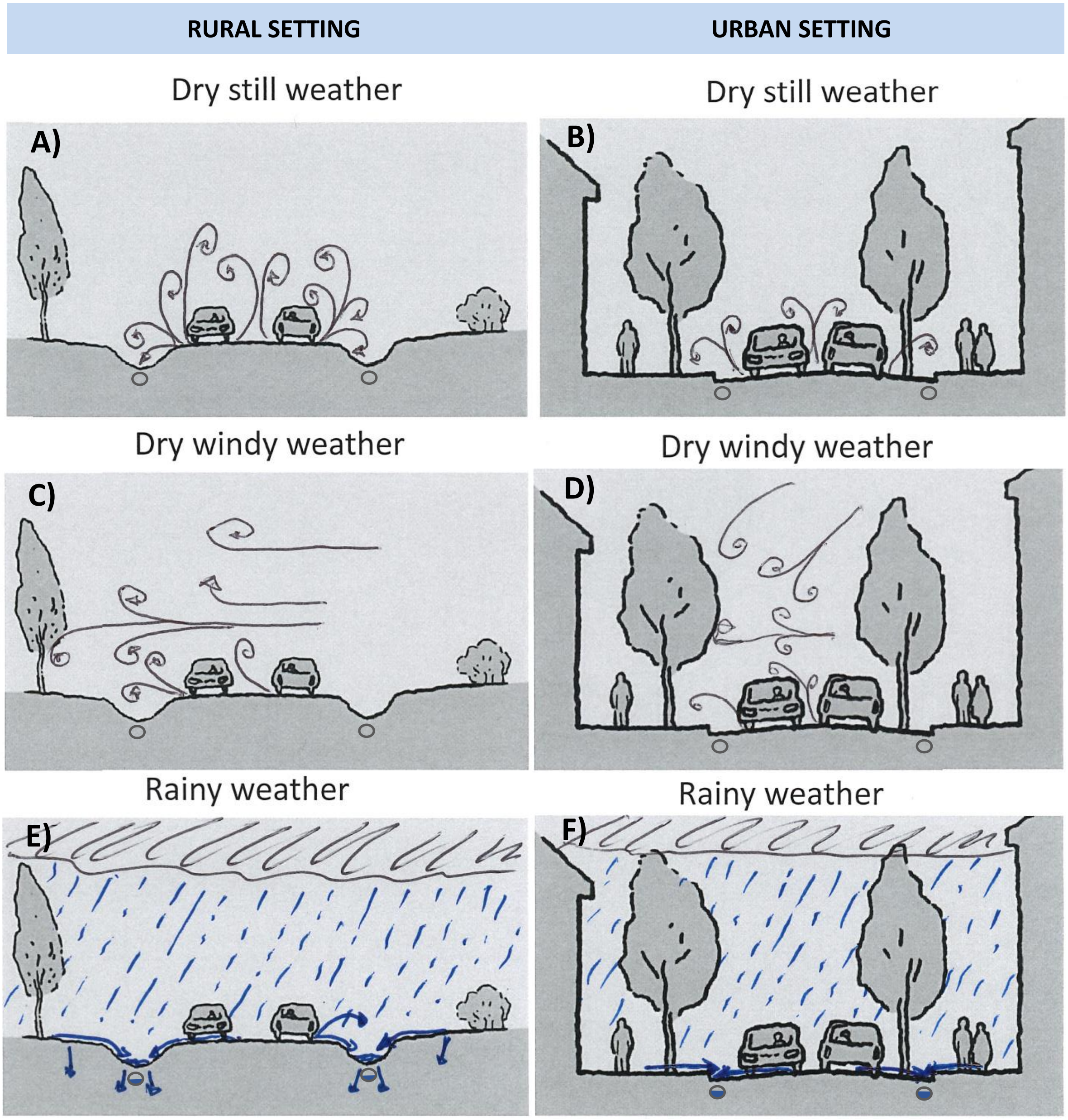

Figure 3.4 *Illustrations of how meteorological conditions may impact the spreading of road dust in a rural setting (left) and in an urban setting (right) (Adapted from Statens vegvesen (2014A).*

Wet weather settling and road runoff

Precipitation (as rain or snow) will drastically increase the deposition of airborne particles on the road or road verge. Since snowflakes are falling slower and have larger surface areas than rain droplets, they will collect more pollution from the air. Furthermore, due to the use of studded tyres (among other things), the airborne particle levels (PM_{10}) are usually also much higher during the winter season.

However, the deposited particles will not necessarily stay on the road. Brodie (2007) found that particles started to accumulate on the road after approximately 2 hours of drizzling rain (0.5-2 mm/h). When the precipitation intensity exceeded a certain threshold, defined by the Rainfall Detachment Index (RDI), particles deposited on the road began to be transported off the road with the road runoff (Brodie 2007). RDI is dependent on the road micro and macro structures and incline, hence how well it is to retain both water and particles. The transported amount increased linearly with the precipitation intensity up to a maximum[32] where it levelled off for rainfall events up to five-hours duration. For long rainfall events, there was no clear relationship between precipitation intensity and amounts of particles transported away from the road. See **Appendix M** for details from the study of Brodie (2007).

In the Netherlands, where almost all highways have been constructed with a very porous asphalt (so-called ZOAB[33]), 95% of all tyre wear particles deposited on the road are claimed to be permanently embedded in the small cavities in the road, or approximately 40% of all TWP in the Netherlands (Verschoor et al. 2016).

Figure 3.5 schematically illustrates the accumulation of particles on the street between rain events or road cleaning events, when they are partially removed depending on the intensity and/or duration of the rain event or on the type of road cleaning that are applied (Snilsberg et al. 2016, Sartor and Gaboury 1984).

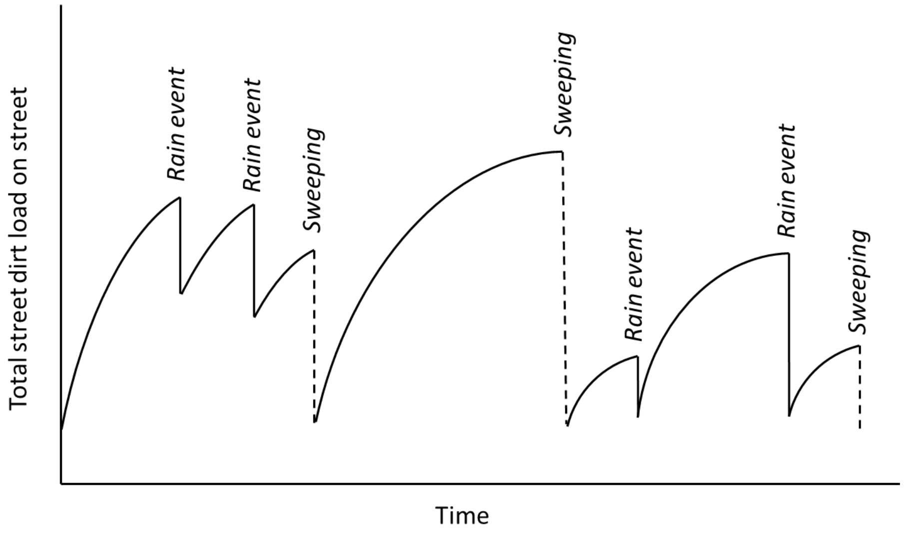

Figure 3.5 *Schematic illustration of how the total load of street dirt on the street depends on the frequency and strength of rain events and street sweeping (based on Sartor and Gaboury 1984).*

Splash and spray

On wet roads, resuspension is minimal (Denby et al. 2013), but splashing (of larger water droplets) and spraying (of smaller water droplets) may spread wear particles within the water droplets over a distance depending on the droplets' size and wind speed and direction, where smaller droplets may deposit further away (**Figure 3.4E,F**).

Norwegian winter conditions

With the typical winter situation in Norway, three factors in particular should be taken into account; most of the precipitation during the winter season may come as snow, the ground may freeze and large amounts of salt are used to keep the roads free from ice and the dust on the road (by using magnesium chloride). Since snow can be present throughout most of the winter season it will be accumulating pollutants in this period, which are subsequently released during snow melt (Bækken 1994, Glenn and Sansalone 2002). To our knowledge, information about accumulation of tyre wear

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[32] This maximum was defined by the maximum Event Mean Concentration (EMC). See **Section 3.5.1**.

[33] ZOAB = Zeer Open Asfaltbeton in Dutch.

particles in traffic contaminated snow is lacking. Salting causes snow to melt, thus increasing washing and road runoff, as well as road and tyre wear. The latter increases the content of wear particles in the runoff. However, the use of hygroscopic magnesium chloride to reduce dusting, makes the particles clog and possibly reduce their escape from the road.

3.3 Potentially prevented discharges

Road and tunnel cleaning

During spring, all national and European roads and tunnels in Norway are swept, washed and cleaned by Norwegian Public Road Administration (NPRA; Statens vegvesen), while all municipal streets are swept, washed and cleaned by the municipalities. The spring cleaning is quite thorough and the whole road area is cleaned as parked vehicles are removed. The rest of the year some selected roads are cleaned regularly, but the frequency varies in different municipalities according to general needs; littering, fallen leaves, air quality levels and weather. Regarding tunnels, they are frequently washed throughout the year. The washing frequency depends on the AADT and range from less than once per year to a minimum of 12 times per year including full wash, half wash and technical wash (Statens vegvesen 2014C). Many tunnels are equipped with gully pots, and some have treatment systems at site (e.g. wet ponds or basins inside the tunnel).

It has been shown that road cleaning is an efficient way of removing the larger sized particulates (>100-125 µm), but has limited effect on the amounts of airborne particles (Amato 2010). Smaller particles will build up more easily within microstructures of the pavement. Most common methods are broom sweepers (see **Figure 3.6**), often used in combination with vacuum suction. The cleaning vehicles commonly use water for damp suspension of dust, and some vehicles also have wet vacuuming as a method for dust removal. Flushing is also used, but mostly in combination with a sweeper. The sweeper passes first, removing most of the larger particles, and then the flusher uses high pressure water to flush the road surface, letting the water run into the sewer system. The efficiency of road cleaning is strongly dependent on the methods used, the area which is cleaned related to, for instance, pavement structure and speed of the cleaning vehicle.

At least in Oslo municipality, the collected road dust and sludge is classified as hazardous waste that needs to be deposed at an authorised landfill[34]. Water from flushing is collected by the sewer system, either the combined sewer or the separate stormwater system.

Figure 3.6 *Sweeping of roads in Oslo (Photo: Knut Opeide, Statens vegvesen).*

Snow deposition

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[34] The municipality has no supervision of the amounts nor on which landfill the collected road dust is deposited.

Snow deposited along streets and roads need to be removed in order to provide safe conditions for vehicles and pedestrians. Management practices for handling of snow vary, but removal by clearing vehicles, loading the snow into trucks, and dumping from the truck to water bodies or storage at designated snow deposits are most common. In the municipality of Oslo, urban snow is treated in a snow melting plant constructed by NCC[35], prior to discharges into the Oslo fjord. Concentrations or amounts of tyre wear connected to snow deposition are not known.

Vehicle-mediated removal

Particles may adhere to anywhere on the vehicle. Tyre wear particles have been shown to become electrically charged when resuspended (Thorpe and Harrison 2008), which will further increase their tendency to stick to surfaces. However, this appears to primarily concern the smaller sized airborne particles, hence the actual volume of particles removed this way may be relatively limited. In the calculations of Dutch road emissions, 31% of the break wear are assumed to remain on the vehicle, while all other wear particles are neglected in that regard (Klein et al. 2017).

The 2,5 million private cars in Norway are regularly washed at public car wash stations where the contaminants in the wash-water are discharged to the local WWTP. Private car wash is allowed in Norway, even though equipment like oil drain filters and manholes for removal of oil and particles, are missing. A considerable amount of runoff water from these sites will be discharged into local water bodies. Concentrations or amounts of tyre wear connected to car wash are not known.

3.4 Retention and loss of wear particles in the road verge

3.4.1 Impervious surfaces in urban areas

Urban areas are typically dominated by a large fraction of impervious surfaces in addition to the streets, such as pavements, parking lots, industrial areas, roofs and house walls. The ability of these surfaces to retain particles may vary considerably, depending on the same factors as mentioned in **Section 3.2** for roads; the type of surface (micro and macro structures) and its incline that contribute to determining the Rainfall Detachment Index (RDI) developed by Brodie (2007) (see **Appendix M**). In general, due to the lack of infiltration, a limited amount of rainwater and/or meltwater is needed to wash off the deposited particles, transporting them together with the surface runoff. This gives rise to a peak in particle content in the first flush of rain water. See **Section 3.5**.

Particles freely deposited on surfaces could be attacked by ultraviolet (UV) radiation if directly exposed to sunlight. Though tyre treads are added anti-oxidants (see **Table B1** in **Appendix B**), these may leach out with time making the tyre wear particles more prone to oxidative degradation and fragmentation during weathering thereby contributing to losses of TWP (Andrady 2017, Cadle and Williams 1980). However, there is a complete lack of data on the (photo)degradation of TWP in ambient air (Kole et al. 2017).

When the TWP are generated at least a part of the SBR rubber is thermally degraded causing partial devulcanisation[36] of the rubber (Fauser 1999), which could mean that it is also more prone to biodegradation. If it is further transformed by UV radiation, the process may be sped up. However,

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[35] https://www.ncc.no/vare-prosjekter/ncc-snowclean-oslo/

[36] The rubber is vulcanised to make it more durable. In the vulcanisation process an accelerator is added to make cross-links between the polymers in the rubber.

that also depends on the conditions for biodegradation (e.g. humidity and oxidative conditions). See also **Section 3.4.2** and **Section 6.3** for more on biodegradation.

3.4.2 Green road structures and soil in peri-urban and rural areas

Contrary to the dominating impervious surfaces in urban areas, road verges in rural and peri-urban areas are typically grassy or filled with soil or gravel. The verge is designed to transport rain and melt water away from the road by either direct infiltration, if the local conditions allow that, or through an open or closed stormwater convey system to a nearby river or lake, if the conditions in the recipient allows it. If not, local treatment is need (see **Chapter 5**) or the water can be directed to a recipient that withstand the load (Statens vegvesen 2014B).

Though the verge is normally not considered a treatment step itself in Norway, some wear particles can be expected to be retained by the soil and vegetation within the verge, depending on the properties of the soil and the vegetation (Åstebøl and Hvitved-Jacobsen 2014, Amundsen and Roseth2004). Removals of up to 70% of suspended solids have been reported (Åstebøl and Hvitved-Jacobsen 2014), but the actual treatment effects are highly variable and uncertain (Shueler 1991). Bäckström (2002) reported 15-20% removal of particles by grassed swales where the verge constituted 50% of the road area. Åstebøl and Hvitved-Jacobsen (2014) list the following constructional details that may improve the treatment efficiency of the road verge:

- Increase the floor area in the verge
- Establish transverse elevations in the verge
- Use sand-blended soil to achieve increased infiltration
- Establish a percolation magazine under the verge

The latter is discussed in more detail in **Chapter 5**, where stormwater treatment systems typical applied in rural and peri-urban areas in Norway and in other countries are presented.

The role of biodegradation of tyre wear particles within the soil of verges is still a question that needs to be answered. Cadle and Williams (1978) estimated that the amount of tyre wear found alongside a highly trafficked[37] freeway in California corresponded to a maximum six-month accumulation period. In that period, a total of 2 mm precipitation had occurred, hence removal by road runoff were ruled out. Interestingly they found that the soil samples had much smaller amounts of unvulcanised SBR compared to freshly generated TWP. As it is not very likely that the SBR would be revulcanised, this may indicate some kind of environmental degradation of the unvulcanised fraction of the SBR. In a later study, Cadle and Williams (1980) determined the half-life of TWP in soil to be approximately 16 months, however this degradation rate will most probably be very site and condition specific.

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[37] 150,000 AADT.

3.5 Concentrations of road dust-associated microplastics in road runoff

3.5.1 Concentration profiles and the event mean concentration (EMC)

From the above discussions it should be clear that many local factors influence both the amounts of pollutants deposited and retained on the road and verge and the volumetric runoff, indicating that it is very difficult to predict the concentration profile of pollutants in the road runoff. It is also very difficult to predict the actual ratio of microplastic particles to other particulates in the road runoff, as well as which particle sizes that will be dominating at a given time. Egodawatta and Goonetilleke (2008) found that particle density rather than size was the critical parameter that influences the process of pollutant wash-off.

A peak “flush” of pollutants often occurs during the early stages of a storm event, before the flow rate in the system reaches its peak (Woods Ballard et al. 2015). See **Figure 3.7**. It is possible to get a high initial pollution concentration for relatively small rainfall events, particularly in areas with high ratios of impervious areas, as it does not take a great deal of rain to wash off the pollutants. The highest reported concentrations of the tyre markers benzothiazoles (BTs) (see **Section 2.5**) in road runoff (Reddy and Quinn, 1997; Kumata et al., 1997, 2000, 2002; Baumann and Ismeier, 1997; Zeng et al., 2004), suggest that the concentrations of tyre wear particles may range from 0.3 to 197 mg/l (Wik and Dave 2009). We have not found any reported values of tyre wear particles in Norwegian road runoff.

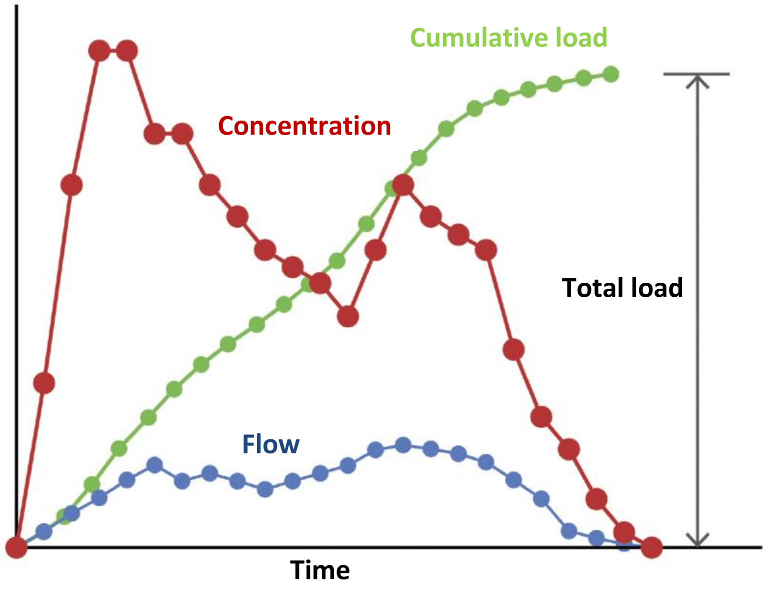

Figure 3.7 *Example of flow, pollutant concentration and pollutant load build-up during a rainfall event (Woods Ballard et al. 2015 with courtesy of CIRIA).*

When dimensioning a treatment unit that will manage road runoff at a particular location, it is the characteristic or typical (i.e. median) total load during runoff events at that location which is used (see **Section 6.1**). For each event, the event mean concentration (EMC) need be determined by frequent sampling and concomitant flow measurements. EMC is the flow-weighted concentration of the pollutant:

$$EMC = \frac{\sum_{i=1}^{n} v_i \cdot C_i}{\sum_{i=1}^{n} v_i} \qquad [3.1]$$

Where:

- v_i is the volume of road runoff corresponding to sample *i* (m^3),
- C_i is the pollutant concentration in sample *i* (mg/l),
- *i* is he pollutant concentration in sample *i* (mg/l), and
- *n* is the number samples collected

Due to the inherent variability in runoff concentrations and volumes, a minimum of 7-10 EMC values based on separate runoff events is needed to determine a satisfactory <u>median</u> value for a particular location (Åstebøl and Hvidtved-Jacobsen 2014).

The total pollutant load, P during an event can be defined as:

$$P = v \cdot EMC \qquad [3.2]$$

v (m^3) is the total runoff volume during the event.

3.5.2 Total suspended solids as a surrogate parameter for microplastics in road runoff

Total suspended solids (TSS) have been a much used parameter in monitoring of road runoff, in Nordic countries and elsewhere. The reported TSS values in road runoff varies considerably, and is particularly dependent on the use of studded tyres (Lundy et al. 1992). Åstebøl and Hvitved-Jacobsen (2014) indicate 200 mg TSS/l and 50 mg TSS/l as high and low levels, respectively. Though road and tyre wear particles could represent major fractions of this, the fraction will most probably vary considerably, both spatially and temporally. Also the particle size distribution (PSD) varies considerably in road runoff, as shown by Charters et al. (2015) in their review article and indicated by the variability in PSD from their own measurements of the runoff from one particular asphalt road during 15 rainfall events (**Figure 3.8**). The mean and peak TSS concentration during first flush was 158 mg/l and 327 mg/l, respectively, while the EMC values varied between 16.4 mg/l and 157 mg/l with an average of 54 mg/l. Furumai et al. (2002) found that during runoff, the fluctuations in TSS concentration was more in line with the concomitant fluctuating levels of the coarser particles (>45 µm) than the smaller particles (<45 µm). Since an apparent 85% of TWP are >50 µm (ref. **Table 2.2**), TSS appears to be an adequate surrogate parameter for TWP. Not enough information is available to conclude in regard to RWP_{RM} and RWP_{PMB}.

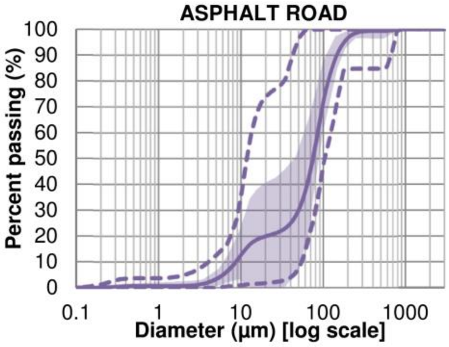

Figure 3.8 *Mean cumulative PSDs (solid lines) ± 1 S.D. (shaded area) and observed ranges (dotted lines) for runoff from an asphalt road in the Okeover catchment (ca. 800 m^2 contributing area), Christchurch, New Zealand (reprinted from Charters et al. 2015 with permission from Elsevier).*

PART II – TREATMENT SOLUTIONS

4 Treatment – where and what

4.1 Where

By 2013, about 161 treatment facilities had been built along Norwegian roads. Based on the guidelines given in earlier handbooks 017 (Statens vegvesen 2008) and N200 (Statens vegvesen 2014B) from the National Public Roads Administration (NPRA), these have primarily been applied along the main national roads with traffic densities from 8-10,000 AADT and upwards (Meland et al. 2016B). The revised version of handbook N200 (Statens vegvesen 2017) will probably change this practice, as the sensitivity of the recipient will be given more consideration and importance. In brief, runoff from roads with traffic densities above 30,000 AADT will require treatment, while runoff from 3,000-30,000 AADT roads will need treatment if the vulnerability of the receiving waters is considered medium or high (see **Appendix A**).

Of the approximately 61,000 km long national road network, ca. 247 km of it has an AADT >30,000, which is estimated to increase by 43% (total of ca. 352 km) until 2029 due to the anticipated increase in traffic load (Meland et al. 2016), and ca. 7,000 km has an AADT of 3,000-30,000[38]. A large part of the >30,000 AADT is within urban areas; e.g. ca. 100 km just in the greater Oslo region where the space for large treatment facilities will be rather limited. Also the density of roads with 3,000-30,000 AADT is typically higher in the urban area than elsewhere. Treatment solutions for road runoff from urban areas are discussed in **Chapter 6**, while treatment solutions from road runoff elsewhere are discussed in **Chapter 5**.

4.2 What type of mechanism will be efficient?

Before looking at treatment, note that source control is the preferred method to avoid environmental contamination. Examples of such (non-structural) measures relevant in terms of controlling RAMP in road runoff are:

- Developing more wear-resistant tyre treads, road markings and road pavements
- Reducing studded tyre use by e.g. use of taxes
- Road and street sweeping (see **Section 3.3**)
- Proper snow handling (see **Section 3.3**)

Table 4.1 discusses the expected importance of potential mechanisms for the removal of the road associated microplastic particles (RAMP). Since all three types of particles (**TWP**, **$\mathbf{RWP_{RM}}$** and **$\mathbf{RWP_{PMB}}$**) can be considered being relatively large and with relatively high densities, sedimentation will be an important removal mechanism. The particle settling velocity may be increased by adding a flocculant (i.e. flocculation in combination with sedimentation). Filtration, and possibly adsorption, may also be important removal mechanisms, for a final 'polishing' treatment step to remove the finer particles[39]. Though, treatment solutions that are based on such removal mechanisms are usually applied to remove total phosphorous or hazardous compounds (e.g. heavy metals and polycyclic aromatic hydrocarbons) from road runoff and not to remove suspended particles, particles will be well removed. Removal mechanisms such as flotation, biodegradation, volatilisation and oxidation are probably not adequate in applied treatment processes, though there are indications

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[38] From www.vegvesen.no/vegkart

[39] Mechanical sieving as applied as the initial treatment step at domestic wastewater treatment plants will remove larger fragments, not microplastics. See discussion in **Section 6.3.3.1**.

that the rubber fraction of TWP may be (partially) biodegradable. This biodegradability may be enhanced by previous oxidation.

The expected importance of different mechanisms for the removal of RAMP are highlighted in **Table 4.1**. It should be noted that **there is a lack of empirical evidence to support the extent to which RAMP will be removed, and to what degree RAMP are present in road runoff entering existing facilities.**

Table 4.1 *Important mechanisms for the removal of road associated microplastic particles.*

Mechanism	Description	Expected importance
Sedimentation	Sedimentation is achieved by reducing flow velocities to a level at which the particles fall out of suspension (finer particles requiring lower velocities) or by encouraging flocculation (which increases particle size). The settling velocity of a particle is dependent on its size, density and shape as well as the salinity and temperature of the water (see **Appendix J**). Very fine particles may remain in suspension and essentially be characterised as dissolved.	**TWP**: A main fraction (ca. 85%) of TWP appears to be >50 µm in size and has a relatively high density (≥1.7 g/cm^3), hence sedimentation is expected to be the main mechanism for the removal of TWP. **RWP$_{RM}$**: In general, RWP$_{RM}$ appear to be larger than TWP, but has possibly somewhat lower density. Anyway, sedimentation is also expected to be the main mechanism for the removal of RWP$_{RM}$. **RWP$_{PMB}$**:
Filtration	Filtration is an efficient way of separating particulate matter from water, either by trapping the particulates in a depth filter (e.g. engineered filter media or local soil matrix including plants/root system) or by a membrane with pore sizes that limit their transport through the membrane (e.g. filter screen/cloth or geotextile). The removal is dependent on the size of the particles and the effective pore size and thickness (in depth filters), but requires adjusted hydraulic loading to function well and proper pre-treatment to prevent rapid clogging if the water contains a lot of particulate matter. Also see “Adsorption” below.	Filtration is a typical second treatment step and could function as an adequate polishing step for the removal of smaller sized particles that are not properly removed by the preceding sedimentation step. Will probably be working well for both **TWP**, **RWP$_{RM}$** and **RWP$_{PMB}$**.
Flotation	Light particles that easily float may be separated by flotation. Flotation may be enhanced with the help of flocculants (see below) and dispersed air.	The larger size fractions of **TWP**, **RWP$_{RM}$** and **RWP$_{PMB}$** probably have too high densities to be properly removed by flotation, but the smaller sized particles may be removed.
Flocculation	Particles may aggregate to larger particles naturally (caused by e.g. increased salinity or the presence of polymeric material) or	Flocculation may be an interesting method to increase the settling rate and, hence, the efficiency of

Mechanism	**Description**	**Expected importance**
	flocculants may be added to improve the flocculation process. The latter is usually carried out in combination with a coagulant to precipitate dissolved and colloidal matter and include these in the flocculation process. The flocs are typically removed by sedimentation, floatation or filtration. Sand particles may also be added to increase floc settling rate (ballasted flocculation). The surface properties of the particulate matter are of importance for the efficiency of the coagulation and flocculation process, but the flocculant can be selected to optimise the removal.	sedimentation to remove the smaller size fractions of **TWP**, **RWP$_{RM}$** and **RWP$_{PMB}$**.
Adsorption	Dissolved or particulate matter may attach or bind to the surface of other particles, soil, sand, plants/roots or artificial material. The actual process is complex, but tends to be a combination of surface reactions. Change in acidity of runoff can either increase or decrease the adsorption, and the winter use of de-icing salts have been shown to encourage the release of e.g. metals from the surface. The efficiency of the adsorption decreases with decreasing number sites for adsorption.	The surface properties (i.e. surface charge and hydrophilic character) of **TWP**, **RWP$_{RM}$** and **RWP$_{PMB}$** have not been reported, hence, it is not possible to predict their removal by adsorption.
Biodegradation	Biodegradation is an important treatment mechanism as it actually reduces the total of amount of a pollutant, not only moves it from one place to another. The efficiency is highly dependent on the compound/pollutant itself and the presence and activity of relevant microbial community. The latter is dependent on a range of local factors such as humidity, pH, temperature, nutrients and concentration of dissolved oxygen or presence of alternative electron acceptors (e.g. NO_3^-, SO_4^{2-}).	There are indications that rubber in **TWP** may be slowly biodegradable in soil (see discussion in **Section 3.4.2** and **Section 5.3**, which will drastically reduce the risk of accumulation of these rubbers in the environment. There are no similar reports on the biodegradability of the polymers in **RWP$_{RM}$** and **RWP$_{PMB}$**.
Volatilisation	Volatilisation involves the transfer of a compound from the solid or solution phase to the atmosphere and is influenced by temperature, reducing pressure, chemical reaction or a combination of these processes. The rate of volatilisation of a compound is dependent on its vapour pressure, as well	Volatilisation is likely not an important removal mechanism for **TWP**, **RWP$_{RM}$** and **RWP$_{PMB}$**, though some of the extender oils in TWP may evaporate with time and increase the likeliness of further degradation (see **Section 3.4.1**).

Mechanism	Description	Expected importance
	as the characteristics of the surrounding soil.	
Oxidation	Compounds may be oxidised (losing an electron) physically (photo-oxidation), chemically (e.g. ozone, hydrogen peroxide), or biologically. The oxidation often makes the compound more readily biodegradable.	Anti-oxidising agents are added to tyre treads to prevent attack from e.g. ozone. During wear, these agents have been shown to vaporise and leach out making the **TWP** more prone to oxidative attacks. There is no similar information on **RWP_{RM}** and **RWP_{PMB}**.

5 Treatment solutions for highway runoff

5.1 Accepted treatment solutions and functional requirements

The revised version of the NPRA's Handbook N200 for building roads (Statens vegvesen 2017) prioritise and partially restrict the relevant treatment options to apply for road runoff (see **Table 5.1**) and when these are needed (see **Appendix A**). Anywhere treatment is needed, the first (and in most places, only) treatment step includes settling of particulate matter. Both nature-based solutions and technical-based solutions are advised and have equal status. The runoff from the assumed most heavily polluted roads (>30,000 AADT) and roads >15,000 AADT that discharge into a vulnerable recipient, need a second treatment step involving sorption of (dissolved[40]) pollutants by infiltration in native soil or filtration in engineered soil.

Table 5.1 *Different treatment steps and their primary function, relevant treatment solutions and general functional requirements (adapted from the revised version of Statens vegvesen 2017).*

Topic	Step 1	Step 2
Primary function	Settling of particle-associated pollutants	Filtration, sorption and biodegradation of fine particles, colloidal matter and dissolved pollutants[41]
Type of treatment	Nature-based sedimentation ponds	Infiltration basin or ditch in native soil
	Technical treatment solutions (closed basin, pipelines etc.)	Filtration basin or ditch with engineered soil
		Closed filtration (basin, pipelines and engineered soil)
Functional requirements	Contaminated road runoff must be collected and directed to the treatment unit.	
	Clean surface water from areas outside the road must be intersected and bypassed treatment.	
	The treatment measure must be functional all year around and should be able to retain acute spills by keeping both inlet and outlet submerged.	
	In case of overload, excess water must be directed through a safe flood path, dimensioned for $Q_{dim, 50}$.	
	The treatment unit should have easy access for mechanical equipment for operation and maintenance (e.g. mud removal, vegetation control, sampling of water and sludge).	

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[40] A large fraction of what can be expected to be removed by infiltration/filtration are residual small-sized and colloidal matter leaving the sedimentation step. Biodegradation (e.g. biological transformations and mineralisation may also be important from spring to autumn) in addition to the chemical sorption processes.

[41] In the original table only sorption of dissolved pollutants is mentioned.

5.2 Step 1 solutions (settling of particle-associated pollutants)

5.2.1 Design requirements

According to Handbook N200 (Statens vegvesen 2017) any step 1 treatment solution should fulfil the following requirements:

- Have a forebay to settle out coarse material.
- Maintain a permanent water mirror with two volumes; a dry weather volume and a retention volume.
- The dry weather volume should have a minimum depth of 1.2 m to ensure aerobic conditions[42].
- The bottom should be sealed to ensure the dry weather volume.
- It should be dimensioned so that the expected treatment performance is minimum 80% for total suspended solids (TSS)

A submerged inlet and outlet is required to ensure retention during periods with ice cover (Statens vegvesen 2014B).

Common step 1 treatment solutions used in Norway are wet ponds (see **Figure 4.1, Figure 5.2** and **Figure 5.3**) and constructed wetlands (**Figure 5.4**). However, constructed wetlands may not be acceptable as a large part of their dry weather depth is often as low as 0.1-0.3 m to allow water plants. Dry ponds[43] (also called dry detention basins) are not accepted as these do not have a permanent water mirror (**Figure 4.4**).

More technical solutions such as closed basins (see **Figure 6.15**) will be allowed, but are not expected to be very common along our national road network. These types of solution are covered in **Chapter 6**, where we look at solutions expected to be applicable to urban areas.

Well-designed wet ponds provide containment of incoming run-off waters, create uniform flow zones (i.e. plug flow), increased flow path length and width and increased sedimentation times to facilitate sedimentation of suspended particles; and discharge water at a controlled rate that permits adequate detention time for sedimentation of suspended particles (GDSC 2011).

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[42] This is actually the opposite of what can be expected; if the water depth increases, the length for diffusion of surface oxygen increases, and the risk of stratification and generation of anoxic (or anaerobic) conditions increases.

[43] The purpose of dry ponds is to collect the water and then slowly drain it out through the outlet built at the bottom of the structure. Given that they are primarily designed for peak flow reduction they do not generally improve the quality of water.

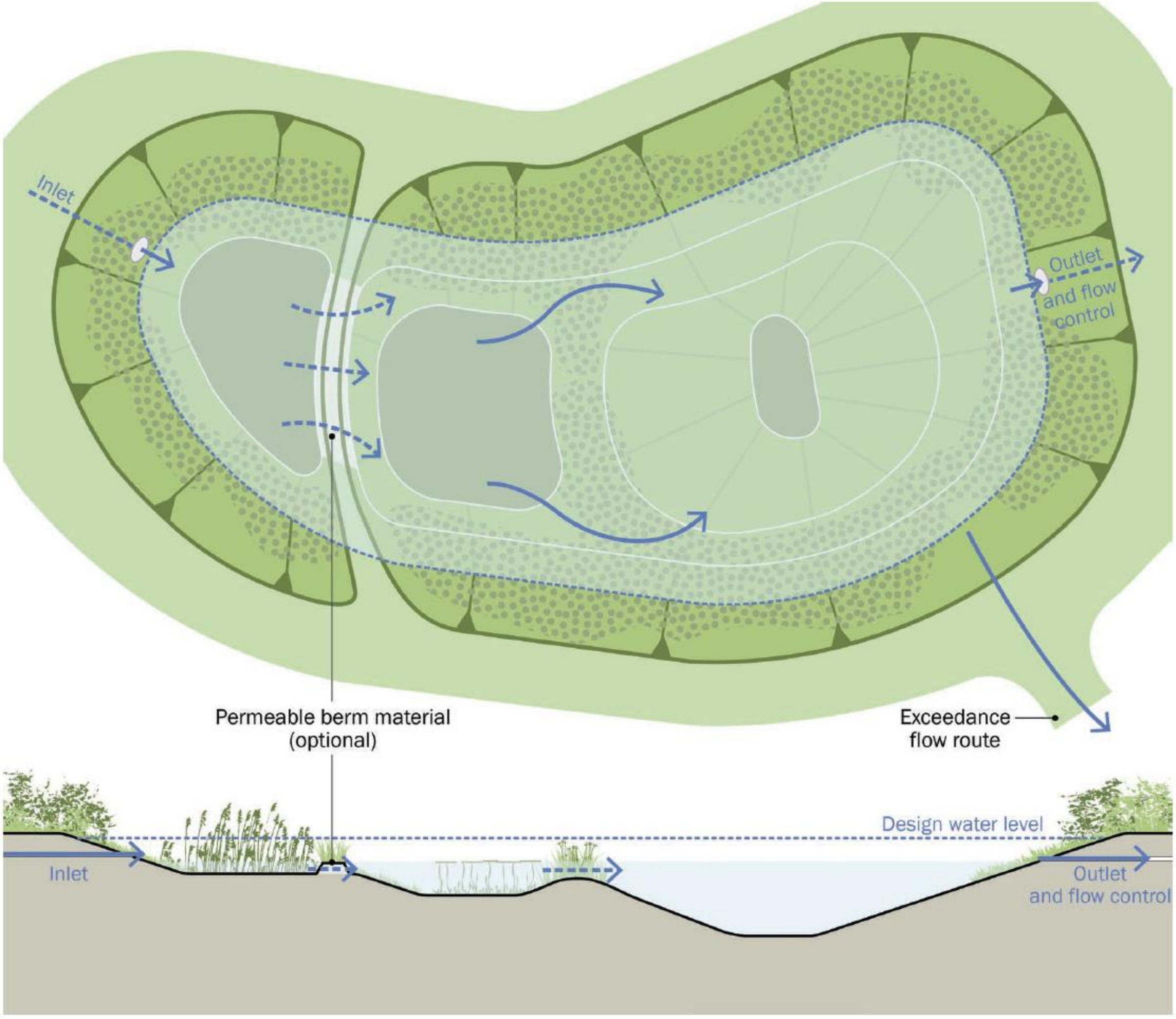

Figure 5.1 *Graphical illustration of a* ***wet pond****; plan view and profile of pond details (Woods Ballard et al. 2015 with courtesy of CIRIA).*

Figure 5.2 *Examples of* ***wet ponds****. Left: In North Carolina (Photo: City of High Point). Right: Hobekk, E16 in Vestfold (Photo: Espen Rise Gregersen, Statens vegvesen).*

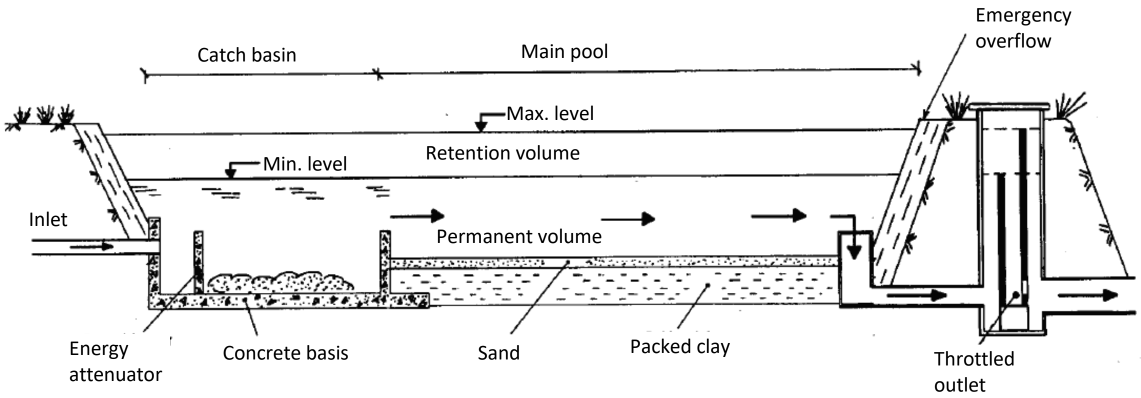

Figure 5.3 *Design of a* ***wet pond with submerged inlet and outlet*** *to ensure retention during periods with ice cover (translated from Åstebøl and Hvitved-Jacobsen 2014).*

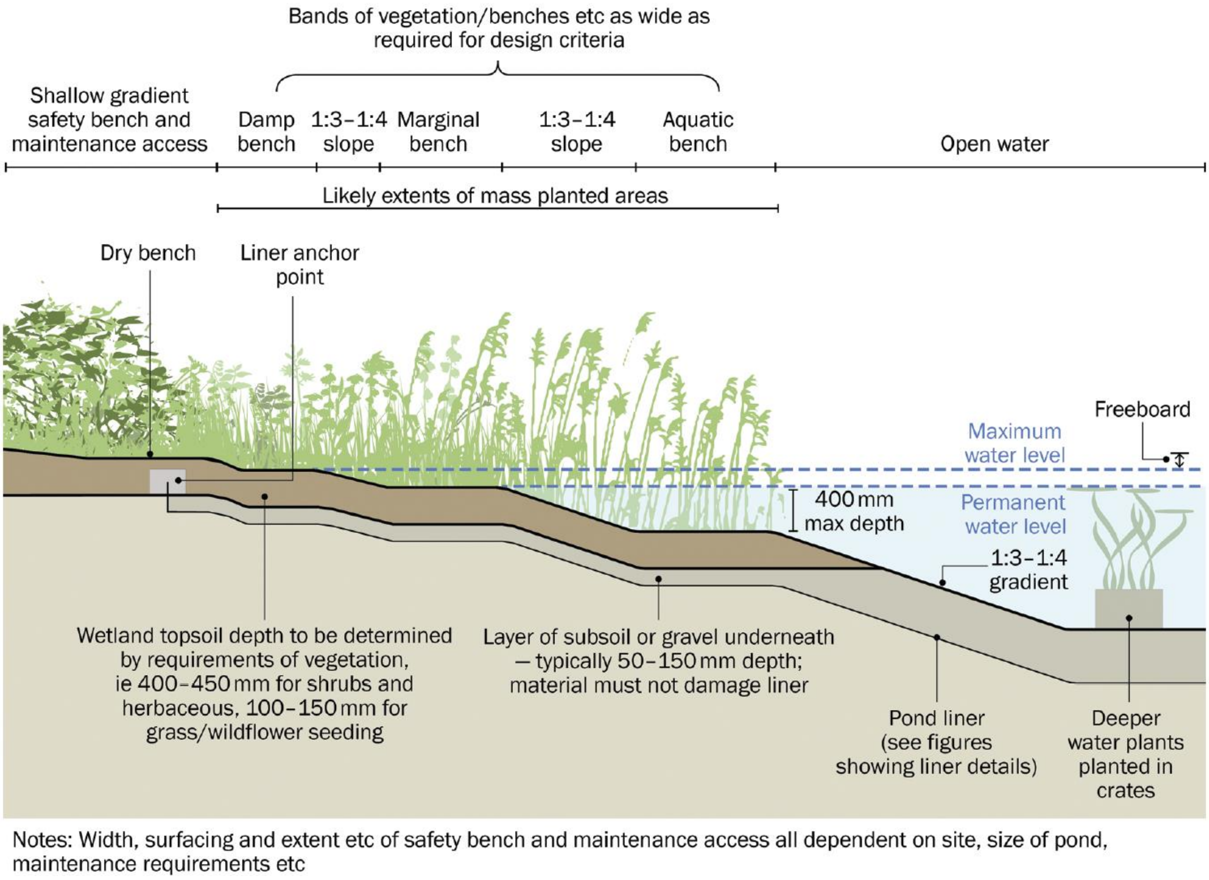

Figure 5.4 *Graphical illustration of a wetland; profile of pond details (Woods Ballard et al. 2015 with courtesy of CIRIA).*

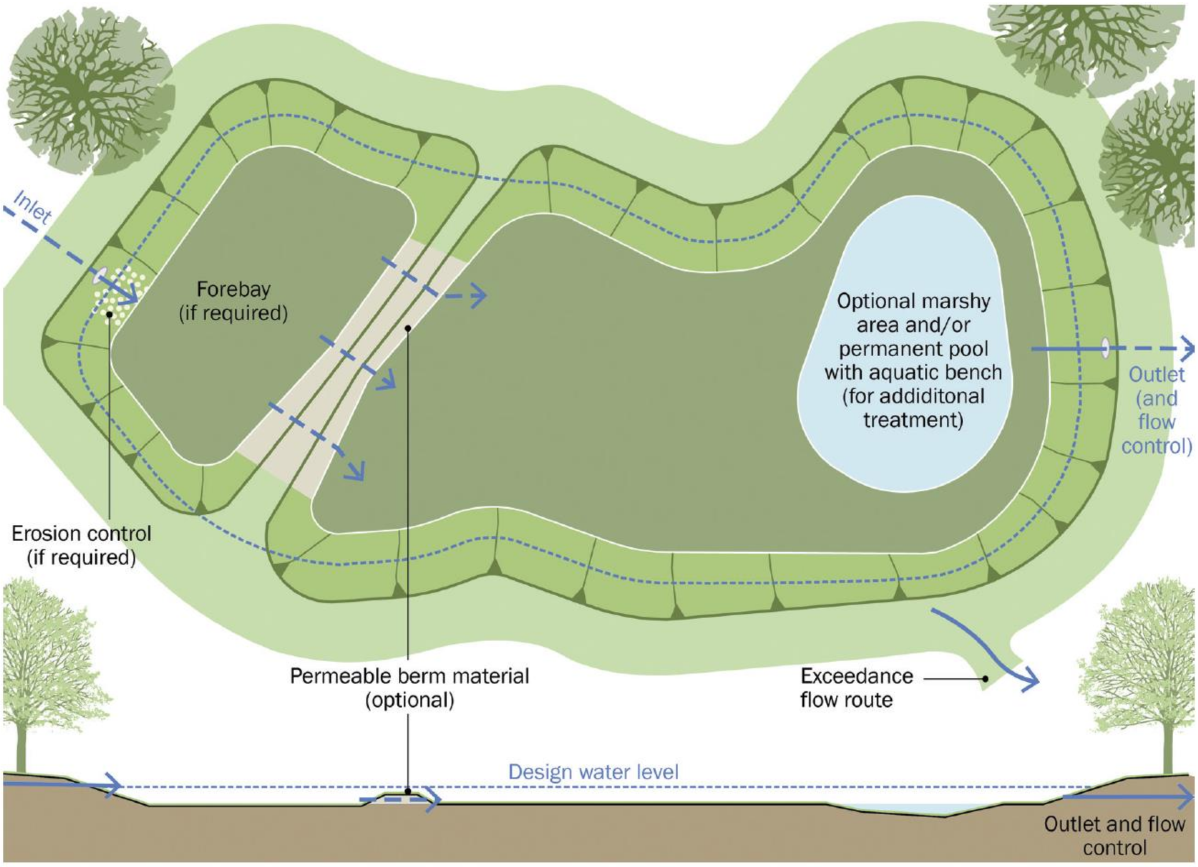

Figure 5.5 *Typical plan view and profile for the design of a dry pond (Woods Ballard et al. 2015 with courtesy of CIRIA).*

5.2.2 Dimensioning

Both the dry weather volume and the retention volume are fundamental design parameters for the wet pond. The larger the volume, the longer residence time for settling of particulate matter. Any wet pond should be dimensioned so that 80% removal of TSS is achieved for the median rainfall event (Statens vegvesen 2017). **Figure 5.6** shows the correlation between expected removal of TSS in a wet pond (based on numerous empirical data[44]) and a volume factor, n that is the ratio between the dry weather volume, V and the dimensioning runoff volume, v_{dim}. The latter is the total volume of runoff water during the mean rain event in the area and is determined based on measurements of several years with individual short-term rain events[45]. According to **Figure 5.6** the dry weather volume of the permanent pool needs to be approximately 6 times larger than the dimensioning runoff volume to reach 80% TSS removal.

The retention time in the forebay should be approximately 3-5 min at the dimensioning flow (Metcalf & Eddy 2003).

The dimensioning depth of the pond needs to take into account (*Statens vegvesen 2017)*:

- Expected accumulated sediment depth according to planned maintenance
- Expected ice cover thickness

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[44] USEPA (1986), Hvitved-Jacobsen et al. (1987) and Hvitved-Jacobsen et al. (1994)

[45] The definition of a rain event as a basis for calculating the mean rainfall is that the event is >0.4 mm and that the delay between two events is at least 1 hour. Necessary data can be downloaded from met.no.

- The expected highest pond depth at the dimensioning runoff volume
- An additional depth of minimum 0.15 m

Other methods and more detailed descriptions of how to dimension wet ponds can be found in e.g. Åstebøl and Hvitved-Jacobsen (2014) and in the CIRIA SuDS Manual (Woods Ballard et al. 2015).

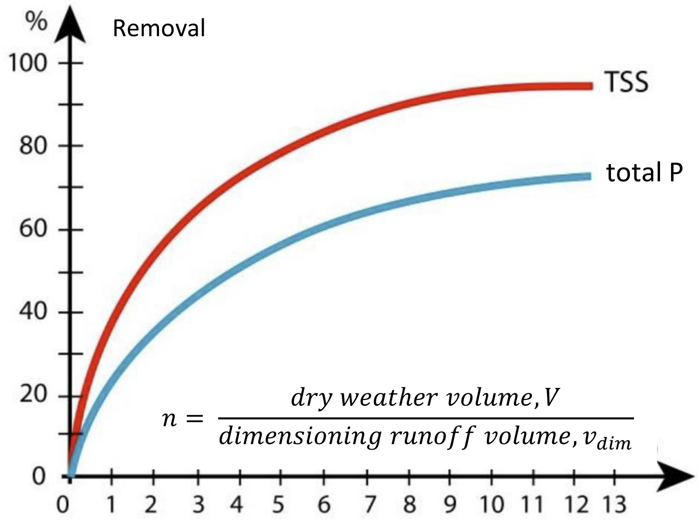

Figure 5.6 *Expected removal of TSS and total phosphorous (total P) as a function of the relationship between the dry weather volume of the permanent pool of a wet sedimentation pond and the dimensioning runoff volume (Statens vegvesen 2014B).*

5.2.3 Prerequisites for proper functioning

For a wet pond to function properly it should fulfil the design requirements (**Section 5.2.1**) as well as the dimensioning criteria (**Section 5.2.2**). These and further recommendations are listed in **Table 5.2**. A more extensive list of expected maintenance needs for ponds (and wetlands), as encouraged by the CIRIA SuDS manual (Woods Ballard et al. 2015), is provided in **Table N1** in **Appendix N**.

Table 5.2 *Recommendation for proper functioning of wet ponds. Adapted from Åstebøl et al. (2013) and Woods Ballard et al. (2015).*

Topic	Advice	Recommendation relevant to TSS removal
Inlet and outlet arrangement	Submerged inlet and outlet	Submerged inlet and outlet is required to ensure retention during periods with ice cover.
	Energy attenuator	The inlet needs a flow damper or energy attenuator to avoid erosion and turbulence in the main pool.
Pre-treatment	Forebay before the main pool	A forebay will retain coarse particles and reduce maintenance need of the main pool.
The main pond	Maintain a permanent water mirror	Permits prolonged settling times for fine particulates between rainfall events.
	Sufficient permanent pond volume according	The dry weather volume is a fundamental design parameter empirically correlated with the treatment effect.

Topic	Advice	Recommendation relevant to TSS removal
	to the catchment area	
	Permanent water depth between 1.2 and 1.5 m[46]	Insufficient water depth will lead to erosion and resuspension of settled solids. A too high water depth will lead to low oxygen concentrations in the bottom water. It should take into account the expected accumulated sediment depth according to planned maintenance (see below) and expected ice cover thickness.
	A length:width ratio of the main pool ≥ 3:1	A long and widening main pool creates uniform flow zones (i.e. plug flow), increased flow path length and width, which are beneficial for the settling process.
	A moderate amount of rooted vegetation	Vegetation will improve the sedimentation process by promoting calm currents (as well as filtration through vegetation)
Maintenance	Good accessibility	The forebay should have easy access for machines/vehicles used during maintenance.
	Sediment removal from forebay	Settled sand in the forebay need to be removed every 1-5 years. If dimensioned properly, this sand will not be significantly polluted.
	Sediment removal main pond	Removal of sediments from the main pond will rarely be required, e.g. every 25-50 years. These sediments can be expected to be highly polluted (heavy metals and other hazardous substances)
	Vegetation trimming	In highly productive ponds, vegetation may need to be cut regularly.
	Inlet and outlet checks	Inlet, outlet and overflow function should be checked regularly.
	Litter and debris	Remove litter and debris that may block water ways.

5.2.4 Expected treatment effects

If the wet pond is well planned, constructed[47] and properly maintained (see **Table 5.2**), a TSS removal as indicated in **Figure 5.6** may be expected. A similar plot showing the correlation between TSS removal rate and the ratio between the permanent pool volume and the stormwater runoff volume is shown in **Figure 5.7**. The extended detention time curves indicate the available time for additional settling and improved TSS removal between rainfall events.

Road-side treatment facilities are not commonly monitored to estimate their actual treatment effects. Both the hydraulic and the particulate loads will vary greatly with pollution and precipitation pattern and with location, as discussed in **Section 3.5**. For instance, it is commonly accepted that it is easier to achieve higher removal efficiencies at high influent concentrations. Hence it may be more adequate to look at the typical effluent concentrations than per cent removal when considering the removal effect of different types of treatment facilities. Hvitved-Jacobsen et al. (1994) determined

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[46] Åstebøl and Hvitved-Jacobsen (2014) recommends that the permanent water depth is 1.0-1.5 m. However, 1.0 m is in conflict with the 1.2 m minimum pond depth stated in the revised Handbook N200 (Statens vegvesen 2017).

[47] Many plants have been well dimensioned and planned, but they have not been constructed according to those plans (Paus et al. 2013).

the following correlation between the inlet concentration, C_0 [mg/l] and the effluent concentration, C_{eff} [mg/l] given the residence time, t [d]:

$$C_{eff} = C_0 \cdot e^{-0.5 \cdot t} \tag{5.1}$$

The best overview of monitoring data from existing treatment facilities for road runoff can be found in the International Stormwater Best Management Practices (BMP) Database. WE&RF (2017) have summarised influent and effluent data from all 315 facilities (primarily in the USA) that have reported values to this database. The expected average effluent concentrations of TSS from **wet ponds** is 11.7 mg/l (10.0-12.3 mg/l for the 95% confidence interval) and an anticipated TSS removal of 75%. The values for **constructed wetlands** are 14.1 mg TSS/l (11.6-15.2 mg/l) for the average effluent concentrations of TSS and an expected average 55% removal of TSS. It should be noted that the presented TSS removal data do not represent the average removal at each facility, but the average difference between all influent and all effluent data. The wet pond at the Skullerud junction (see **Figure 2.5**) achieved 82.5% based on the difference between the annual average influent and effluent concentrations (Åstebøl and Coward 2005).

The indicated expected removal of TSS is considered to coincide with the expected removal of TWP (see discussion in **Section 3.5.2**).

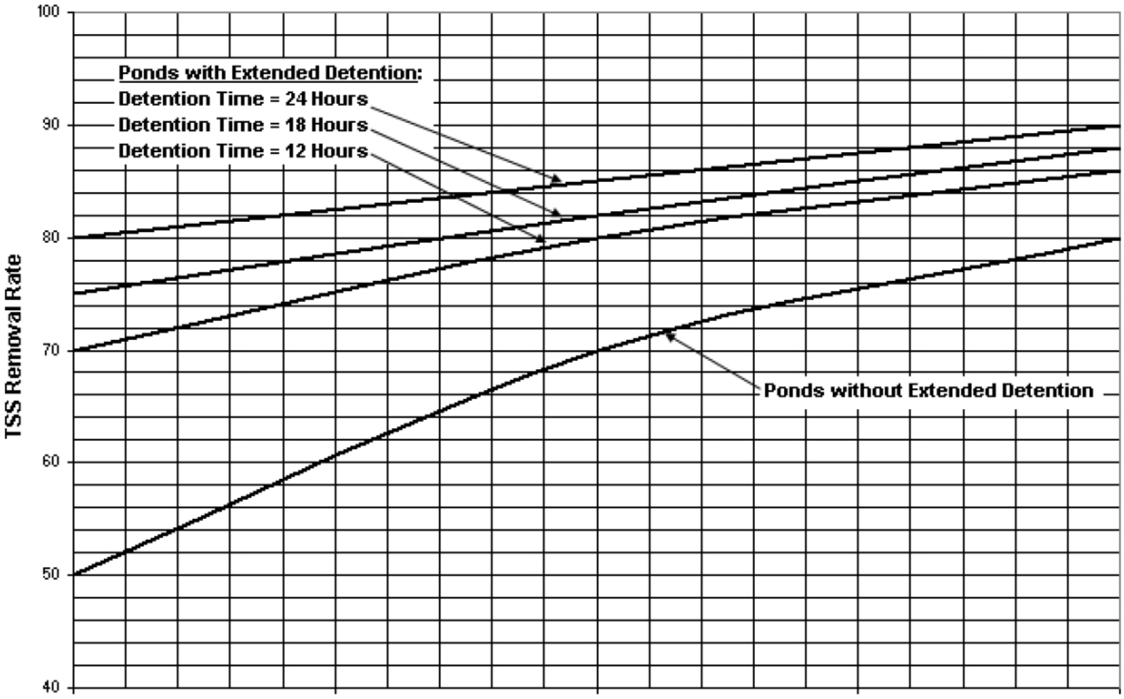

Figure 5.7 *Correlation between expected TSS removal rate (in %) and the ratio between the permanent pool volume and the stormwater runoff volume for wet ponds. The extended detention time curves indicate the available time for additional settling between rainfall events. (NJDEP 2014).*

5.2.5 Norwegian experiences

Wet ponds are by the far the most applied treatment system along Norwegian roads (Meland 2016). This system is also very common in other European countries, e.g. Sweden and Denmark. However, their performance is heavily dependent on their design, the building quality at site, and equally important the operation and maintenance quality when put into action. The reports published by Paus et al. (2013) and Gregersen et al. (2015) disclosed that many of the existing wet ponds were in poor shape and malfunctioning, either due to poor building quality or poor, or even neglected, operation and maintenance. Hence, there may be a mismatch between expected treatment performance and what is actually performed on site.

Constructed wetlands are also frequently used, but the uncertainty regarding proper dimensioning and expected treatment effects (Åstebøl and Hvitved-Jacobsen 2014) as well as the inconvenient, and often lacking, maintenance at these facilities (Åstebøl et al. 2013 and Gregersen et al. 2015), have contributed to that these treatment solutions are no longer recommended.

5.2.6 Roughly estimated costs

Wet ponds have proven to be effective and cost efficient measures in terms of protecting water bodies from polluted road runoff (Åstebøl and Coward, 2005). The estimated costs for building a sedimentation ponds will vary from site to site. A rough estimate is 5 – 10 mill NOK. The previous version of the CIRIA SuDS Manual (Woods-Ballard et al. 2007) indicated a capital cost range of £15-25 per m^3 treatment volume, noting that large constructions may have relatively lower costs since costs of inlet and outlet structures are relatively similar regardless of component size. The estimated annual costs for regular maintenance was estimated to be approximately £0.5-1.5 per m^2 of sedimentation pond surface area.

5.3 Step 2 solutions (sorption of dissolved pollutants)

5.3.1 Design requirements

According to Handbook N200 (Statens vegvesen 2017) any step 2 treatment solution should fulfil the following requirements:

- The surface at the bottom of the infiltration pool should be grass covered to reduce the risk of fouling due to settled fines.
- Groundwater[48] should be more than 1 m below the bottom of the infiltration pool.
- The thickness of the applied filter mass in a filter pool should be at least 30 cm.

As indicated in **Table 5.1**, a broad spectre of treatment solutions based on infiltration in native soil or filtration through engineered soil may fulfil the listed functional requirements. The typical features of an infiltration basin are illustrated in **Figure 5.8**, with the pre-sedimentation pond being step 1, ideally as described in **Section 5.2**. The infiltration facility has a pond structure to retain water that is infiltrating through the native soil pond and ultimately into groundwater.
Other infiltration concepts such as soakaways[49] could be used. These are rectangular or circular excavations lined with geotextile fabric and filled with clean granular stone or other void forming material (**Figure 5.9**). The runoff enters the soakaway through a perforated pipe that allow it to infiltrate into the native soil.

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[48] The maximum likely groundwater level should always be adopted (Ballard et al. 2015).

[49] The infiltration trench is a similar infiltration concept and is of particular interest in urban areas with limited available space for infiltration (see **Section 6.4.2**).

Where the native soil does not allow infiltration, engineered filtration media such as sand with specific grain size variability may be used (**Figure 5.10**). Adsorbents may also be added to improve removal of heavy metals (Ilyas et al. 2017).

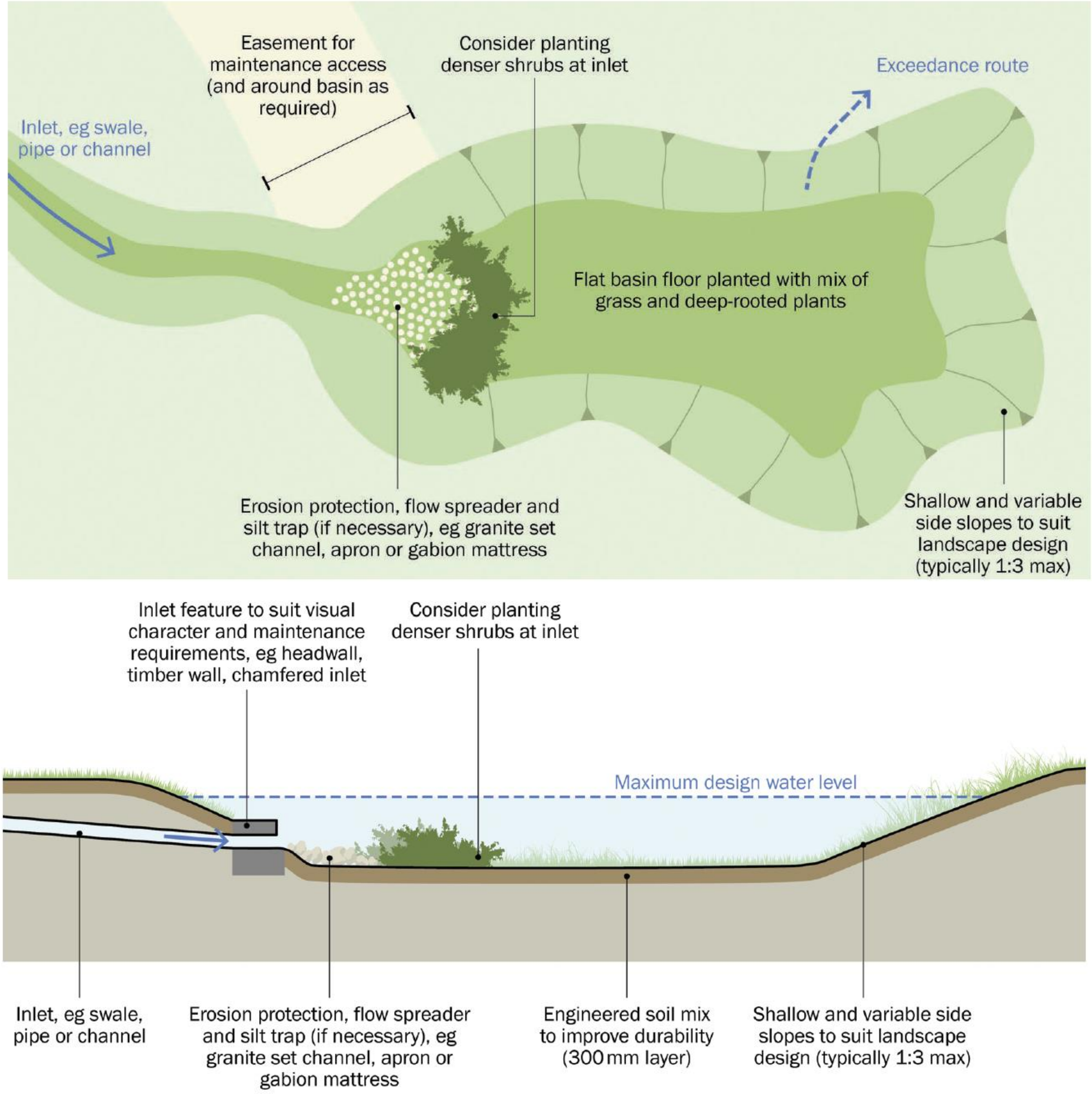

Figure 5.8 *Principle drawing of an infiltration basin from above when it is empty (upper) and in profile when it is filled (below) (Woods Ballard et al. 2015 with courtesy of CIRIA).* Note that *just a simple forebay is not adequate, according to the revised version of Handbook N200 (Statens vegvesen 2017).*

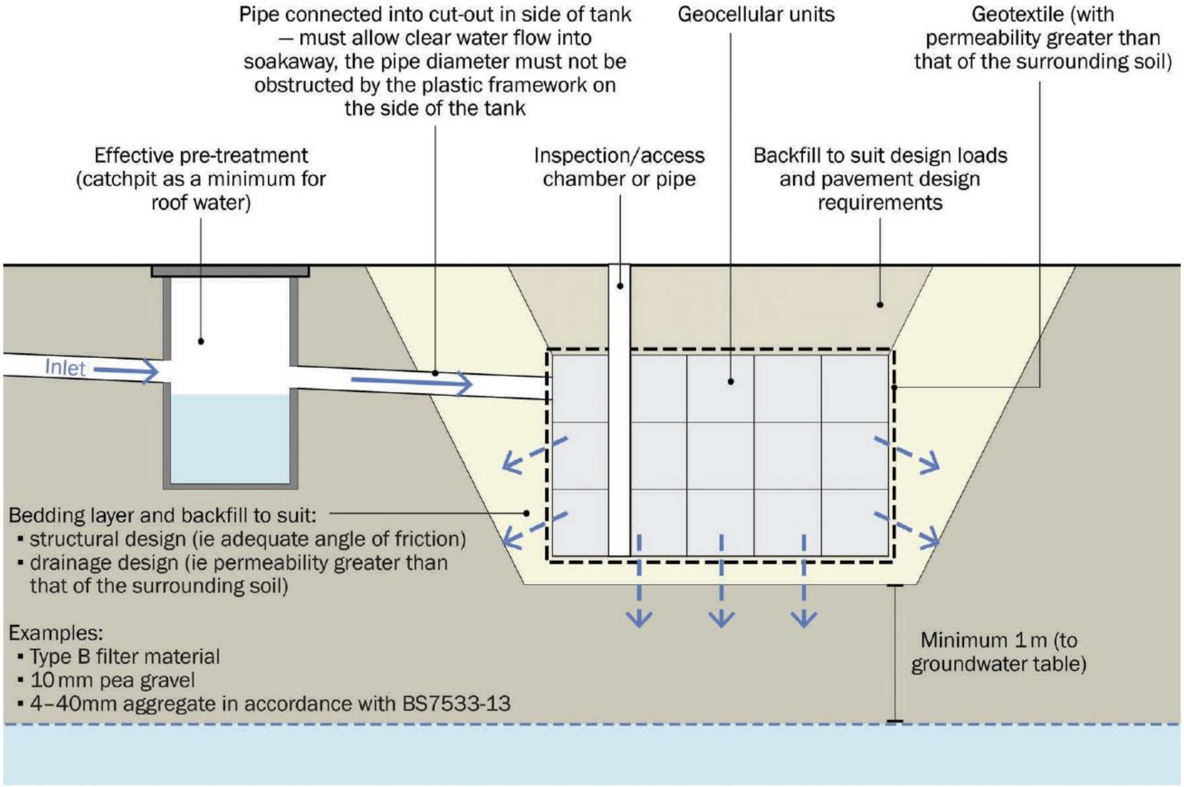

Figure 5.9 *Principle drawing of a soakaway with a catch pit as pre-treatment. The soakaway may receive the effluent from e.g. a wet pond (Woods Ballard et al. 2015 with courtesy of CIRIA).*

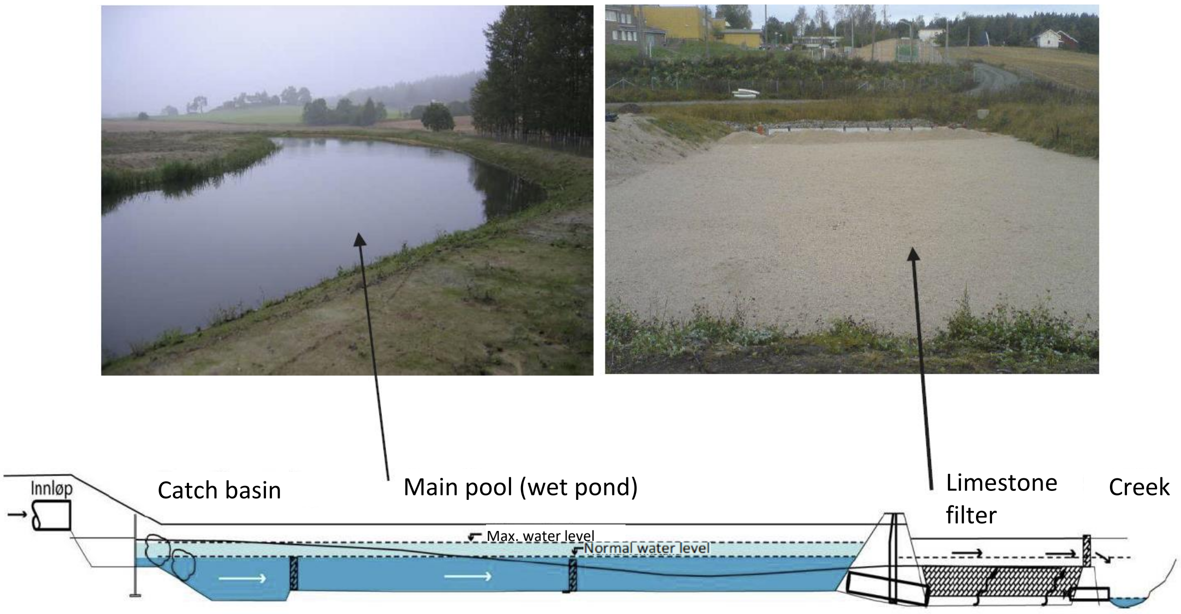

Figure 5.10 *Example of an engineered filter bed solution. An up-flow limestone filter treats the effluent from a wet pond (Åstebøl et al. 2013; photos: courtesy of COWI).*

5.3.2 Dimensioning

Removal of contaminants is based on three process mechanisms; filtration, sorption to soil particles and biodegradation, hence residual fine particles, colloidal matter, nutrients and biodegradable organic compounds may to some degree be removed.

Three factors influence the above mentioned removal mechanisms (Åstebøl and Hvidted-Jacobsen 2014):

1) The infiltration rate of the soil (measured as hydraulic conductivity)
2) Sorption rate of pollutant to the soil matrix
3) The capacity of the soil matrix to accumulate pollutants as well the soil's ability to retain and convert these.

This means that the infiltration rate should not be too quick (limits sorption) nor too slow (reduced available attenuation volume for next storm event within 2-5 days). A hydraulic conductivity of 5-60 mm/h is a compromise, indicating that a mixture of silt (0.002-0.06 mm grain size) and sand (0.06-2 mm grain size) would be an appropriate matrix for infiltration. However, some organic matter and clay should also be included to improve the sorption capacity. A detailed description of the dimensioning principles and conditions influencing the above factors can be found in Hvidted-Jacobsen et al. (2010) or in the CIRIA SuDS Manual.

According to the revised Handbook N200 (Statens vegvesen 2017), the storage capacity (i.e. the dimensioning runoff volume, v_{dim}) of the infiltration basin should be based on the dimensioning runoff[50] during a rainstorm event lasting from 10 min to 24 hours, although no recurrence period is mentioned. In the previous version this was set to 1-2 years. Since the infiltration step will be step 2 in the treatment train, the inherent detention capacity of the first step should be taken into account.

During winter, the use of infiltration systems is challenging because frozen soils can significantly reduce, or stop, the rate of infiltration. This must be emphasized in the dimensioning of the magazine volume. As it may function more as wet pond during winter, it must be equipped with an overflow for controlled discharge during flooding (Åstebøl and Hvidted-Jacobsen 2014). The overflow may be treated in a closed filtration system such as a soakaway (**Figure 5.9**).

5.3.3 Prerequisites for proper functioning

For infiltration systems to function properly they should fulfil the design requirements (**Section 5.3.1**), dimensioning criteria (**Section 5.3.2**), as well as being well maintained. These and further recommendations are listed in **Table 5.3**. More extensive lists of expected maintenance needs for infiltration systems, as encouraged by the CIRIA SuDS manual (Woods Ballard et al. 2015), are provided in **Table N2** (infiltration basins) and **Table N3** (soakaways) in **Appendix N**.

A common cause for low infiltration rate is compaction triggered already during the construction work with the basin. To avoid compaction as light machinery as possible should be used.

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[50] This should be calculated using the rational method as outlined in Handbook N200 (Statens vegvesen 2017).

Table 5.3 Prerequisites for proper functioning of infiltration ponds.

Topic	Advice	Recommendation relevant to TSS removal
Pre-treatment	A wet pond or equivalent treatment	For the infiltration to function properly, the infiltration surface should not be blocked by silt and the soil should not be clogged. This is ensured by the preceding wet pond.
Infiltration pond	Overflow	To provide controlled discharge during flooding, particularly during winter time. The overflow may be treated in soakaway.
	Grass-covered pool floor.	The surface at the bottom of the infiltration pool should be grass covered to reduce the risk of fouling due to settled fines.
	Proper infiltration rate	The infiltration rate (determined by the soil characteristics) should allow adequate sorption to the soil while providing enough storage capacity for the next storm event occurring in 2-5 days.
	Filter thickness	The thickness of the applied filter mass in a filter pool should be at least 30 cm.
	Distance to ground water	Groundwater should be more than 1 m below the bottom of the infiltration pool. Hence, areas with shallow groundwater tables are not appropriate for infiltration.
Maintenance	Good accessibility	The forebay should have easy access for machines/vehicles used during maintenance.
	Sediment removal from forebay	Sediments in the pre-treatment system need to be removed when approximately 50% full.
	Inspect for compaction and ponding	Remove sludge if necessary or rehabilitate infiltration surface.
	Sediment removal from main pond	Removal of sediments from the main pond will rarely be required, e.g. every 25-50 years. These sediments can be expected to be highly polluted (heavy metals and other hazardous substances)
	Vegetation trimming	In highly productive ponds, vegetation may need to be cut regularly.
	Inlet and overflow function	Inlet and overflow function should be checked regularly
	Litter and debris	Remove litter and debris that may block water ways.

5.3.4 Expected treatment effects

According to Åstebøl and Hvitved-Jacobsen (2014) the expected removal efficiencies of infiltration basins are approximately 80-95%, while up to 100% can be achieved by soakaways. The New Jersey Stormwater BMP Manual (NJDEP 2004) assume 80% TSS removal for all infiltration systems. However, the storage capacity of the infiltration pond will be important for the actual removal. An estimate made for infiltration basins in the US showed that basins that could store the first 13 mm of a rainfall event where likely to remove on average 75% of the incoming TSS. Basins with a capacity to store the first 26 mm or 52 mm of a rainstorm event would remove an estimated 90% or 99% of TSS, respectively (FHWA 1996). It should be noted that removal, in this case, means that TSS is accumulating in the sediments or within the soil or is transported downwards to groundwater. The treatment efficiency of infiltration systems is actually seldom measures as it is difficult to assess the real effluent concentration.

There are no reported results from infiltration basins in the International Stormwater BMP Database, but there are 25 treatment facilities applying filter media that are included in the WE&RF (2017) summary, of which most are sand filters. The average effluent concentration of TSS from these is 9.0 mg/l (with 6.4 – 10.0 mg/l 95% confidence interval), and the average TSS removal efficiency, based on the difference between the average influent and effluent data from all the facilities, is 84%. The New Jersey Stormwater BMP Manual (NJDEP 2004) assume 80% TSS removal for sand filters.

Since the infiltration (or filtration) step will be step 2 in the treatment train using the effluent from step 1 as influent, the actual removal efficiency in per cent will probably be significantly lower. A simplified equation may be used to calculate the removal rate for the two-step treatment train (NJDEP 2004):

$$R = A + B - \frac{A \cdot B}{100} \qquad (5.2)$$

Where:
- R is the total TSS removal efficiency [%]
- A is the removal efficiency of the first treatment step
- B is the removal efficiency of the second treatment step

Assuming 80% TSS removal for the wet pond and also 80% for the subsequent infiltration/filtration step, the overall removal efficiency will be 96% according to Equation 5.2.

5.3.5 Norwegian experiences

Infiltration is rarely used in Norway today[51], but it will probably be more common along densely trafficked roads (>30 000 AADT) and >15,000 AADT roads discharging to vulnerable recipients (ref. **Table 6.1**). There were only two infiltration facilities included in the status reports published by Paus et al. (2013) and Gregersen et al. (2015), and both of these facilities were not functioning as intended. One of the infiltrations basins functioned more as a wet pond, but with too low permanent water level to provide efficient settling.

5.3.6 Roughly estimated costs

The estimated costs for building an infiltration basin will vary from site to site. A rough estimate is that the construction costs will increase with 50% when building a second treatment step in addition to the first sedimentation step, hence a total cost of approximately 7.5-15 million NOK. The previous version of the CIRIA SuDS Manual (Woods-Ballard et al. 2007) indicated a capital cost range of £10-15 per m^3 detention volume, noting that large constructions may have relatively lower costs since costs of inlet and outlet structures are relatively similar regardless of component size. The capital costs for soakaways were indicated to be >£100 per m^3 stored volume.

Infiltration basins need to be controlled frequently, particularly concerning silt reducing the infiltration rate. Hence, the operating costs will also increase somewhat, but probably not as much

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[51] One example is the infiltration facility built along Rv174 close to the main airport at Gardermoen (Åstebøl and Hvitved-Jacobsen 2014)

as construction costs (in %). Woods-Ballard et al. (2007) indicated that the annual costs for regular maintenance would be approximately £0.1-0.3 per m^2 of infiltration basin area. The annual costs for soakaways were estimated to be £0.10 per m^2 of treated area.

6 Compact treatment solutions for road runoff in urban areas

6.1 Stormwater management principles in urban areas

6.1.1 Available space and impervious areas as challenges in urban areas

The traditional management practice for stormwater in urban areas has been to convey it in underground pipelines to the nearest creek or other available aquatic recipients. To prevent silting and subsequent clogging of the pipelines, gully pots have been installed all around the cities' streets and roads to collect rapidly settling particulate matter. For example, Oslo city has approximately 30,000 gully pots (Ræstad 2014). If pipelines in the domestic sewer network are nearby, the stormwater runoff has often been connected to these (i.e. combined sewer system). This provides easy, quick and cost-effective transport out of the area as well as treatment before discharge to the environment. However, during heavy rainstorm events the latter causes strain on downstream wastewater treatment plants (WWTPs) and results in combined sewer overflows (CSOs) that also contain large amounts of untreated domestic wastewater (e.g. toilet paper, faeces, pathogens, nutrients and other particulate and dissolved contaminants). Partially due to the complexity of the underground networks of the two systems (i.e. the combined and the separate sewer systems), and frequent misconnections, the actual split between the two systems is often not known. The potential retention of RAMP by existing gully pots is discussed in **Section 6.2**, while we discuss the expected fate of RAMP in the combined sewer systems and in treatment processes typically applied at the WWTPs in **Section 6.3**.

The above description illustrates the two main challenges related to the treatment of road runoff in urban areas:

1) There is limited natural attenuation of surface runoff in the built environment due to a high ratio of impervious surfaces.
2) There is limited space available for treatment units for capturing fine solids such as RAMP.

There are four main alternative types of measures to meet these challenges:

A) Reduce the need for treatment by implementing non-structural measures such as road sweeping, restrictions on use of studded tyres and reduced road traffic (more biking and public transport by trackways)
B) Prevent low-polluted stormwater from entering the combined sewer where possible, combined with increased local and/or centralised detention capacity to prevent CSOs, and increase the capacity for centralised treatment (i.e. WWTP), if needed.
C) Apply nature-based solutions – in the following called sustainable drainage systems (SuDS)[52] – that utilise natural features to mimic the undeveloped hydrologic properties of the site to retain and prevent runoff on the surface, and where needed and possible, treat the runoff by infiltration in native soil as close to the source area as possible. These types of solutions are discussed in **Section 6.4**.
D) Apply local underground technical treatment units with low footprint requirements. These types of solutions, which are typically proprietary systems, are discussed in **Section 6.5**.

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[52] The terminology varies between countries. In the UK they are called sustainable drainage systems (SuDS), while in the US and Canada green infrastructures or low impact development (LID) is used. SuDS cover also units that are regarded as Best Management Practices (BMPs) in the US, which includes all types of stormwater measures, bot non-structural and structural. The treatment solutions discussed in **Chapter 5** (e.g. wet ponds, infiltration basins and soakaways) are considered as SuDS.

As all cities have to take their existing infrastructure into account, all four alternatives may be applicable in the same city depending on local preferences for areal use and future developments. This is illustrated in **Figure 6.1**, showing map excerpts from different parts of Oslo where also the traffic density is indicated; >30,000 AADT, where treatment is required and 3,000-30,000 AADT, where treatment may be required if the recipient is regarded as moderately or highly vulnerable.

Figure 6.1A: Most of the heavy traffic through the centre of Oslo is placed in underground tunnels, which requires frequent tunnel cleaning. Tunnel washwater treatment is discussed in **Chapter 7**. Other surface runoff from this part of the city is collected in the new stormwater detention tunnel '*the Midgard Serpent*' and sent to Bekkelaget WWTP for treatment. Underground compact technical treatment units could be an alternative in such areas. However, SuDS could also play an important role in this part of the city, to reduce both peaks and the total runoff volume by implementing e.g. green roofs and rain gardens.

Figure 6.1B: Main roads pass developments with somewhat more green areas, but still restricted space for treatment units in other parts of the city. Where possible, SuDS should be a first choice in these areas particularly for retention and detention. They are low cost solutions and, since they are typically surface features, their operational performance and need for maintenance is easy to monitor. Proprietary treatment systems may also be appropriate where additional treatment is needed and infiltration not recommended. They may be cost efficient, both for pre-treatment (e.g. vortex separators) and for post-treatment (e.g. filtration devices and ballasted flocculation).

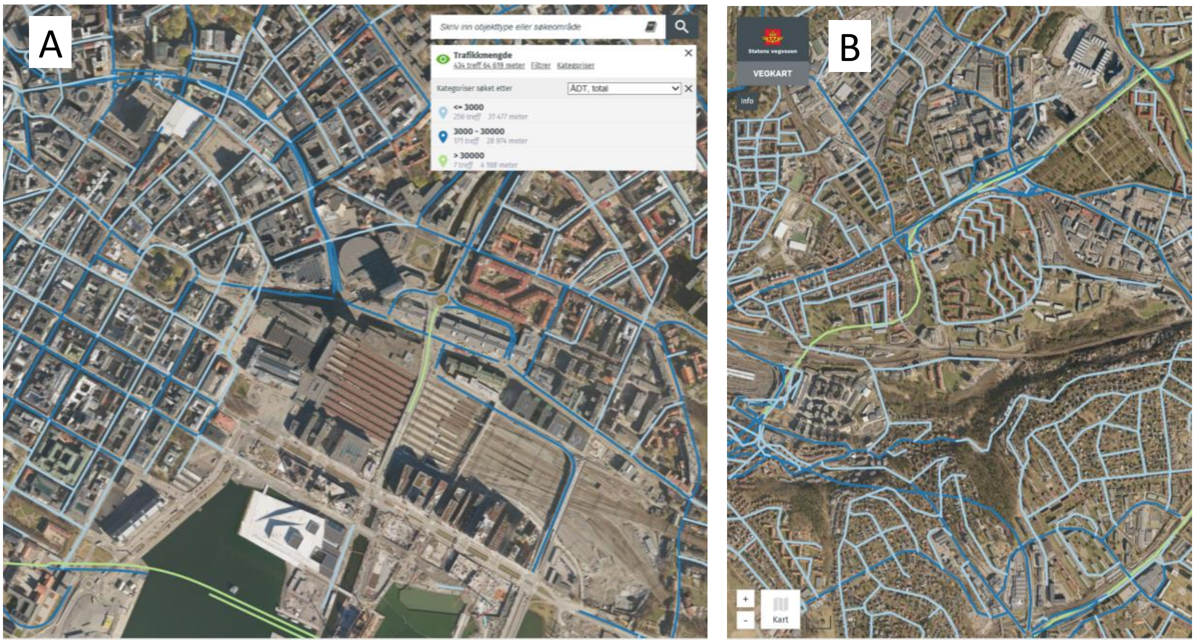

Figure 6.1 *Maps showing two adjacent parts of Oslo city; the city centre (***A***) and Etterstad-Manglerud with the Svartdal park in the middle (***B***). Traffic density is indicated with green (>30,000 AADT), blue (3,000-30,000 AADT) and light blue (<3,000 AADT) lines. The maps are copied from* www.vegvesen.no/vegkart.

6.1.2 Dimensioning road runoff in urban areas

Treatment solutions designed for highway runoff need to be dimensioned so that the entire volume of the average rainfall event is properly treated by the system (see **Section 3.5.1**). However, the proposed new guidelines[53] state that only the 'first flush' from road structures in confined spaces in urban areas need to be treated. However, the boundaries of first flush are not well defined. According to Miljøstyrelsen (2000), first flush may appear as early as within the first 3-5 mm precipitation, but there are large local variations. Åstebøl (2007) suggested the following criteria to determine the dimensioning capacity of SuDS in very confined areas, based on the required level of protection of the recipient:

1. Where required protection is moderate: the first 6-8 mm of the rainfall event is treated
2. Where required protection is high: minimum the first 10-15 mm of the rainfall event is treated
3. All runoff from a rainfall event with 3-month or 6-month recurrence interval

Furthermore, according to the CIRIA SuDS Manual (Woods Ballard et al. 2015), using different types of SuDS should be possible to prevent runoff and the associated pollution load from the majority of small rainfall events up to approximately 5 mm (i.e. Interception) by using e.g. pervious surfaces and vegetated collection systems.

6.1.3 Requirements to roadside treatment solutions in urban areas

Typical roadside treatment solutions applied along highways require long hydraulic retention times to support sufficient settling (e.g. sedimentation ponds) and sorption (e.g. infiltration systems). This implies spacious treatment systems (see **Chapter 5**). In urban areas with limited space for treatment and rapid runoff due to high ratios of impervious surfaces, these treatment solutions are usually not applicable.

Åstebøl (2007) suggests three requirements to treatment solutions in urban areas:

1. Due to the expected short retention time, the treatment solution should have a high capacity in terms of hydraulic load and treatment efficiency relative the area it serves.
2. Under these circumstances it should be reliable and require limited need for maintenance.
3. It may have a technical design and function and may be located underground as it does not necessarily need to appear as a landscape element.

It should be noted that above ground treatment systems have practical benefits such as simplified maintenance and easy identification of poor treatment performance or component damage/failure (Woods Ballard et al. 2015).

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[53] Statens vegvesen (2017)

6.2 Expected removal of TWP by roadside gully pots

6.2.1Design of gully pots

The main function of roadside gully pots is to retain solids in storm runoff from urban roads and streets, to prevent sediments from clogging the sewerage system (Lindholm 2015). Gully pots are small retention basins embedded in the ground, with no more than 60-70 m distance in between to limit the hydraulic loading during heavy rains. A typical design of a Norwegian gully pot is shown in **Figure 6.2**. According to Statens vegvesen (2014B), the minimum diameter of the gully pot is 1 m and the outlet should then be at least 100 cm from the bottom, leading directly to the sewerage system. The total available volume for retention of particulates is then approximately 0.8 m^3, but to maintain adequate retention they are recommended to be emptied when they are about 50% filled up (Mosevoll and Lindholm 1986, Lindholm 2015).

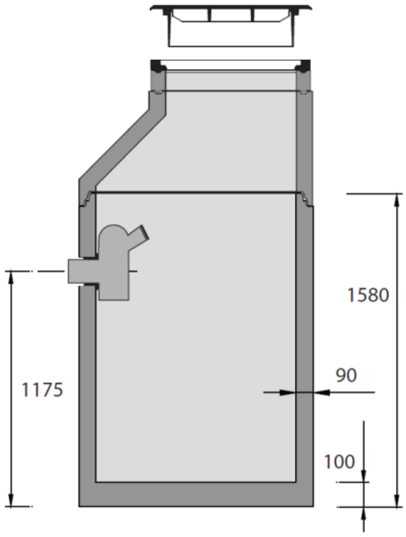

Figure 6.2 *Typical design of a Norwegian roadside gully pot (Courtesy of Basal). The minimum inner diameter is 1000 mm.*

6.2.2Expected retention of tread wear particles in gully pots

The fraction of solids captured by gully pots has been studied extensively. Retention efficiencies reported in field studies typically range from 20% to 50% (Deletic et al., 2000; Pitt and Field, 2004). The trap efficiency (ε; -) of gully pots can be expressed as a function of the particles' settling velocities, the inflow rate and the cross section of the gully pot (Karuranatne 1992, Butler and Karuranatne 1995):

$$\varepsilon = \alpha \cdot \sum_i \frac{V_i}{V_i + Q/A_g} \qquad [5.1]$$

Where:

- V_i is the settling velocity of particle *i* with diameter d_i (m/s),
- Q is the flow rate into the gully pot (m^3/s),
- A_g is the cross section of the gully pot (m^2), and
- α is a correction factor included to take the expected turbulence in the gully pot during rain events into account.

See **Appendix J** for a more detailed discussion on the settling velocity in general and **Appendix K** regarding the trap efficiency in gully pots.

Figure 6.3 shows the estimated efficiency of a gully pot to trap TWP with diameters between 1 µm and 350 µm when the influent flow velocity to the gully pot is 5-25 L/s. There is, of course, a clear correlation between increasing particle diameter and the trap efficiency, since larger particles settle faster. The expected trap efficiency for particles <50 µm is very low, even during low influent velocities. To get an impression of the overall retention of the particles, the particle size distribution of TWP (**Table 2.2**) needs to be taken into account. **Figure 6.4** shows the estimated removal ratios of the different particle size ranges compared to the total particulate matter in the influent to the gully pot. It is evident that particles between 50-80 µm cannot be expected to be retained to a significant degree. The apparent relatively high trap efficiency of the 80-350 µm particles is primarily due to the expected good retention of the larger particles, and could be significantly overestimated depending on the actual content of larger particles. As discussed in **Section 2.3.2**, the size distribution of the TWP is based on a very limited number of studies and is therefore very uncertain.

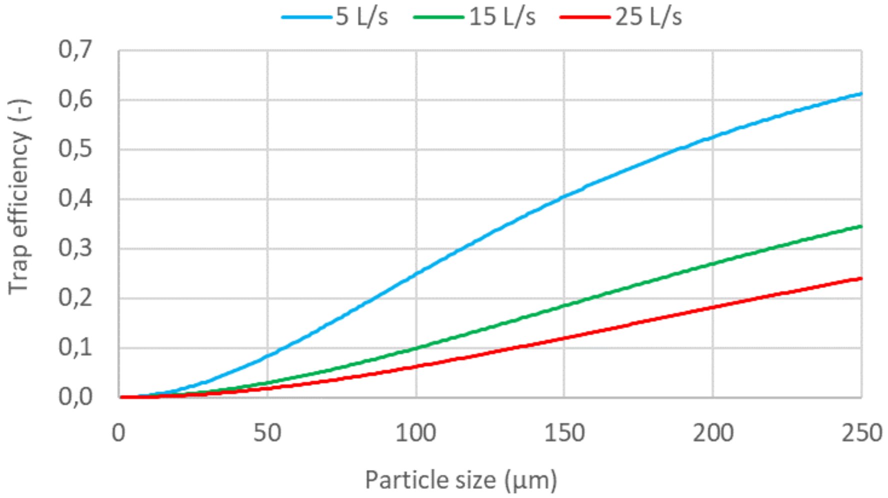

Figure 6.3 *Estimated efficiencies of a gully pot to trap particles with diameters between 1 µm and 350 µm and a density of 1.7 g/cm^{3}when the influent flow velocity to the gully pot is 5-25 L/s. The gully pot has an inner diameter of 1 m.*

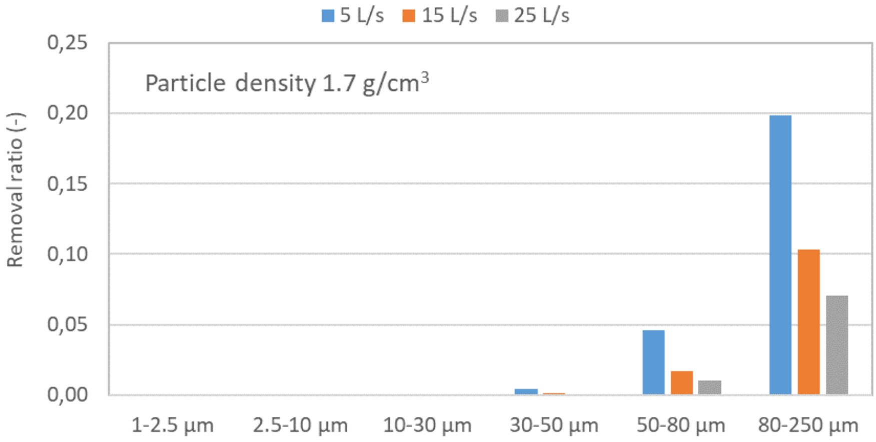

Figure 6.4 *Estimated trap efficiencies of gully pots for given volumetric loadings of 5-25 L/s for particles with densities of 1.7 g/cm^3 and 2.1 g/cm^3 using Equation 4.1. See* ***Appendix K*** *for more details.*

As shown in **Figure 6.3** and **Figure 6.4**, the retention of particles is also very sensitive to increases in the flow velocity into the gully pot. According to Mosevoll and Lindholm (1986), Norwegian gully pots usually receive runoff from an area of 0.5-2 ha (2,000-20,000 m^2) with typical maximum volumetric loading capacity of 25 L/s. The estimated critical rain intensity for these gully pots are approximately 56 L/s·ha for the 0.5 ha gully pot and 14 L/s·ha for the 2 ha gully pot, as calculated using the following equation:

$$I_c = \frac{Q_m}{\varphi \cdot A_{c,g}} \qquad [5.2]$$

Where:

- I_c is the critical rain intensity for the gully pot (L/s·ha),
- Q_m is the maximum runoff capacity that the gully pot can handle (L/s),
- φ is the runoff coefficient for the catchment (-), typically set to 0.9 for paved roads (Lindholm 2004), and
- $A_{c,g}$ is the catchment area of the gully pot (ha).

According to Lindholm (2015), the typical concentration time (t_c) (i.e. the time it takes rainwater to run from one end of the catchment to the other) is about 5 min for a normal gully pot. According to Rainfall Intensity-duration-frequency (IDF) curves[54], the two-year recurrence precipitation intensity for Oslo, Blindern for a t_c = 5 min is 187 L/s·ha (**Appendix L**), which is considerably higher than the critical rain intensities of 14 L/s·ha and 56 L/s·ha (0.5 ha catchment) calculated above for the 0.5 ha and 2 ha catchments, respectively.

6.2.3 Maintenance needs and risk of resuspension of sediments

To maintain adequate retention, it is recommended to empty gully pots when they are about 50% full (Mosevoll and Lindholm 1986, Lindholm 2015) as this will increase the trap efficiency (Memon and Butler 2002, Mineart and Singh 2000). However, this is often not the case. For instance, according to Ræstad (2014), Oslo municipality has approximately 30,000 roadside gully pots, but has allocated funding to empty only 1,500 a year. In a study of 35 gully pots along two roads in Oslo, Leikanger and Roseth (2016) it was found that it would take from 207-505 days before 50% of the

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[54] Prepared by Met.no.

volume was filled up with sediments, depending on the site and the frequency and effect of street sweeping.

It is often claimed that it is important to empty the gully pots to prevent resuspension of already settled solids. However[55], Sartor and Boyd (1972) applied flushing tests equivalent to heavy storms and found only 1% of the sediment bed to be re-suspended. This confirms earlier results reported by Fletcher and Pratt (1981), who mentioned that the majority of solids discharged from gully pots are due to a lack of sedimentation rather than re-suspension. As the top layer of the sediment bed is more unstable, these solids may be eroded (Pitt and Field, 2004). However, bed erosion decreases substantially as these particles are depleted and the bed becomes graded (Butler and Karuranatne, 1995). It should be noted that potential erosion may be significantly impacted by gully pot design.

Summary: TWP size fractions >80 µm may, to a certain extent, be trapped in common gully pots during normal rainfall events, and approximately 8% at 25 L/s. This requires that the gully pots are emptied when they are approximately 50% full of sediments.

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[55] The following is an excerpt from Post et al. (2016).

6.3 Fate of wear particles in wastewater treatment plants

6.3.1 Pathways for wear particles in the domestic sewer system

In urban areas with a combined sewer system, part of the road runoff may end up in the influent to the local wastewater treatment plant (WWTP), depending on the chosen strategy for managing stormwater in the area. In many places, stormwater may unintentionally end up in the combined sewer, due to misconnections or leaks. Hence, wear particles from treads, PMB and road markings may end up in the WWTPs (Kole et al. 2017, Magnusson 2014, Lassen et al. 2015). Further possible pathways through the sewer system are illustrated in **Figure 6.5**.

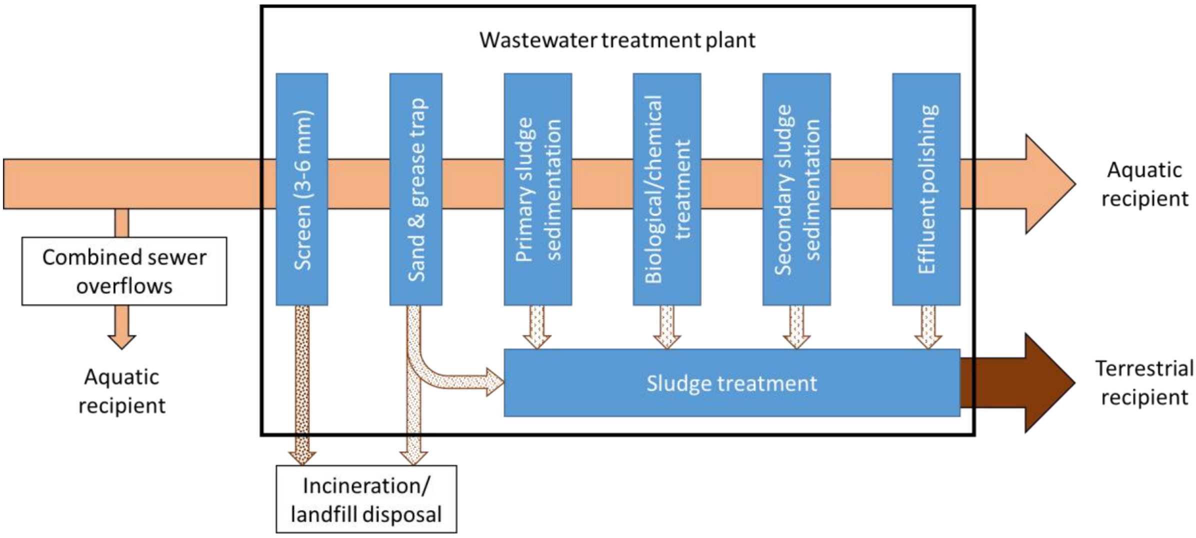

Figure 6.5 *Possible pathways through the sewer system to aquatic and terrestrial environments.*

6.3.2 Road dust-microplastics in the influent of Norwegian WWTPs

6.3.2.1 Findings in international studies

In recent years a number of studies have focused on WWTPs showing an abundance of microplastic from a wide variety of municipal sources (Murphy et al. 2015, Mahon et al. 2017, Michielssen et al. 2016, Vollertsen and Hansen 2016, Mintenig et al. 2016, Magnusson 2014, Magnusson and Wahlberg 2014, Dris 2016). However, for the majority of these studies, road dust-associated microplastics has not been the focus.

Verschoor et al. (2016) estimated that 2,300 tonnes of the 17,300 tonnes (i.e. 13%) of tread particles released annually in the Netherlands ended up the Dutch WWTPs, assuming that the combined sewer system receives 60% of all urban road runoff. Blok (2005) estimated that tyre tread accounted for 16% of all zinc in the final sludges from Dutch WWTPs. Sörme and Lagerkvist (2002) studied the contributions of heavy metals from different road-associated sources to the influent to Henriksdal WWTP in Stockholm, and found that tyre treads accounted for 920 kg zinc of the annual total load of 10,290 kg zinc (i.e. 9%). All of the above studies lean on assumptions more than direct measurements.

As far as we have been able to find, the best attempt to make an inventory of microplastics in the influent to WWTPs that also included microplastics in tyre tread, was conducted by Vollertsen and Hansen (2016). They sampled influent, effluent and sludge samples from 10 different WWTPs, covering 26% of all treated domestic wastewater in Denmark. They analysed for SBR rubber, which is the dominant rubber type in tyre treads of passenger cars (see **Table B1** in **Appendix B**), but found no SBR in any of the samples. They did a thorough investigation into the analytical aspects of the identification and quantification of tread particles, which is discussed in more detail in **Section 2.4.2**. However, since they were careful only to sample during dry weather conditions (maximum 3 mm rain for 48 h before and 24 h during sampling), it was expected that the concentrations of SBR would be rather low in the influent and effluent samples. However, it was somewhat more surprising that they did not find any SBR in any of the sludge samples. Since the sludge treatment typically lasts for 1-3 weeks, the final sludge will reflect other influent conditions if sampled at the same time as the influent, and they may also reflect a much longer time period due to the inherent equalisation during treatment.

The minimum size of particles that would be included in the study by Vollertsen and Hansen (2016), was 20 µm. Since the average volume size of the TWP is found to be in the range of 65-85 µm, they would be expected to be detected using the described analytical methodology. However, it is not known if the TWP may fragment to smaller bits when exposed to wastewater (probably not likely) or the conditions during sample preparation (see **Section 2.4.2**), which could make them below the minimum size of the applied methodology.

6.3.2.2 Estimated annual load of road-associated microplastics to Norwegian WWTPs

Any estimate of the annual load of road-associate microplastics to Norwegian WWTPs would be based on a long range of more or less questionable assumptions. The most important are summarised in **Table 6.1**. If using these, the total estimated loads of road-associated microplastics to Norwegian WWTPs would amount to 1020-1350 tonnes of tread rubber, 7 tonnes of polymers from PMB and 21-76 tonnes of road marking paints. It should be emphasised, as indicated in **Table 6.1**, that these estimates are highly speculative and should be interpreted with much caution.

In theory it would be possible to establish tyre tread load estimates to Norwegian WWTPs on regular measurements of zinc in samples (primarily of sludge) collected at the plants. However, as mentioned earlier, there are potentially a range of other and more dominating sources to zinc in domestic wastewater. We are not aware of any attempts to quantify TWP in influents (nor in effluent) at Norwegian WWTPs based on more appropriate TWP markers such as extractable organic zinc, the rubber polymer SBR, the benzothiazole 24MoBT and n-alkanes with more than 35 carbons (see **Section 2.5**). Lusher et al. (2017) included SBR in their FT-IR analysis of sludge samples from eight different WWTPs in Norway, but only two out of the 60 particles identified as microplastics where positively confirmed to be composed of SBR. One of these was a high-density particle (≤1.8 g/cm^3), while the other was a low-density particle (<1.0 g/cm^3).

Table 6.1 *A summary of factors and associated assumptions to estimate the influent load of road-associated microplastics to Norwegian WWTPs.*

Factor		**Assumptions**	**Level of confidence**
Total emissions from all sources	Rubber in tyre tread	4,300-5,700 tonnes	Relatively high
	Polymers in PMB	28 tonnes	Speculative
	Polymers in road marking paints	90-320 tonnes	Speculative
Fraction of emissions occurring in urban areas		45%[56]	Indicative
Fraction of emissions ending up in road runoff		$PM_{10\text{-}350}$: 40%[57] PM_{10}: 10%[58]	Indicative
Fraction of road runoff in urban areas that ends up in the combined sewer system		60%	Indicative
Fraction of the emissions in the combined sewer system that ends up in sewer overflows or leaks out		10%	Speculative

6.3.3 Fate of TWP in the wastewater treatment line of WWTPs

From the above discussions, it is apparent that there is not enough specific data on road-associated microplastics available to base any conclusions regarding expected fate and removal in WWTPs. However, based on the documented properties of TWP we may at least indicate what would be their fate.

Management of domestic wastewater in Norway differs to some extent from those applied in other Nordic and European countries. In that many plants have chemical treatment as their main treatment step, and some have only a mechanical treatment step. However, the largest WWTPs that discharges to sensitive freshwater recipients or to coastal water in the area from the Swedish border to the southern tip of Norway, apply more advanced treatment that include chemical-biological treatment steps. See **Figure 6.6**.

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[56] The emissions within the catchment area og Bekkelaget WWTP was estimated to 285 tonnes/year accumulating from an estimated 816 km of urban roads. For the 25 largest urban centres in Norway, accounting for approximately 50% of the Norwegian population, the approximate number of inhabitants per km urban road is 500 (varies between ca. 400 and 1000 innh./km). As a very rough estimate, it was assumed that the specific emissions by the average urban inhabitant in these urban areas equalled that within the catchment area of Bekkelaget WWTP.

[57] Sörme and Lagerkvist (2002) estimated that 40% of all tyre dust particles for Stockholm ended up n road runoff, while the remaining was released to soil. This distribution was deemed realistic for Danish urban areas by Lassen et al. (2015), and is also used here.

[58] Broeke et al. (2008) assumed that none of the airborne (PM_{10}) would end up in the road runoff. We argue that the typically wet conditions in Norway would, to a significant degree, contribute to deposit PM_{10} to the ground, assumingly 25% of that for the larger particles.

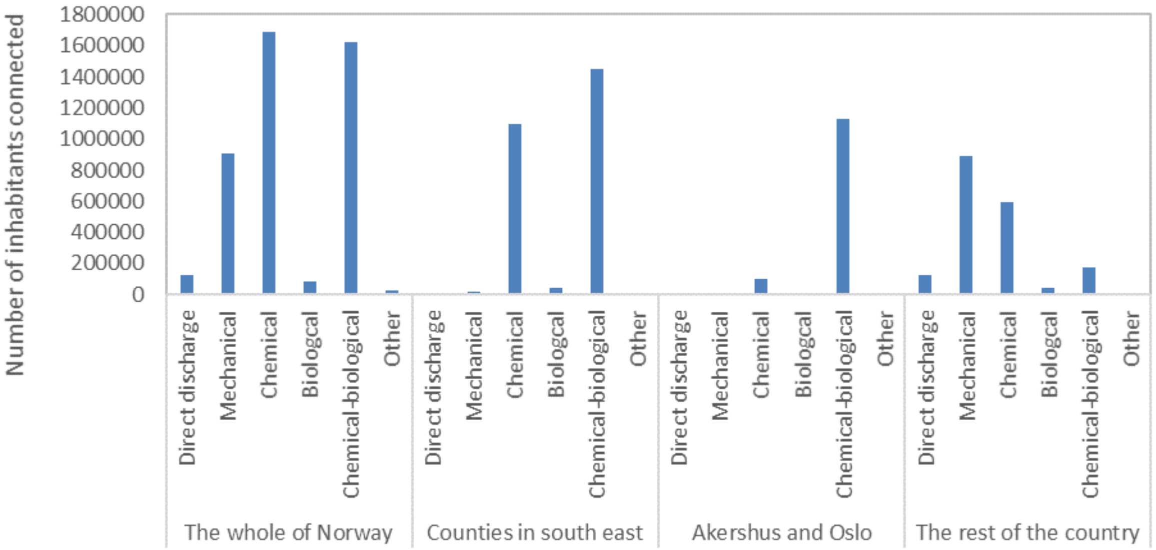

Figure 6.6 *Main treatment principle applied in different areas of Norway. Source: KOSTRA (SSB)*

The different treatment processes are designed for specific purposes, but may have effects on other things than their primary target. However, the expected removal may also be highly influenced on the operating conditions. This could be of particular concern with regards to the removal of road-associated microplastics, since these, as indicated in **Section 3.5.1**, may enter the treatment plants when the hydraulic load of the treatment plants could be much higher than normal. For instance, the biological treatment step usually has the lowest hydraulic capacity and the part of the wastewater that exceeds the capacity is bypassed to protect the biological processes. Some plants (e.g. VEAS and Bekkelaget WWTPs, Norway's two largest plants) have implemented an additional treatment step to treat the bypassed wastewater.

6.3.3.1 Mechanical treatment

All WWTPs apply some kind of mechanical treatment, either as the sole treatment step, or as a pre-treatment step to protect or avoid disturbance of subsequent treatment processes. Typically, the plants have a grid (3-6 mm between bars) to remove larger objects, and a sand and grease trap to remove fast-settling gravel, sand and floating matter. Many plastic items are removed by the grease trap (Murphy et al. 2015), but it is not likely that TWP would be caught by any of these processes.

Many plants have also implemented screens with variable pore sizes, but only the fine screens are expected to remove significant amounts of particles in the main size range of TWP (approximately 30-150 µm; ref. **Table 2.2**). In their report concerning criteria for dimensioning wastewater treatment processes, Ødegaard et al. (2009) suggest 40% removal of suspended solids by using fine screens with pore size of approximately 0.1 mm. Based on the observed particle size distribution of wastewater at a Swedish WWTP (Carlstedt and Stahre 1973), similar removal efficiency may be expected for TWP.
In many places, primary settling without any addition of coagulants to improve the settling behaviour of the particles. For relatively dense particles, such as TWP with an apparent density in the range of 1.7-2.1 g/cm^3, settling will be an efficient method to separate the particles from the water. The calculated settling velocities for such particles in freshwater during laminar flow (i.e. no turbulence) are shown in **Figure 6.7**. The grey dashed line shows the dimensioning surface load (Q_{dim}) of 1.6 m/h for primary settlers as sole treatment step (Ødegaard et al. 2009), indicating that

TWP particles >30-40 µm will be settling out at the dimensioning load. At the maximum dimensioning load (Q_{maxdim}) of 2.5 m/h (shown by the black dashed line) only TWP particles >40-50 µm can be expected to settle out. However, as indicated in **Table 2.2**, approximately 85% of the TWP volume is estimated to constitute of particles with size >50 µm and 93% >30 µm. It should, however, be emphasized that the apparent size distribution presented in **Table 2.2** is based on very limited data. Furthermore, the volumetric loading of the WWTPs when they receive TWP could be very high. This may also impact the flow pattern in the influent to the sedimentation basin, thereby disturbing the settling. This should, however, usually have been taken into account when dimensioning the basin (Ødegaard et al. 2009).

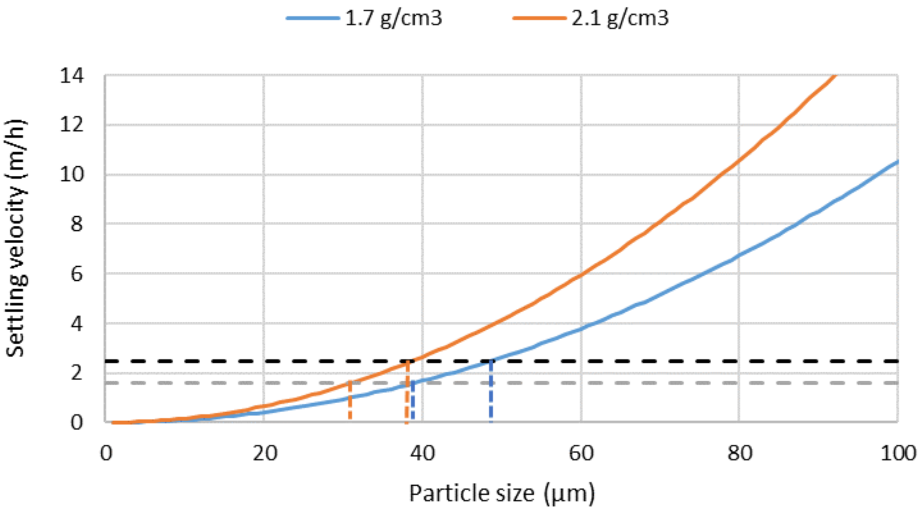

Figure 6.7 *Estimated settling* velocities *of TWP with density of 1.7 g/cm^3 or 2.1 g/cm^3 at 10°C in freshwater. The grey and black dashed lines indicate the dimensioning surface load of 1.6 m/h and the maximum dimensioning load of 2.5 m/h, respectively. The calculations for the settling* velocities *and associated assumptions are described in* ***Appendix J****.*

6.3.3.2 Chemical treatment

Chemical treatment is a very common treatment process at Norwegian WWTPs, either alone or combined with biological treatment (i.e. co-precipitation). In the coagulation process a chemical coagulant (usually iron or aluminium based) is added to precipitate dissolved compounds (e.g. phosphates and metals) and coagulate particulate matter (e.g. suspended solids and colloids). The precipitated and coagulated matter is flocculated to large flocs that are subsequently separated from the water by sedimentation or flotation. Polymers may also be added to improve the flocculation process. The surface properties of the particulate matter are of importance for the efficiency of the coagulation and flocculation process, but we have not found any literature regarding the surface properties of the TWP in this context. Nevertheless, TWP settles well, and Q_{dim} for the sedimentation step is even lower than for the primary sedimentation basin (1.0-1.3 m/h[59] compared to 1.6 g/h). But if flotation is used, the dense TWP will probably not be sufficiently lifted to the surface of the flotation tank (Q_{dim} is 5 m/h[60]) unless they are trapped with other lighter material.

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[59] Depending on the depth of the sedimentation basin.

[60] 5 m/h indicate that >50% of the TWP particles (>65-85 µm) may be settling faster, as can be read from the tentative settling curve in **Figure 6.7**.

6.3.3.3 Biological treatment

TWP have been shown to be very slowly biodegradable in soil (half-life of 16 months), hence, biodegradation may not be an important removal mechanism in WWTPs. However, the conditions in the biological steps of a WWTP are quite different than soil. Therefore, partial biodegradation should not be ruled out. It should be noted that nitrifying bacteria, which are key components at WWTPs applying biological nitrogen removal, have been shown to have the ability to biodegrade organic hazardous compounds not easily attacked by other bacteria[61]. As with chemical treatment, it's the separation step that will remove the TWP from the water. The Q_{dim} of sedimentation basins after biological treatment is in the same range as after chemical treatment, hence, the same considerations are valid here.

6.3.3.4 Effluent polishing

If applied, the effluent polishing step is usually implemented as a safeguard to reduce loss of flocs escaping the secondary sedimentation basin and residual biological oxygen demand (BOD), usually as a rapid sand filter. We do not have an overview of the number of Norwegian WWTPs which have implemented such a polishing step, but it is probably relatively few. The removal efficiency is dependent on the characteristics of the treated wastewater (e.g. size distribution and surface properties of the particles), volumetric loading and ageing of the filter, as well as type of sand use and grain size distribution. But typically, approximately 90% of 10 µm-particles are removed but only approximately 10% of 2 µm-particles are removed (Metcalf & Eddy 2003).

6.3.4 Fate of TWP in the sludge treatment line of WWTPs

As indicated above, all road-associated microplastics removed by the different wastewater treatment processes end up in the produced sludge at the WWTP. The sludge has to go through consecutive thickening, dewatering, stabilisation and hygienisation (**Figure 6.8**) before it can be used further (e.g. soil conditioning, **Figure 6.9**).

We have not found any data on the fate of TWP during sludge treatment, but studies on other microplastics in sludge treatment have indicated potential fragmentation, particularly during lime stabilisation due to the combination of high pH and mechanical mixing (Mahon et al. 2017, Cole et al. 2013, Zubris and Richards 2005). It is possible that also the TWP will fragment, but under other conditions, as they are by nature composite particles (see **Section 2.3.2**). Even if limited biodegradation of the road-associated microplastics may be expected, it should not be ruled out. The hydrolysis processes could be key in this regard, making the particles more prone to biodegradation in the subsequent anaerobic fermentation process. Some WWTPs utilise thermal hydrolysis, which could be of particular interest to study further.

Microplastic particles that enter the sludge line but are not degraded, will end up in the final sludge, which in Norway, in large degree is applied to agricultural land (**Figure 6.9**).

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[61] Even if nitrifying bacteria are autotrophic (i.e. utilise CO_2 instead of organic carbon for growth) they may play a key role in the biotransformation of pharmaceuticals in WWTPs. It has been shown that their enzyme ammonium monooxygenase, which is necessary for the oxidation of ammonium, is able to co-oxidize pharmaceuticals such as iopromide and trimethoprim (Batt et al. 2006).

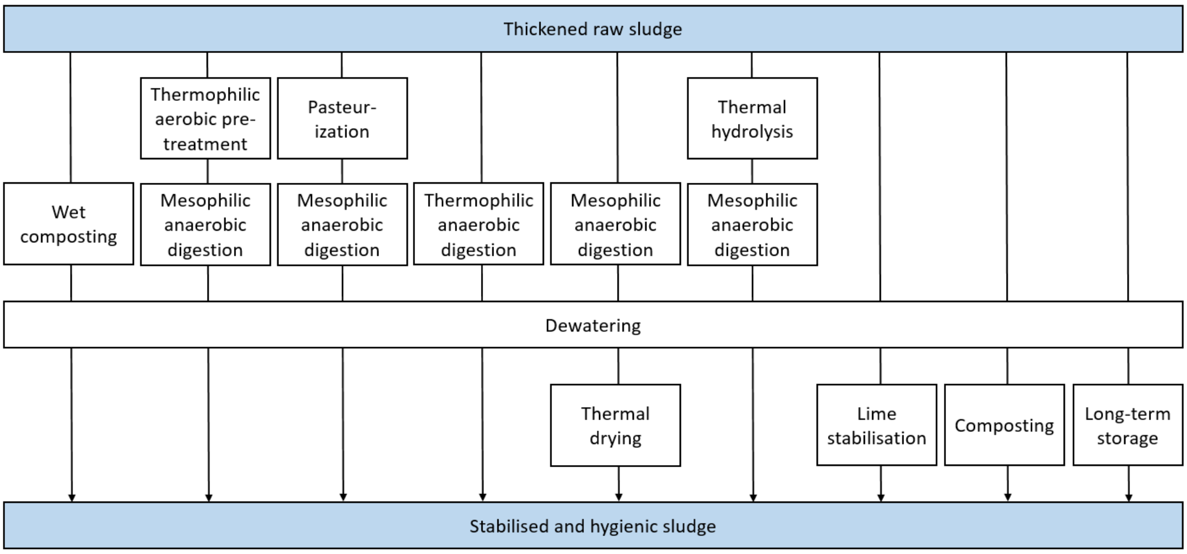

Figure 6.8 *Overview of sludge treatment processes. Adapted from Ødegaard et al. (2009).*

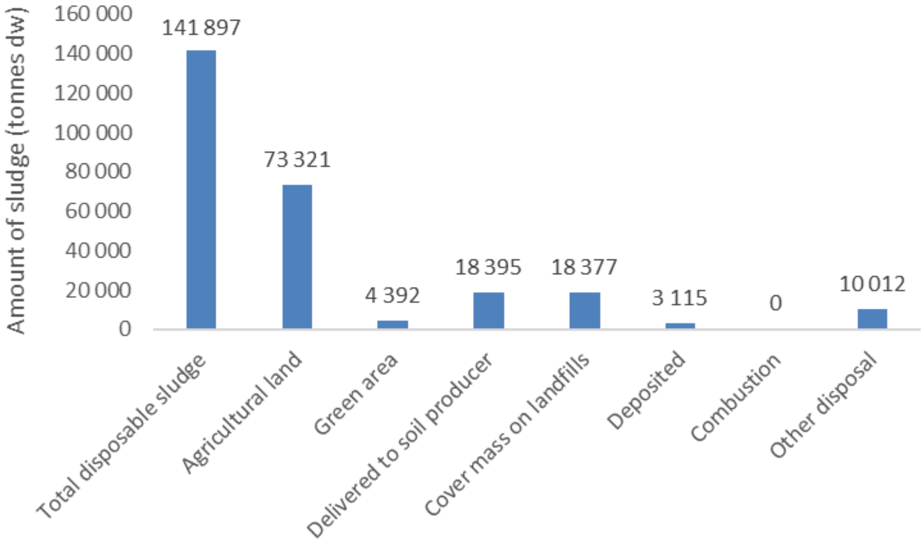

Figure 6.9 *Overview of the final application of sewage sludge in Norway in 2015. (Source: KOSTRA/SSB).*

6.4 Sustainable drainage systems

6.4.1 Design principles at a glance

City centres have developed infrastructures that tend to increase the fraction of surfaces impervious to water. The roads are only a part of this, in addition, sidewalks, roofs, carparks, squares and industrial sites are usually dominated by concrete pavement, metal, tar or other impervious material. However, this is now changing: municipalities see the many potential benefits from introducing more green and blue infrastructures to the urban environment (**Box 6.1**). Hence, when designing a system for managing road runoff in urban areas, it should be regarded as an integrated part of the general surface water management strategy for the surrounding area. This management strategy should include how to manage, treat and make best use of surface water, from where it falls to the point at which it is discharged into the receiving environment.

Box 6.1 *Potential benefits from using SuDS.*

The CIRIA SuDS Manual (Woods Ballard et al. (2015) lists the following potential benefits of SuDS:

- *Flood prevention*: Protecting people and property from increased flood risk resulting from the development.
- *Pollution prevention*: Protecting the quality of groundwater and surface waters from polluted runoff from the development.
- *Protecting natural flow regimes* (and thus the morphology and associated ecology) in rivers, lakes and streams.
- *Promoting biodiversity*: Supporting local natural habitats and associated ecosystems by encouraging greater biodiversity and linking habitats.
- *Improving soil moisture and replenishing depleted groundwater levels*.
- *Water supply*: Providing society with a valuable supply of water.
- *Beauty and tranquillity*: Creating attractive places where people want to live, work and play through the integration of water and green places with the built environment.
- *Urban cooling*: SuDS can be used to insulate buildings (green roofs), support natural ventilation (green walls and vertical gardens), provide shade (trees) and cool the air (water features).
- *Supporting education*: Improving people's understanding of how runoff from their development is being managed and used, and the benefits of more sustainable approaches.
- *Climate change adaptation*: Supporting the creating of developments that are more able to cope with changes in climate.
- *Cost-effectivity & carbon footprint*: Delivering cost-effective infrastructure that uses fewer natural resources and has a smaller whole-life carbon footprint than conventional drainage.

A key principle for the design of SuDS management trains is that rainwater should be managed as close as possible to where it falls:

- **Limit the total amount of runoff** by promoting evapotranspiration (e.g. green roofs, trees, vegetated storage systems), infiltration (e.g. soakaways, bioretention systems, infiltration basins) and rainwater harvesting and use[62].
- **Control peak runoff rates** by capturing and slowly releasing the water (e.g. swales, detention basins).

Some further key principles are worth mentioning (CVC AND TRCA 2010):

a) Important hydrologic features and functions in the natural landscape should be preserved to provide filtration, infiltration and flood management. These include stream buffers (also intermittent and ephemeral channels), areas of undisturbed soil and vegetation cover (i.e. avoid topsoil stripping and compaction), permeable soils as well as existing trees and tree clusters.

b) Reduce the impervious area by reducing e.g. street width, building footprint and parking footprint.

c) Use natural drainage systems by taking advantage of undisturbed vegetated areas and natural drainage patterns, thereby extending runoff flow paths and slow down flow to allow soil and vegetation to treat and retain it.

As is discussed in **Section 6.4.2**, many SuDS provide removal of particulate matter (and also dissolved pollutants). The four general pollution control measures to support the management of water quality in the receiving surface waters and groundwaters are presented in the CIRIA SuDS Manual (Woods Ballard et al. 2015):

1. *Pollution prevention*: Stopping contaminants becoming mixed with runoff, for example road sweeping, preventing misconnections, bunds for oil tanks, controlling sediment.
2. *Interception*: Preventing runoff (and the associated pollution load) from the majority of small rainfall events, for example through the use of pervious surfaces and vegetated collection systems. Interception helps facilitate the retention of pollutants in surface vegetation, soil or other material layers from where a proportion can often be degraded.
3. *Treatment*: Implementing SuDS components (in series where required) that use a range of treatment processes to reduce contaminant levels in the runoff to acceptable levels. Treatment components will often deliver Interception and usually also meet conveyance and storage requirements.
4. *Maintenance and remedial work*: Remove captured pollutants and maintain system performance.

It is, however, beyond the scope of this report to go into any detail on the design of SuDS management trains. Detailed guidance on how SuDS should be designed can be found in e.g. the CIRIA SuDS Manual (Woods Ballard et al. 2015 and www.susdrain.org), the CVC Low Impact Development Construction Guide (CVC 2012 and CVC and TRCA 2010), and, for the Norwegian readers, Lindholm et al. 2008).

6.4.2 SuDS and functional requirements

There are a number of SuDS components that will provide removal of particulate matter. Those we consider as most appropriate for treating runoff from road with up to medium traffic density (CVC

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[62] Harvested rainwater can be used for irrigating landscapes, private or communal gardens and allotments, car washing and toilet flushing.

and TRCA 2010) are shortly described in **Table 6.2**. Illustrations are provided in **Figure 6.10** (filter strips), **Figure 6.11** (dry swale), **Figure 6.12** (infiltration chamber) and (perforated pipe system). Also recommended use, functional requirements and space requirements are indicated. Soakaways may be applicable in urban areas (as described in **Section 5.3.1**). Other SuDS types, such as infiltration trenches, bioretention systems, raingardens and wet swales are not included as these are regarded as more appropriate to treat less polluted runoff (CVC and TRCA 2010). Permeable pavement is primarily used for low traffic roads, parking lots, driveways etc. and is therefore not included. Filter strips (also called vegetated buffer strips or grass strips) are included because they are recommended pre-treatment for the other SuDS components as well as they provide additional treatment.

SuDS of more ‘technical’ nature are described in **Section 6.5**.

6.4.3 Expected treatment effects

All the mentioned SuDS are infiltration systems. If a practice infiltrates and evaporates 100% of the runoff from a site, then there is essentially no pollution leaving the site in surface runoff. Hence, the same considerations noted with infiltration basins are valid here; the system’s capacity to store and infiltrate runoff before the next stormwater event decides the treatment effect. Neither dry swales, infiltration chambers nor perforated pipe systems are directly mentioned in the latest summary from the International Stormwater BMP Database provided by WE&RF (2017), but the bioretention category is probably the most relevant to look at. The reported average effluent concentrations of TSS from the 25 facilities included are 10.0 mg/l (with 8.0-10.0 mg/l 95% confidence interval) and an average removal of TSS of 75%[63]. As noted earlier; the New Jersey Stormwater BMP Manual (NJDEP 2004) assume 80% TSS removal for all infiltration systems.

Filter strips (i.e. biofilter – grass strip) are included in the International Stormwater BMP Database, and the reported effluent of TSS from the 19 facilities included are 19.0 mg/l (with 15.5-21.0 mg/l 95% confidence interval) and an average removal of TSS of 57%.

As for infiltration basins (**Section 5.3.1**), winter conditions are challenging as the top soil may freeze. However, perforated pipe systems and soakaways will provide good infiltration if the infiltration zone is situated below the freeze zone (CVC and TRCA 2010).

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[63] Average difference between all influent concentrations and all effluent concentration; $(C_0\text{-}C_{effl}) \cdot 100\%/ C_0$.

Table 6.2 *Description of SuDS appropriate to treat runoff from roads with up to moderate traffic density (CVC and TRCA 2010, Woods Ballard et al. 2015).*

SuDS	Description	Functional requirements	Space requirements
Filter strips (pre-treatment)	Gently sloping, densely vegetated areas that treat runoff as sheet flow from the road. Slows down runoff velocity and filter out suspended sediment, and providing some infiltration into underlying soils.	• Strip slope 1-5% • >1 m to seasonal high groundwater • <25 m max. flow path length across the road	• >5 m width
Dry swales	Vegetated conveyance channel that includes a filter with engineered soil that overlays a (optimal) perforated pipe underdrain that provide additional treatment and conveyance capacity beneath the base of the swale. Åstebøl (2007) do not recommend the use of geotextile to separate different soil types in the swale. Vegetation or aggregate material on the surface of the swale slows the runoff water to allow sedimentation, filtration through the root zone and engineered soil bed, evapotranspiration, and infiltration into the underlying native soil. To prevent infiltration, or where groundwater levels are high, a liner could be introduced at the base.	• Longitudinal slopes 0.5-4% • Side slopes ≤3:1 (horisontal:vertical) • >1 m to seasonal high groundwater • May be located over any soil type, but where infiltration rates are <15 mm/h, an underdrain is required. • Pre-treatment required; e.g. filter strip and/or sedimentation forebay. • Typically treat drainage areas <2 ha.	• Footprint ca. 5-15% of contributing drainage area (5:1-15:1).
Infiltration chambers	Include a range of proprietary manufactured modular structures installed underground, typically under parking or landscaped areas that create large void spaces for temporary storage of stormwater runoff and allow it to infiltrate into the underlying native soil. Structures typically have open bottoms, perforated side walls and optional underlying granular stone reservoirs.	• Natural slopes <15% • >1 m to seasonal high groundwater • May be located over any soil type • Pre-treatment required; e.g. filter strip or dry swale.	• Footprint ca. 10-20% of contributing drainage area (5:1-10:1)
Perforated pipe system	Perforated pipes installed in gently sloping granular stone beds that are lined with geotextile fabric that allow infiltration of runoff into the gravel bed and underlying native soil while it is being conveyed from source areas or other BMPs to an end-of-pipe facility or receiving waterbody.	• In place of conventional storm sewer pipes, where topography, water table depth, and runoff quality conditions are suitable. • Natural slopes <15% • Gravel bed slopes 0.5-1% • >1 m to seasonal high groundwater	• Little or no surface footprint

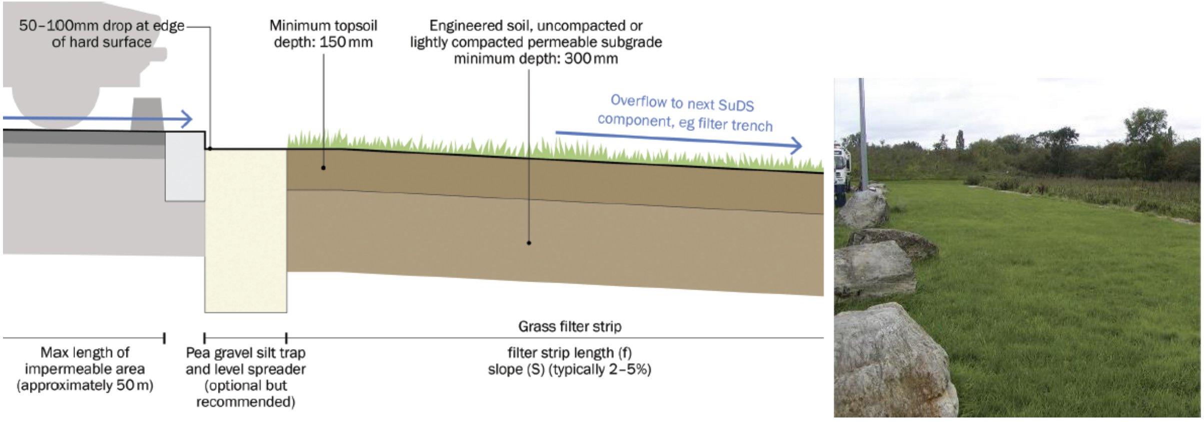

Figure 6.10 *Schematic design of a* ***filter strip*** *(Woods Ballard et al. 2015 with courtesy of CIRIA; photo: Illman Young with courtesy of CIRIA).*

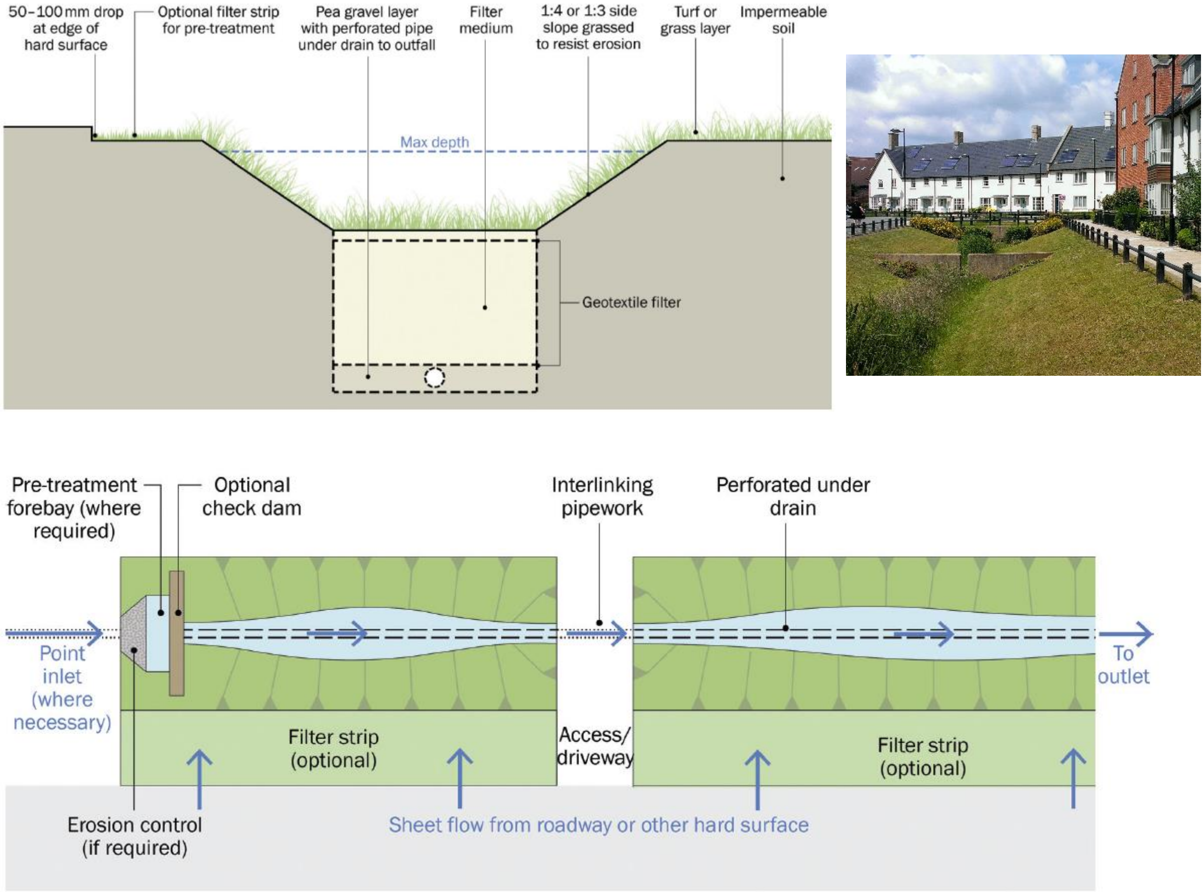

Figure 6.11 *Schematic design of a* ***dry swale*** *in profile (upper) and plan view (below) (Woods Ballard et al. 2015 with courtesy of CIRIA; photo: Peterborough City Council).*

Figure 6.12 *Schematic design of an* ***infiltration chamber system*** *below a parking lot (CVC and TRCA 2010)*

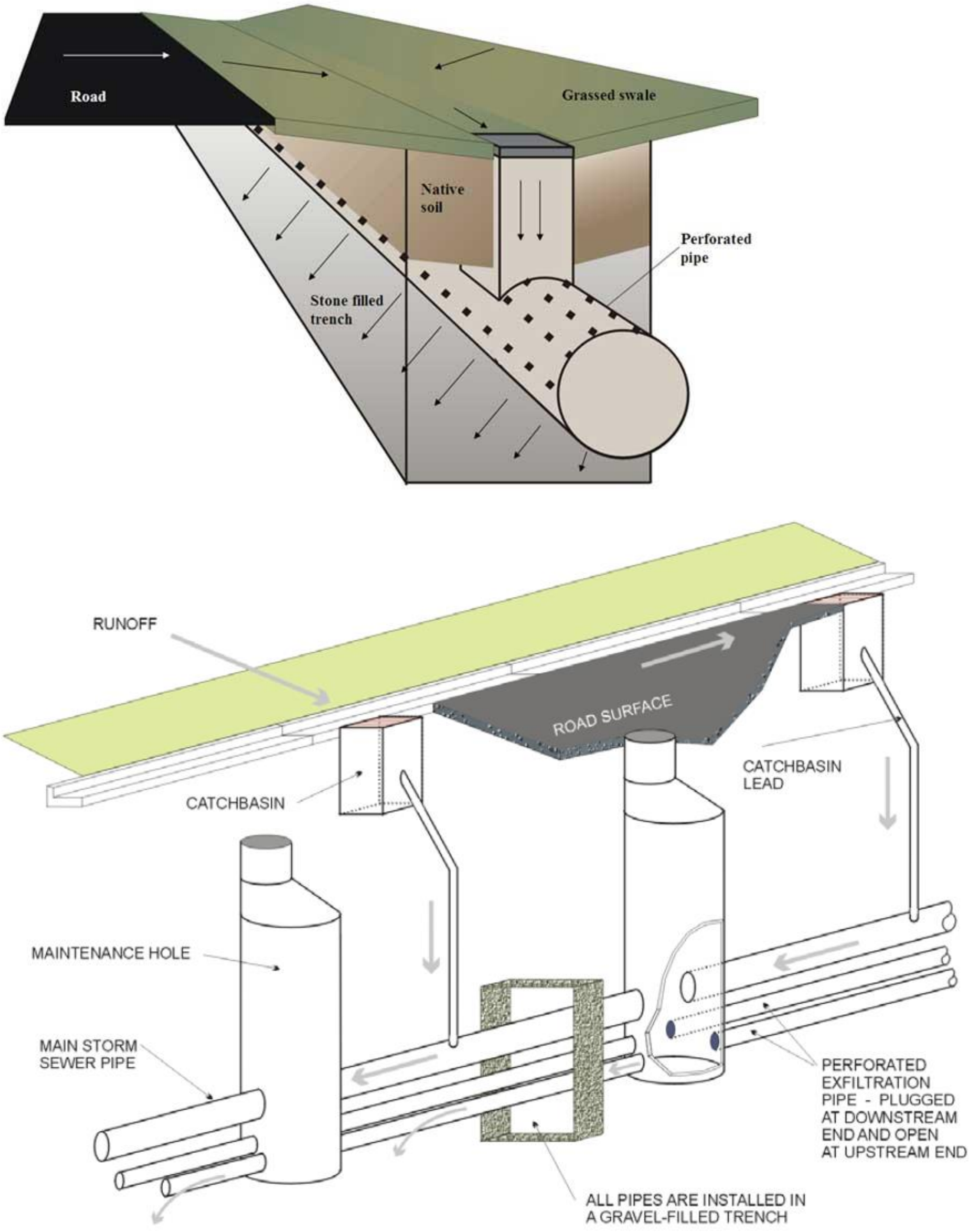

Figure 6.13 *Schematic design of* ***perforated pipe systems****.* ***Above****: An illustration of a system used in Ottawa with a grass swale as pre-treatment.* ***Below****: A perforated pipe system connected to catchbasins in Toronto; runoff from catchbasins enters the systems by way of catchbasin leads connected to the sewer pipes or maintenance holes in the conventional manner. At each maintenance hole, runoff enters the perforated pipes to be distributed into the gravel bed from where it exfiltrates into the soil. If the volume or rate of runoff exceeds the exfiltration capacity of the system, the water level in each maintenance hole increases to the point at which the excess flow 'overflows' to the conventional sewer pipes. (Illustrations: CVC and TRCA 2010).*

6.4.4 Maintenance needs and roughly estimated costs

Filter strips:

Maintenance requirements for filter strips typically involve a low level of activity after vegetation becomes established. Routine inspection is important to ensure that dense vegetation cover is maintained and inflowing runoff does not become concentrated and short circuit the practice. Vehicles should not be parked or driven on filter strips. For routine mowing of grassed filter strips, the lightest possible mowing equipment should be used to prevent soil compaction (CVC and TRCA 2010).
Costs: The previous version of the CIRIA SuDS Manual (Woods Woods-Ballard et al. 2007) indicated a capital cost for filter strips in the range of £2-4 per m^2 filter strip area, and an annual operating cost related to regular maintenance of £0.10 per m^2 of filter surface area.

Dry swales:

Maintenance of dry swales mostly involves maintenance of the vegetative cover as well as periodic inspection for less frequent maintenance needs. Inspections annually and after every major storm event (> 25 mm), will determine whether corrective action is necessary to address gradual deterioration or abnormal conditions (CVC and TRCA 2010).
Costs: The indicated capital cost for swales were £10-15 per m^2 filter strip area, and an annual operating cost related to regular maintenance of £0.10 per m^2 of filter surface area (Woods-Ballard et al. 2007).

Infiltration chambers:

Maintenance typically consists of cleaning out leaves, debris and accumulated sediment caught in pre-treatment devices annually or as needed. Inspection via manholes should be performed to ensure the facility drains within the maximum acceptable length of time (typically 72 hours) at least annually and following every major storm event (>25 mm) (CVC and TRCA 2010).
Costs: We have not been able to retrieve any information on capital or operation cost estimates for infiltration chambers.

Perforated pipe systems:

Maintenance: As for infiltration chambers. With proper location and adequate pre-treatment, perforated pipe systems can continue to function effectively with very low levels of maintenance activities (Saborin et al. 2008).
Costs: We have not been able to retrieve any information on capital or operation cost estimates for perforated pipe systems.

6.5 Compact technical treatment units

Where sites are constrained or surface systems are precluded for other reasons (e.g. when retrofitting existing sites), and where local infiltration is unacceptable, the use of subsurface proprietary systems tends to become more cost efficient. There are a large variety of such treatment units designed to remove, among other pollutants, particulate matter from stormwater. The following categories may be used, based on the main mechanism for separation of the particulate matter:

- Units based on centripetal force-enhanced settling
- Units based on gravitational settling
- Units based on chemically enhanced settling
- Units based on filtration

Depending on the component and final treatment target, they may deliver pre-treatment quality water or final water quality for direct discharge to the local aquatic recipient.

6.5.1 Functional descriptions at a glance

Centripetal force-enhanced settling units

This type of units is completely dominated by the large variety of swirl/vortex separators. These are vault structures with a gravity separation unit in which the water moves in a circular manner from the inlet to the outlet, thus facilitating the sediment removal process within a small space. The centrifugal forces created by the circular motion cause suspended particles to move to the centre of the device. The flow velocity here are lower and they settle down to a sump at the bottom. The typical flow pattern is illustrated in **Figure 6.14**. A wide range of devices exist that include internal components that provide isolated zones for captured sediments to prevent resuspension and washout under peak conditions (**Figure 6.14**).

Gravitational settling units

Closed wet basins (**Figure 6.15**) function as the wet pond described in **Section 5.2.1**, but their footprint has been made somewhat smaller by using vertical walls. They can also be tube structures (**Figure 6.15**) or channel structures. Lamella basins (**Figure 6.15**) include slanted lamellae in the sedimentation basin to increase the surface settling area.

Oil and grit separators are not included here as they are primarily designed to remove particles >250 µm (Woods Ballard et al. 2015) and are therefore not relevant.

Chemically enhanced settling units

Worth mentioning here is ballasted flocculation (**Figure 6.16**), which increases the particle formation by coagulation (using iron or aluminium based coagulants) and flocculation (using polymer) while also creating good conditions for rapid settling by adding microsand (0.1-0.3 mm grain size) prior to settling in a lamellar separator. The settled sludge and microsand is separated in a hydrocyclone, returning the microsand to the flocculation unit and sludge to e.g. the main sewer.

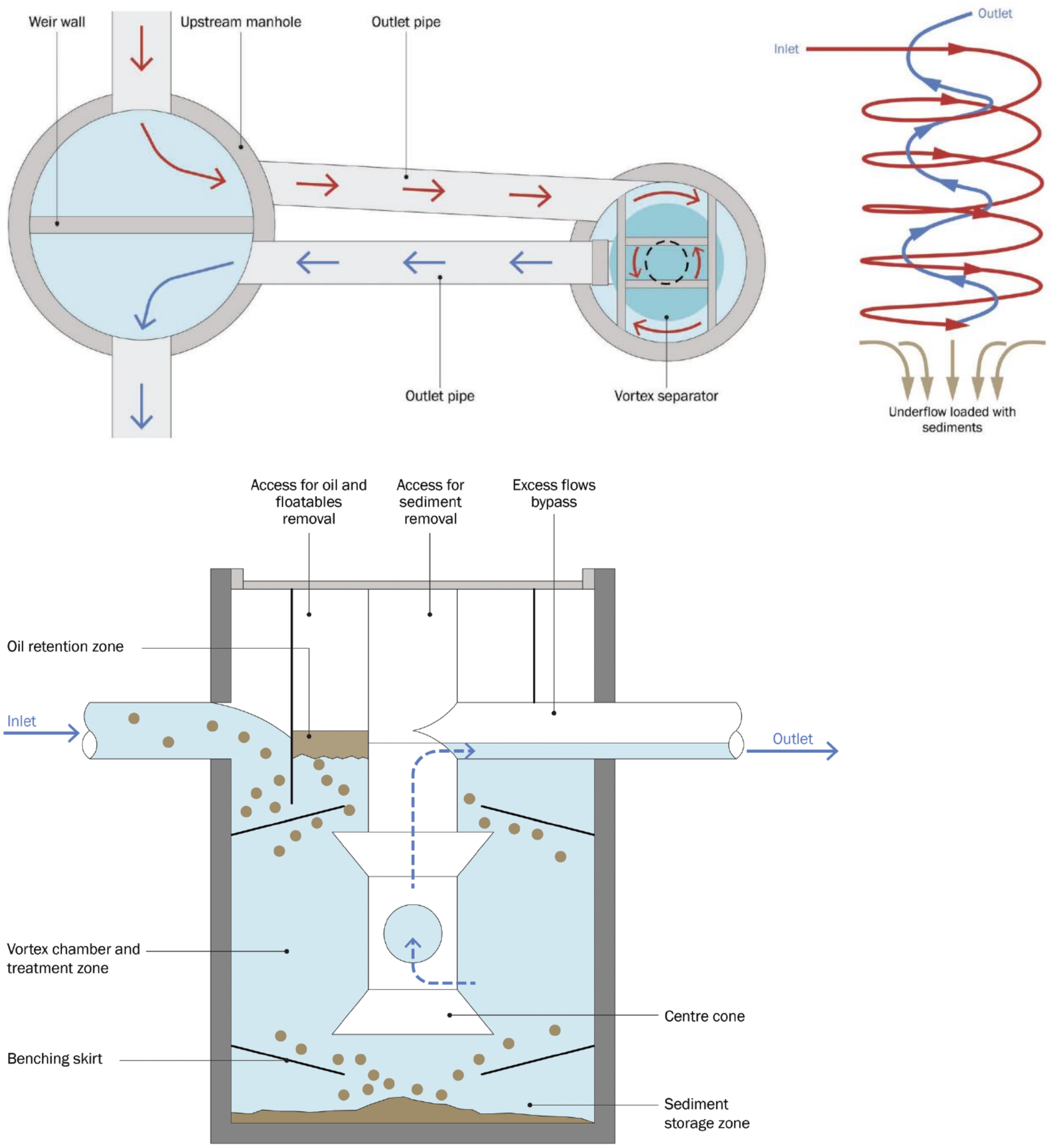

Figure 6.14 ***Centripetal force-enhanced settling units****.* ***Upper left****: Schematic of a hydrodynamic separator with a separate external bypass (Woods Ballard et al. 2015 with courtesy of CIRIA).* ***Upper right****: Simplified flow pattern in a vortex separator (NJCAT 2005).* ***Bottom****: Schematic of an advanced vortex separator with internal components that provide isolated zones for captured sediments to prevent resuspension and washout under peak conditions (Woods Ballard et al. 2015 with courtesy of CIRIA).*

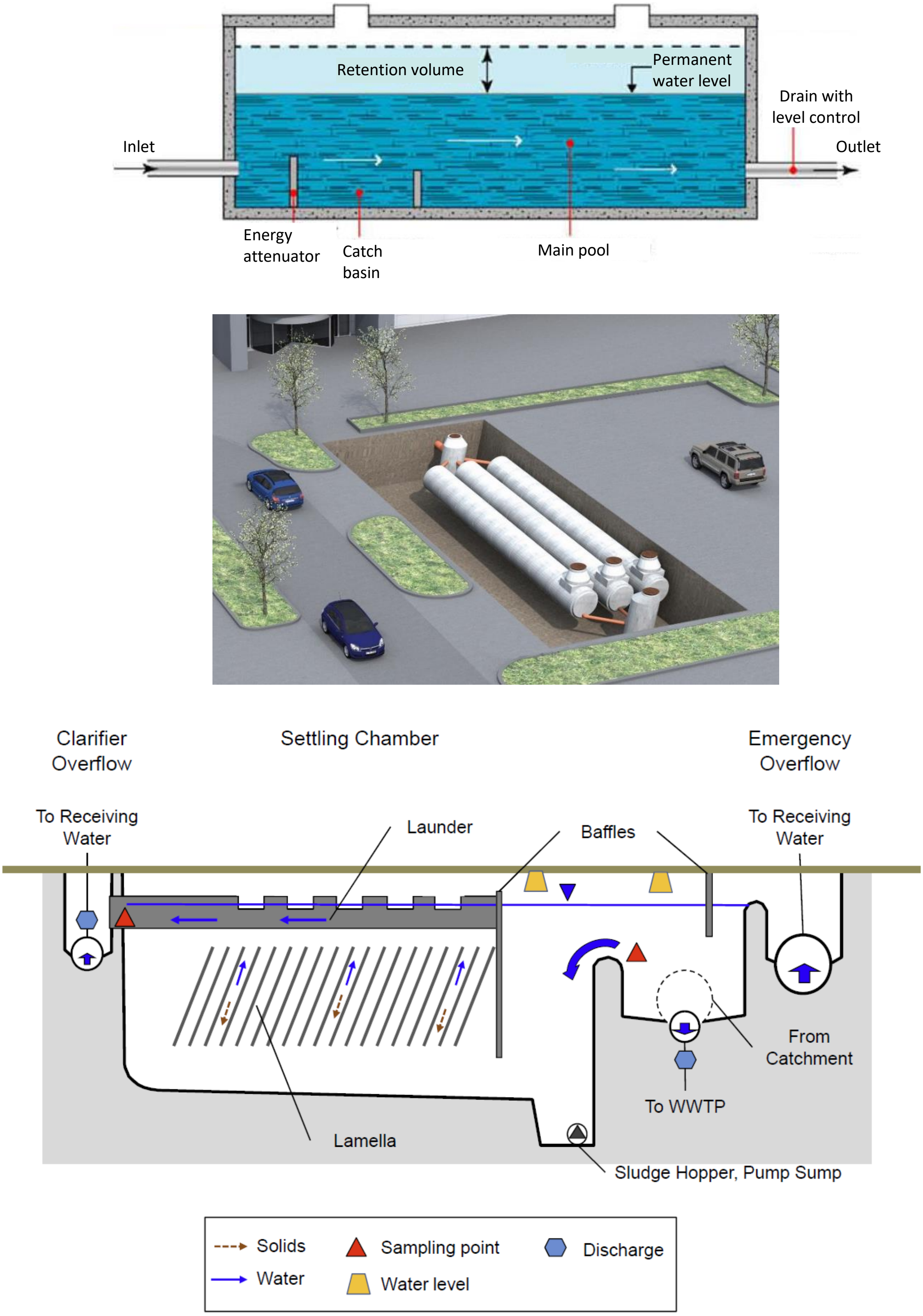

Figure 6.15. ***Gravitational settling units***. ***Upper***: *Schematic of a closed wet basin (translated from Åstebøl (2007).* ***Middle***: *A closed settling tube system (Courtesy of Basal).* ***Bottom***: *Schematic of a lamella settler treating stormwater runoff with discharge of settled sediments to central WWTP and treated water to the aquatic environment (reproduced from Fuchs et al. 2014 with permission from the copyright holders, IWA Publishing).*

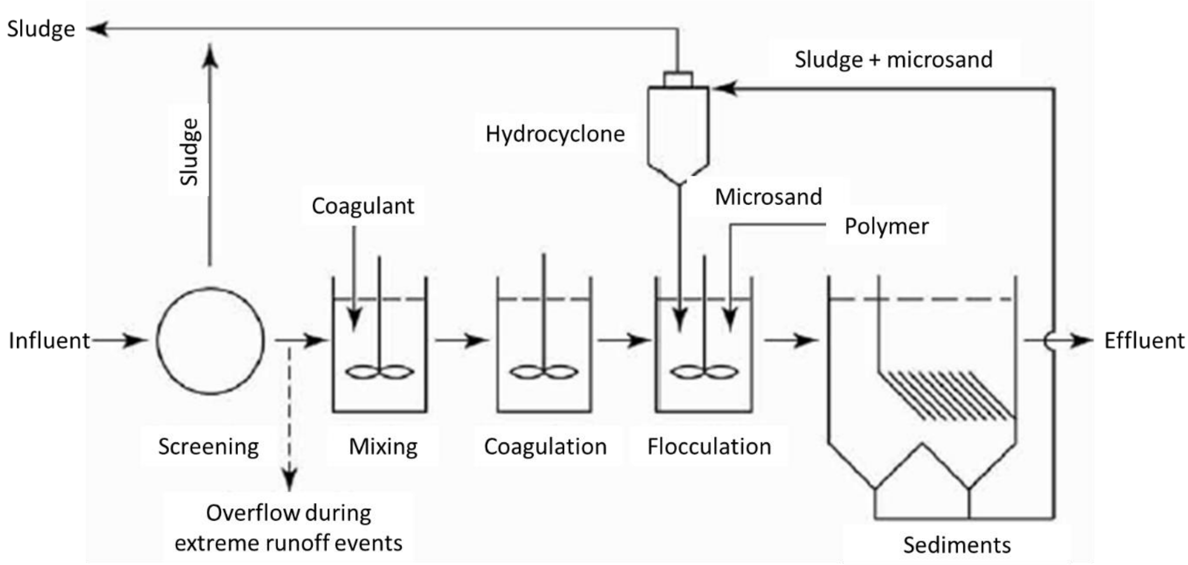

Figure 6.16 ***Chemically enhanced settling units***. *Schematic drawing of a version of the ballast flocculation process (translated to English from Åstebøl 2007).*

Filtration units

These are up-flow or down-flow filtration systems typically using cartridge filters (**Figure 6.17**) with a wide array of filter media including leaf compost, pleated fabric, cellulose, active carbon, perlite, amended sand and perlite and zeolite. They can be connected to the drainage network in a manhole or vault. Hollow fibre membranes have also been used (**Figure 6.17**). Media filters (**Figure 6.18**) are depth filters with an active media. The media can be mineral-based (e.g. sand, olivine, aluminium silicate, calcite, zeolite and filtralite), or organic based (e.g. peat and bark) (Åstebøl 2007, Ilyas et al. 2017). Some of the filter systems discharge directly to the local aquatic recipient, while others infiltrate in native soil, where possible[64]. They can be pre-fabricated standard units or custom-made to suit site conditions. They all require pre-treatment to remove coarse particles, typically using a vortex separator. Maintenance involves emptying sediment traps and changing filter media cartridges.

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[64] Where the native soil allows it and potential groundwater interests allow it.

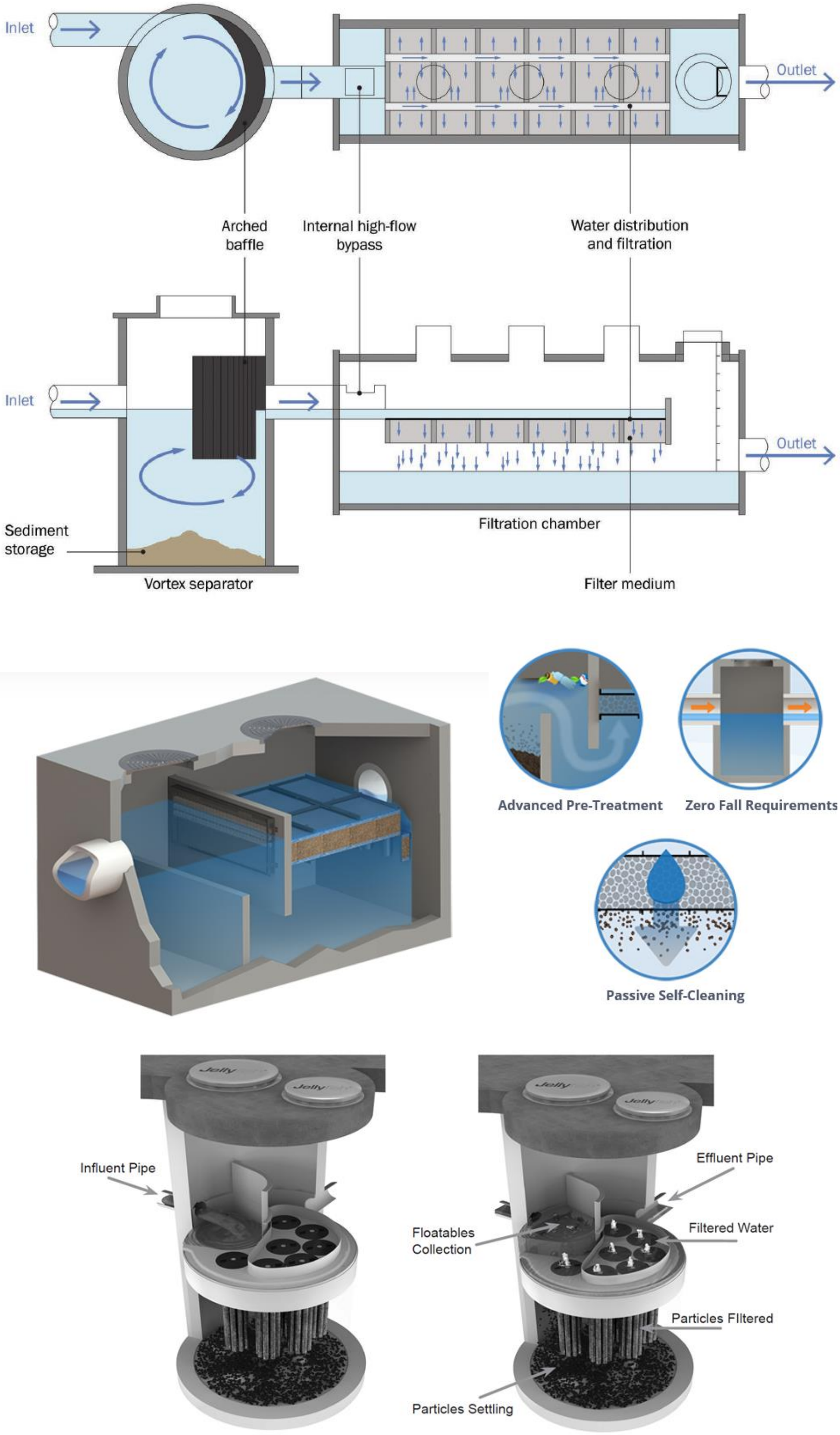

Figure 6.17 ***Units based on filtration***: ***Top***: *Vortex-separated runoff enters a down-flow cartridge filter system; from above (uppermost) and in profile (below) (Woods Ballard et al. 2015 with courtesy of CIRIA).* ***Middle***: *An up-flow cartridge filter (Courtesy of Bio Clean).* ***Bottom***: *Example of a hollow fibre membrane cartridge filtration system (Courtesy of Contech ES).*

Figure 6.18 ***Units based on filtration****: A pre-sedimentation catchbasin (in front) and a down-flow media filter treating first flush (15 min, one-year return period) in Austria (Photo: Courtesy of ASFINAG).*

6.5.2 Expected treatment effects

As mentioned, in urban areas with confined space for treatment, the treatment solutions may be dimensioned so that only the first flush is treated (see **Section 6.1.2**). Hence, any runoff that is bypassed will not be treated and should be taken into account in the overall pollution budget. It is important that the proprietary systems are designed so that flows from larger rainfall events can be managed by the units without significant resuspension of sediments or other pollutants. If not, then larger flows will need to be diverted around the systems.

There appears to be a growing market for these types of treatment solutions, and many new designs are released. Many of the claims that are provided by the manufacturers are based on laboratory testing under controlled conditions, showing very good TSS removal. Field tests tends to be as variable as more traditional SuDS such as swales or basins, probably due to the many factors influencing the results; e.g. characteristics of the pollutants, influent concentrations, inflow rates and maintenance history (Woods Ballard et al. 2015). It is therefore important that the manufacturer of a device provide evidence to support any performance claims. It is also highly recommended that (adapted from Woods Ballard et al. 2015):

- Tests are following available standardised tests applicable to the type of treatment unit or system to be tested.
- Both laboratory and field tests are included.
- All testing is undertaken by organisations that are independent of the manufacturer.
- Testing is conducted over a representative range of rainfall events that are applicable to the design and operation of the system.
- Laboratory tests should use particle sizes that are representative of the range of sizes likely to be present in sediment in runoff, with particular focus on those <63 µm. The density and grading of tested particles should be clearly stated.
- Measurements of particle size distribution should be included in any sampling and analysis programme.
- Flow-proportional sampling is required during field test, taking also bypass flows and resuspension into account

- A sufficient number of storms should be sampled to cover a wide a range as possible of operating conditions to which the device will be subjected.
- The treatment performance should be analysed by considering the total load of pollution.
- Storms should be sampled sequentially, to allow for a mass-balance evaluation.

There are already internationally available standard tests (e.g.):

- UK: http://www.britishwater.co.uk/Publications/manufactured-treatment-devices.aspx
- New Jersey Corporation for Advanced Technology (NJCAT) Program: http://www.state.nj.us/dep/dsr/bscit/FinalVer_Hydro.pdf
- Washington State: https://fortress.wa.gov/ecy/publications/documents/1110061.pdf

Proprietary systems that have passed the criteria set by Department of Environmental Quality in Virginia is listed on the Virginia Stormwater BMP Clearinghouse Virginia website: http://www.vwrrc.vt.edu/swc/ProprietaryBMPs.html

Indicative removal efficiencies for the four proprietary treatment system categories are given in the following.

Centripetal force-enhanced settling units

It has been stated that the practical lower limit of vortex separators is a particle with a settling velocity of 0.10-0.14 cm/s (3.6-5.0 m/h) (CASQA 2003). At 10°C and in freshwater, this indicates that vortex separators may be able to, at least partially, remove TWP that are larger than 60-70 µm in size if they have a density of 1.7 g/cm^3[65]. For TWP with a density of 2.1 g/cm^3, the size range limit will be 45-55 µm. As discussed in **Section 2.3.2**, approximately 50 volume% of the released TWP is larger than 65-85 µm and approximately 85% of TWP is larger than 50 µm. This indicates that vortex separators may be an efficient method to remove the coarser part of TWP. However, head loss and turbulence caused by internal structures in the vortex chamber, may significantly impact the retention of particles smaller than approximately 150 µm (CASQA 2003). According to Tchobanoglous et al. (2003), vortex separators typically remove 95% of 300 µm particles, 85% of 240 µm particles and 65% of 150 µm particles.

Many of the commercially available vortex separators have been officially approved for use for stormwater treatment in different states in the US, and they have typically passed the 50% TSS removal threshold. Most of these tests have been conducted under controlled conditions in the laboratory, but field tests have documented in excess of 80% removal of TSS (CASQA 2003). However, the average difference between all influents and effluents at the 22 "vortex separator-like[66]" facilities that have reported to the International Stormwater BMP Database indicate a mere 12% removal of TSS, but the low average influent TSS concentration (33.6 mg/l) to these facilities may explain the observed apparent poor removal efficiency (Leisenring et al. 2012). The average effluent concentration from these facilities was 29.7 mg/l.

In summary, vortex separators may remove as much as in excess of 50% of TSS (and hence also TWP) under optimum conditions, but the actual result is also highly dependent on the influent (type and concentration of TSS, flow conditions etc.) and structural details of the unit.

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[65] This size range was found from **Figure 6.7** by cross-reading the settling velocity (m/h) on the y axis with particle size on the x axis for TWP with a density of 1.7 g/cm^3. The numbers can also be calculated using Equation J1 in Appendix J.

[66] The category is called "gravitational settling with hydrodynamic devices".

Gravitational settling units

The dimensioning principles behind the closed wet basin and sedimentation tube system are similar to that of the wet pond (see **Section 5.2.2**). As discussed there, the removal of particulate matter is determined by the residence time and the flow pattern during settling together with the particle characteristics (size distribution, particle density) and the temperature and salinity of the water. In areas with confined space, the unit will probably only treat the 'first flush', and if dimensioned properly, similar removal efficiencies as observed with the wet pond can be expected (approximately 80% TSS removal). The lamella settler improves the settling and a somewhat smaller sedimentation tank can be used to.

Chemically enhanced settling units

Åstebøl and Hvitved-Jacobsen (2014) report 70-90% removal of TSS with ballasted flocculation. This process is used at the stormwater treatment facility at VEAS WWTP, and they have reported 88.5% removal of total phosphorous when treating diluted combined sewage, indicating even higher removal of TSS (VEAS 2016).

Filtration units

Treatment performance provided by manufacturers and usually tested under laboratory controlled conditions typically show above 80% removal of TSS, sometimes almost 100%[67]. The seven filtration facilities (cartridge filters, vertical bed filters etc.) that have reported to the International Stormwater BMP Database indicate 56% removal of TSS (Leisenring et al. 2012). The average effluent concentration from these facilities was 14.2 mg/l (with a 95% confidence interval of 10.0 - 15.0 mg/l).

6.5.3 Maintenance

Proprietary treatment systems will require routine maintenance to ensure continuing operation to design performance standards. The manufacturers should provide detailed specifications and frequencies for the required maintenance activities along with likely machinery requirements and typical annual costs for any given site (Woods Ballard et al. (2015). Access to the device for maintenance purposes is important and should play a role in siting.

To determine the necessary sediment removal frequency, subsurface treatment units should be visually inspected to give the operator an idea of the expected rate of sediment and oil deposition.

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[67] See filtering manufactured devices on the list of proprietary systems that have passed the Virginia Stormwater BMP Clearinghouse test criteria: http://www.vwrrc.vt.edu/swc/ProprietaryBMPs.html

7 Treatment of tunnel wash water

Norway has approximately 1100 road tunnels with a combined length close to 800 km. The tunnels are routinely washed to maintain the construction and safety of road tunnels. The frequency of tunnel washes depends on the specific tunnel's size and traffic load, and Norwegian tunnels are usually washed two to twelve times per year (Meland 2012). Three types of washing are performed; technical wash, half-wash and full wash. During technical wash, technical gear and traffic signs are washed. In half-wash tunnel walls and road pavement are washed while in full-wash the entire tunnel surface including technical gear/infrastructure and traffic sign are washed. Water consumption during tunnel wash varies with respect to the equipment used and the type of wash routine executed. Typical water consumption can be from 60 L to 140 L for each meter of tunnel washed, potentially generating around 60 to 140 m^3 polluted water during the cleaning of a 1-km tunnel (Meland 2012). Tunnel wash water from a full-wash has a larger volume and is normally more polluted than tunnel wash water from a half-wash. Technical wash involves relatively low volumes of tunnel wash water compared to the two latter. Although tunnels represent a small amount of the total road network, these represent hot-spots in terms of polluted runoff water because the pollutants accumulate over longer periods (time between washing events may span over weeks, months or even years) and are not very affected by weather conditions such as wind and precipitation. TSS concentrations up to 31 000 mg/l have been observed (Meland and Rødland 2018). As of today, very few of these tunnels have systems for treatment of wash water.

7.1 Existing solutions

Tunnel wash water is normally treated using sedimentation basins and/or ponds. Many countries such as Switzerland and Germany often use indirect or direct discharge of tunnel wash water into existing nearby wastewater treatment plants. Application of this solution is influenced by capacity of the wastewater treatment plant as well as local discharge requirement. An example of such approach is applied in Sweden (Mroz et al 2008) where the tunnel wash water is collected by the washing vehicle and transferred to the WWTP where it is treated by sedimentation, mechanical sieving, chemical precipitation and oil skimmer (if high amount of oil is detected). Several investigations have been performed on testing treatment technologies for treatment of tunnel wash water. Most of these studies were carried out in laboratory scale and typical tested technologies includes: sedimentation, chemical precipitation (coagulation/flocculation followed by sedimentation), membrane filtration and adsorption with organic and inorganic adsorbents (Garshol et al. 2015, Nersten 2016, Vik et al. 2016).

7.2 Reported particle removal efficiency – lab investigations

Extensive laboratory testing of different treatment technologies for cleaning of tunnel wash water was performed by Garshol et al. (2015). Tunnel wash water during both summer and winter wash was collected from Nordby tunnel and different techniques such as sedimentation, biological treatment, chemical precipitation as well as filtration and adsorption were applied. **Table 7.1** summarizes the reported TSS values after sedimentation and biological treatment. The best results were achieved after 4 weeks of sedimentation under anaerobic condition for both summer and winter samples.

Table 7.1 *Effect of sedimentation and biodegradation on TSS of tunnel wash water (Garshol et al. 2015).*

Water quality	TSS (mg/l)	TSS removal (%)
Wash water – summer	544	
1-week sedimentation at 20°C	72	87
1-week sedimentation at 4°C	81	85
4-weeks aerobic biodegradation at 20°C	40	93
4-weeks anaerobic biodegradation at 20°C	18	97
Wash water – winter	28,000	
4-weeks anaerobic biodegradation at 15°C	21	~100
4-weeks anaerobic biodegradation at 4°C	20	~100

The variation in particle size distribution was only reported for summer wash water sample, before and after sedimentation (see **Figure 7.1**). After 24-hours sedimentation, the median particle size (d_{50}) was 4 µm at 20°C and 8 µm at 4°C, respectively. It should be noted that studies show that the presence of detergents (used during washing procedure) in the tunnel wash water can increase the mobilization of heavy metals associated with small particles during sedimentation (Aasum 2013). Sedimentation was later followed by chemical precipitation and/or filtration where almost all the remaining particles were removed, and the turbidity of final treated water was between 0.4 and 1 NTU[68]. However, the toxicity, possibly caused by the presence of the detergents, remained a problem in many tested process combinations.

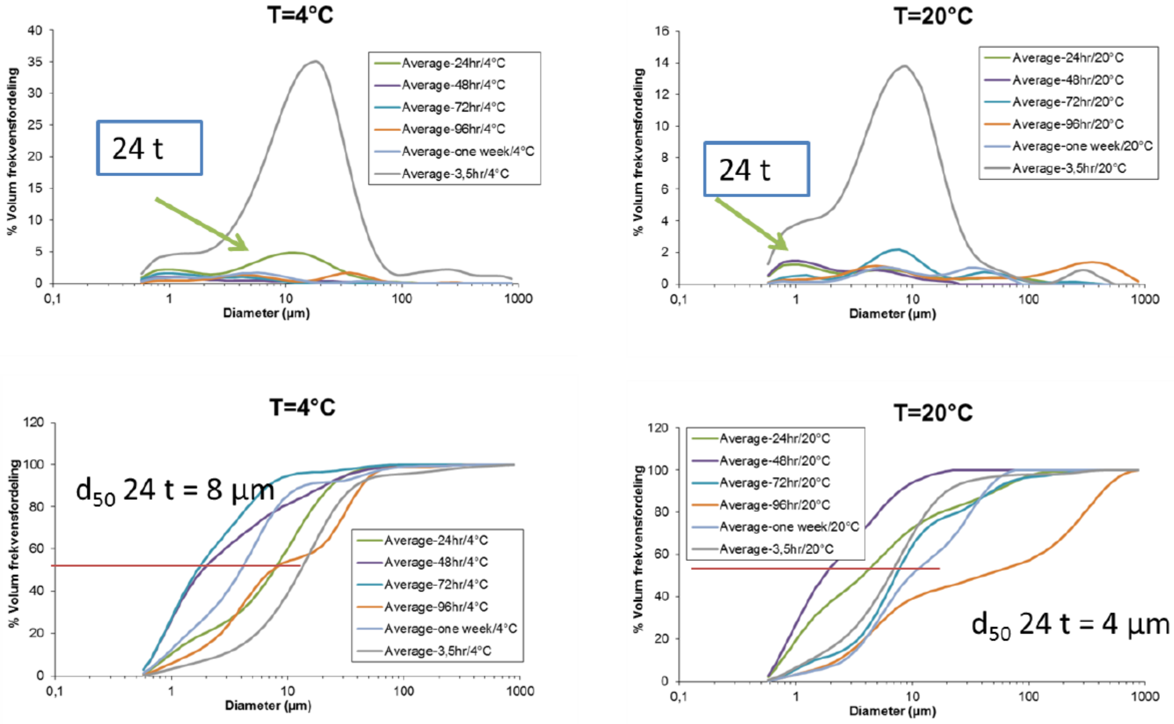

Figure 7.1 *Particle size distribution (as in concentration frequency distribution) after sedimentation at 4 and 20°C (Garshol et al. 2015).*

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[68] Nephelometric Turbidity Units

7.3 Future practices in Norway

Local solutions: This includes sedimentation basin/pond with additional local treatment. In a local solution one might imagine that the water is settled in existing sedimentation basin/pond. After 1-2 days the water is pumped through a coagulation and flocculation step, optionally followed by a sand filter and finally an adsorption filter and an alkaline filter before discharge to the recipient. The last part of the plant can process a smaller amount of water so that the process is completed within approx. 1 month when sludge is removed, and the plant is prepared for the next tunnel wash.
Mobile solutions: A mobile solution (trailer-based) could in principle take responsibility for the post-treatment of the wash water (after sand trap and sedimentation) or the entire cleaning process for many tunnels (depending on the size of the tunnel and volume of water produced). This may include different process combinations, such as chemical precipitation combined with flotation for removal of chemical precipitated sludge, followed by sand filtration, adsorption and alkaline filter if necessary.

An example of a potential mobile solution – SWAT technology

This technology (see **Figure 7.2**) combines application of coagulation/flocculation and rotating filters (Salsnes filter). This was suggested as a possible solution for treatment of tunnel wash water by Garshol et al. (2015). However, considering the high concentrations of dissolved heavy metals as well as toxicity of detergent, this process cannot treat the tunnel wash water to the desired level to satisfy the recipient requirement and it should be combined with a polishing step (e.g. adsorption).

The combination of such processes can be placed in a trailer and applied as a mobile solution (Garshol 2015).

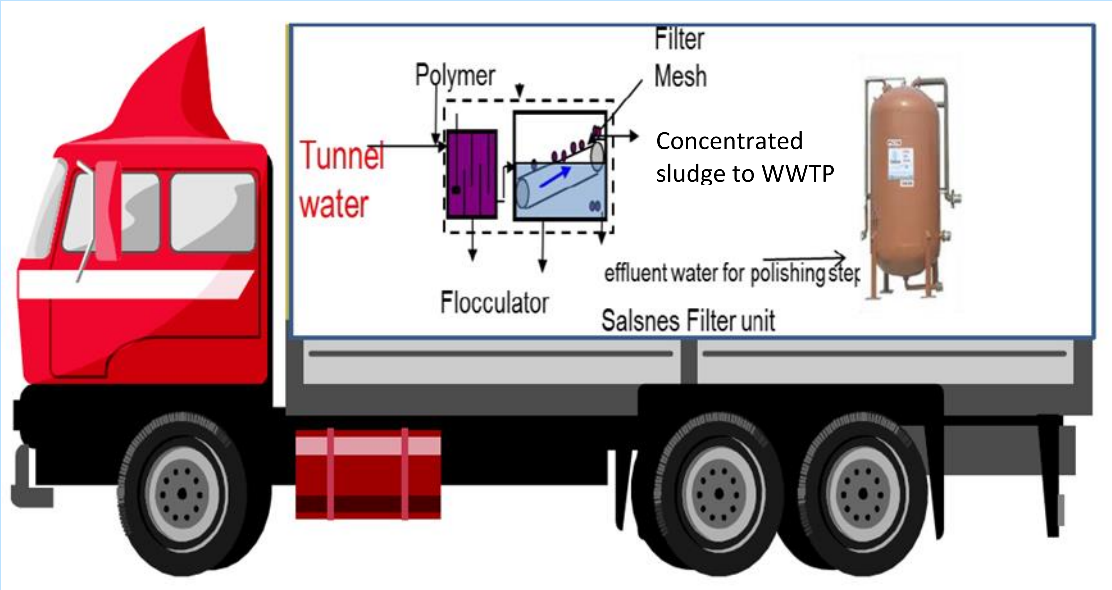

Figure 7.2 *Schematic of a potential mobile solution as presented by Garshol et al. 2015.*

8 Overall conclusions

The expected main contributors to road dust-associated microplastic particles (RAMP) are rubber compounds in tyre treads, polymers used to strengthen the bitumen used in road pavement (asphalt) and thermoplastic elastomers used in road marking paints, where the former appears to dominate. The major fraction of RAMP is expected to be found in the runoff from the road and road verge generated during rainfall events. However, even if domestic wastewater treatment plants (WWTPs) are expected to be main recipients of road runoff in urban areas, their presence in the influents or effluents (neither treated water nor sludge) have not been undisputedly documented. There is generally a complete lack of actual evidence to support the extent to which RAMP are removed by existing treatment facilities, and to what degree they are present in road runoff entering these facilities. In addition, the release of tunnel wash water is probably a major point source of RAMP. The estimated treatment efficiencies referred to in this report is based on total suspended solids (TSS) as a proxy for RAMP as well as reported particle size distributions and densities. Hence, the expected fate and removal of these particles in applied treatment systems are based on an assumption that they are likely to behave like particles having a certain size distribution and a given density. However, also the assumed size distributions and densities are founded on limited empirical evidence. Sedimentation is expected to be the most important mechanism for the removal of the larger size fractions if sufficient settling time is provided (traditional Norwegian gully pots do not). There is reason to believe that treatment systems that are efficient in removing high-density particles (~1.8 g/cm^3) with a particle size above approximately 30 µm, also will be efficient in removing the major fraction of RAMP in road runoff.

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Appendix A. Treatment requirements

Requirements regarding treatment of road runoff

Until now, the Norwegian criteria for when to treat road runoff has been strongly dependent on the traffic density (AADT), as in many European countries (Meland 2016). In practice, the minimum AADT-threshold for requiring treatment of road runoff in Norway has been 8,000-10,000 AADT, as compared to the typically 10,000-15,000 AADT in other European countries (Meland 2016). Currently, England is the only country in Europe that utilise a more evidence-based risk assessment that takes into account biological considerations in combination with hydraulics and traffic characteristics.

There are two main weaknesses in letting a (more or less) fixed AADT determine if treatment is needed or not:

1) The correlation between the concentrations of pollutants, including particles, in the road runoff and ADT is rather weak (e.g. Kayhanian et al. 2003).
2) The vulnerability of the recipient is not taken into account.

Hence, in 2016 a new method for decision making on when to treat road runoff (including tunnel wash water) in Norway was published (Meland et al. 2016B). This approach combines grouping of AADT and factors determining the vulnerability of a waterbody from road runoff. See **Table A1** The methodology to determine the vulnerability of a waterbody relies on criteria given in the WFD and the Norwegian Biodiversity Act[69] and is outlined in Ranneklev et al. (2016). The new decision making methodology is incorporated in the coming revised version of the NPRA's guidelines for building roads (Statens vegvesen 2017), which has been on a public hearing and it is expected published early 2018[70].

Together with the new decision-making method, the revised N200 also includes more strict guidelines on which treatment methods that should be applied on Norwegian roads. See **Table A1**. In brief, roads with traffic density above 30,000 require a two-step treatment system, i.e. sedimentation followed by infiltration or filtration. The same requirements are mandatory on roads with lower AADT (>15,000), but where the receiving waterbody is classified as highly vulnerable. In all other cases, where treatment is mandatory (>3,000 AADT with discharge to a recipient of medium or high vulnerability), a one-step treatment system based on sedimentation is satisfactory. Hence, treatment systems consisting of more than one treatment process will be in place in Norway for the first time probably in a few years from now. This will be in line with the current practice in some of the other European countries (Meland 2016).

In city areas, where space limitations may be strict, the revised N200 allows to dimension so that only the first flush is treated, while the excess is directed to overflow without any treatment. It gives, however, no definition of the boundaries of first flush.

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[69] https://lovdata.no/dokument/NL/lov/2009-06-19-100

[70] We are not aware of any major changes on the new decision-making approach.

***Table A1** Assumed risk of biological effects in the recipient due to discharges from roads with different traffic densities and the associated treatment requirement according to the stated risk. (adapted from the revised version of Statens vegvesen 2017).*

AADT	Biological effect	Treatment
<3,000	Low probability of biological effects in the recipient.	No treatment required. Runoff over road shoulder and infiltration in the ground.
3,000-30,000	Medium to high probability of biological effects in the recipient. The vulnerability (low, medium, high) of the recipient is decisive.	Treatment is required if the vulnerability of the recipient is medium or high. For recipients with high vulnerability and where AADT> 15,000 the treatment should at least consist of two treatment steps.
>30,000	High probability of biological effects in the recipient.	Treatment is required, also if discharge to coastal waters. The treatment should at least consist of two treatment steps.

The only specific treatment performance requirement stated in the new guidelines is regarding the removal of total suspended solids (TSS) by sedimentation: The sedimentation pond should be dimensioned to remove a minimum of 80% of TSS, however it is not stated how this should be determined. This is discussed in **Section 5.2.2**.

Requirements regarding treatment of tunnel wash water

In Norway, which has more than 1,000 tunnels, tunnel wash water is in most cases discharged untreated[71]. However, in most of the bigger tunnels in and around cities built from the mid-1990s, tunnel wash water is discharged into sedimentation basins inside or ponds outside the tunnel (Meland et al. 2016B). In new tunnelling projects, a permit from the regional environmental authorities (Fylkesmannen) is needed to discharge tunnel wash water. Meland et al. (2016B) suggested that tunnel wash water should not be discharged to any waterbody without proper treatment, regardless of traffic density. However, the latter is not included in the NPRA's recently guideline for tunnel building (N500). Anyway, there appears to be an increasing awareness that tunnel wash water is a 'hot-spot' in terms of causing unacceptable damage to the aquatic environment, which is why most tunnels are now built with sedimentation basins.

Requirements regarding discharges to the combined sewer system in urban areas

The municipality can grant permission to discharge road runoff to the combined sewer system. A common requirement is that the discharge should go via a gully pot to reduce silting and clogging of the sewer network (Lindholm 2015). The gully pots are operated and maintained by the municipal road administrations, but the common situation is that proper maintenance is lacking caused by strained budgets and the fact that the effects of poor maintenance is primarily a challenge for the sanitation agencies.

According to the Pollution Act (forurensningsforskriften[72]) wastewater treatment plants should be regarded as vulnerable recipients because their (biological) treatment processes are somewhat sensitive to e.g. toxic compounds in the influent, and if knocked out it may have detrimental impacts

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[71] The tunnels are equipped with catch pits and sometimes oil interceptors, which are not viewed as treatment systems in the present report.

[72] https://lovdata.no/dokument/SF/forskrift/2004-06-01-931

in the receiving aquatic environment. The main concerns related to road runoff are the large amounts of heavy metals, oil and polycyclic aromatic hydrocarbons it brings, but large volumes of water also cause general dilution of the influent to the WWTPs causing operational challenges. This problem is even more pronounced in period with snowmelt, decreasing the temperature of the influent water. The WWTPs anyway have to fulfil their treatment requirements.

Appendix B. Composition of tyre treads

Table B1 shows a modified version of the composition of model passenger car tyre tread described by Ahlbom and Duus (1994) and Barbin and Rodgers (1994). There are compositional differences between passenger cars and heavy-duty vehicles; Because natural rubber (NR) has a lower heat build-up, high elasticity, resilience, and tackiness, it is a preferable ingredient in the treads of tyres used for buses, trucks, and racing cars (Chi et al. 1978). For less demanding vehicles, SBR and PBR are commonly used, with a reduced SBR/PBR ratio for winter tyres compared to summer friction tyres. The rubber polymers of tyre treads are elastomers with a typical amorphous character to exhibit the necessary elasticity under strain. However, the tyre rubber is gradually altered during use due to changing operating temperatures (caused by friction), mechanical wear, oxidant and radical attack and the loss of protective ingredients (Kaidou and Ahagon, 1990; Ahagon and Kaidou, 1990).

Table B1. *A modified version of the composition of model passenger car tyre tread described by Ahlbom and Duus (1994) and Barbin and Rodgers (1994) by inclusion of updates described by Grigoratos and Martini (2014).*

Component/ additive	Ingredient	Typical content		Plastics?
Rubber polymer	Natural rubber co-polymers (NR)	16-24%	40-60%	Yes
	Styrene-butadiene rubber (SBR)	12-18%		Yes
	Poly-butadiene rubber (PBR)	8-12%		Yes
	Other rubbers; nitride rubber, neoprene rubber, isoprene rubber, and polysulphide rubber	4-6%		Yes
Reinforcing agent (filler)	Carbon black (to improve hardness and wear resistance)	20-35%		No
	Carbon black recently partially substituted with silica incorporated with a silane coupling agent, carbon-silica dual-phase filler (CSDP) and/or “nanostructure” carbon blacks (to decrease rolling resistance without compromising strength and longevity)			No
Process oil/ extender oils	High aromatic oils rich in polyaromatic hydrocarbons (PAHs)	15-20%		No
	The use of mild extract solvates (MES) and treated distillate aromatic extracts (TDAE) is increasing			No
Vulcanisation agent	S, Se, Te, thiazoles, organic peroxides, nitro-compounds (to improve the durability of tyre rubber)	1%		No
Vulcanisation activators	Zinc oxide	1.5%		No
	Stearic acid	1%		
Vulcanisation accelerators	Lead, magnesium, zinc, sulphur compounds (e.g. sulphonamide or thiazoles) and calcium oxides	0.5%		No
Vulcanisation retardants	Terpene-resin acid blends			
Protective agents	Preservatives (halogenated cyanoalkanes), anti-oxidants (amines, phenols), anti-ozonants (diamines and waxes), and desiccants (calcium oxides).	1%		No
Processing aids	Peptisers	<1%		
	Plasticizers (synthetic organic oils and resins) (to provide elasticity and stickiness to the tyre)			
	Softeners			

Appendix C. Composition, shape and density of tyre wear in road dust

General composition and density

Kreider et al. (2010) measured the composition of TP, TWP and RP with RP collected on-road using an aspiration system devise mounted very close to one of the tyres and TWP collected during a simulation run under laboratory controlled conditions. The measured general composition of the three types of particles are shown in **Table C1**. RP and TWP had similar compositions, although the RP was comprised of slightly more oils, plasticizers and polymers, whereas TWP had a higher mineral content. The mineral content of TP was significantly lower than in RP and TWP, primarily in exchange of a much higher content of polymers. This has a huge impact on the density (or specific gravity relative to water[73]) of TP, which is reported to be in the range of 1.15-1.18 g/cm^3 (US Federal Highway Administration 2016, Banerjee et al. 2016, Dumne 2013). In comparison, Snilsberg (2008) measured the density of collected road dust downfall during two periods; 2.12 g/cm^3 in March-April 2015 and 1.71 g/cm^3 in April-May 2015, the lower density of the April-May sample was suggested to be caused by a higher natural occurring organic content being closer to summer. The densities of the mineral components themselves were in the range of 2.63-2.76 g/cm^3. Kayhanian et al. (2012) measured the density of size-fractionated samples[74] from a highway shoulder and a parking lot, both showing similar average densities of 1.78 g/cm^3 and 1.73 g/cm^3, respectively and no clear trend related to size fraction.

***Table C1** General composition of RP, TWP and TP particles as determined by thermogravimetric analysis. Source: Kreider et al. (2010).*

Chemical family	RP (% dw)	TWP[75] (% dw)	TP (% dw)
Plasticisers and oils	13	10	19
Polymers	23	16	46
Carbon black	11	13	19
Minerals	53	61	16

Shape

Kreider et al. (2010) also measured the morphology of the collected RP and TWP qualitatively using scanning electron microscopy (SEM) and quantitatively using transmission optical microscopy, and found that the particle shapes of RP and TWP were nearly identical with modes of distribution of circularity measures of 0.84 and 0.83[76], respectively. The length-to-width ratios were also very similar for RP and TWO with values for the modes of distribution of 0.63 and 0.64, respectively. However, RP appeared to be somewhat smaller than TWP, in general, with a mean particle size (based on the mass distribution) of approximately 50 µm compared to 72-83 µm for TWP (Kreider et al. 2010). Tyre treads are added antioxidants to limit oxidative degradation[77] (see **Table A1**).

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[73] The density of clean freshwater at 20°C is 1.000 g/cm^3.

[74] The samples were collected by vacuum and separated in seven fractions: <38 µm; 38-75 µm; 75-125 µm; 125-250 µm; 250-425 µm; 425-600 µm; 600-1000 µm.

[75] Due to inefficient collection of generated TWP during the laboratory tests (ca. 20% recovery according to the supplementary material). However, this was corrected for by using internal tracers (Mo) in the tyre tread used in the test.

[76] A value of 1.00 identifies a perfect sphere and is sensitive to changes in form and surface roughness.

[77] Plastics with an amorphous structure (e.g. polyvinyl acetates and polyacrylates) are more prone to oxidative degradation than the ones with higher degree of crystallinity (Andrady 2017).

However, these may leach out with time making the tyre wear particles more prone to oxidative degradation and fragmentation during weathering (Andrady 2017).

Residues of TP in TWP and RP

The work by Kreider et al. (2010) seems to be one of few studies that have characterized and quantified differences in bulk particulate collected from both street dust, TWP generated under controlled conditions in a laboratory and TP cryogenically ground from pieces of tread rubber. In this way, TWP only contained material originating from TP and the pavement used in the laboratory tests (this pavement was, however, not characterised). The rubber part, shown as polymers in **Table C1**, constituted 46 dw% of the TP, but only 16 dw% of the TWP. A significant portion of the additional matter added to TP when TWP were generated was determined as minerals[78] (from 16 dw% to 61 dw%), which had to come from the pavement. The polymers can be expected to primarily come from the rubber content of the TP, whereas plasticisers, oil and carbon black can be expected to come from both TP and pavement. Though, due to the heat generated by the frictional forces, some of the polymers may have been thermally degraded and the oils may be vaporised (Fauser 1999). **Table C2** shows the results from a theoretical calculation of the contributions from TP, the pavement and loss to end up with the measured component mix of TWP, and the further contributions from the environment to end up with the measured component mix of RP, as shown in **Table C2**. According to these rough estimates, the original TP material made up approximately 40% of the TWP, and the original rubber material (i.e. microplastics) made up approximately 8% of the total polymers of RP and approximately 2.4% of the total mass content of RP. This is in reasonable compliance with Rogge et al. (1993) who determined that polymers from TP could not constitute more than 1.6% of the total RP mass based on n-alkanes measurements. To make the mass balance between TP and TWP go up, 22% of the rubber in the TP was assumed lost during the wear process. Though chemical degradation of approximately 30% of the SBR rubber with concomitant emissions of monomers and dimers of SBR have been reported (Cadle and Williams 1978), the rubber is primarily devulcanized and not necessarily lost from the tread wear particles. Note that any expected differences in densities between the different constituents were not taken into account.

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[78] Primarily salts as indicated by the measured concentrations of different compounds in TP and TWP shown in **Appendix A**.

Table C2 *Estimated contributions from TP (including losses due to evaporation/degradation) and pavement to TWP as generated in the tests conducted by Kreider et al. (2010). It was assumed that TP would constitute approximately 5% of the mass content of RP. Differences in densities were not taken into account.*

Chemical family	**TWP calculations**						**RP calculations**			
	Amount from TP	**Loss from TP**	**Amount from pavement**	**Amount in TWP**	**Ratio in TWP**	**Ratio from TP in TWP**	**Amount from environment**	**Amount in RP**	**Ratio in RP**	**Ratio from TP in RP**
	(g)	**(g)**	**(g)**	**(g)**	**(-)**	**(-)**	**(g)**	**(g)**	**(-)**	**(-)**
Plasticisers and oils	190	0	25	215	0.10	0.88	2300	2490	0.13	0.076
Polymers	460	100	0	360	0.16	1.00	4200	4560	0.23	0.079
Carbon black	190	0	100	290	0.13	0.66	1800	2090	0.11	0.091
Minerals	160	0	1250	1360	0.61	0.12	9000	10310	0.53	0.015
Total	**1000**	**100**	**1250**	**2225**	**1.0**	0.40	**17300**	**19450**	**1.0**	**0.046**

Appendix D. Size distribution of tread wear particles

The main part of the wear is believed to be caused by mechanical share, mainly releasing coarse particles or shreds >10 µm, but a substantial amount (ca. 1-10%) also as smaller airborne particles (Grigoratos and Martini 2014). The friction also generates heat, and when the temperature reaches >180°C in local hot spots on the tread, tyre polymers can be thermally degraded and extender oils can be vaporised and subsequently condensate as particles in the nanometre scale (Fauser 1999, Boulter 2006, Mathissen et al., 2011). See **Table D1**.

Table D1. *Type of tread wear particles, the cause of wear and typical size range.*

Tread wear particles	Cause of wear	Notation	Size range
Coarse particles, shreds	Mechanical share	$PM_{>10}$	10-350 µm
Coarse airborne particles	Mechanical share	PM_{10}	1-10 µm
Fine and ultrafine airborne particles	Thermal degradation, volatilisation and subsequent condensation	$PM_{0.3}$	5-300 nm

The size distribution of the wear particles is crucial in terms of predicting their fate in the environment and in the applied treatment systems. The reported volume size distributions of tyre wear particles vary quite a lot with peaks from the nano-scale range (10-100 nm) via the low micrometre-scale (1-10 µm) to the high micrometre-scale (50-100 µm) (Grigoratos and Martini 2014). However, many of the apparent discrepancies may be due to differences in methodological approaches and analytical techniques applied. Moreover, Dannis (1974) found that mean particle diameter decreases with increasing speed, and this may be an additional factor contributing to the differences in the reported findings.

When looking at the studies that have been designed to include also non-airborne particles, there are indications that these may make up 90-99.9% of the total suspended particulate (TSP) in tyre wear (Grigoratos and Martini 2014). In road simulation tests with summer friction tyres on standardized asphalt conducted by Kreider et al. (2010) (see **Appendix C**), they found a volume size distribution of the TWP in the size range of 1-133 µm with an average particle size of 72 µm. Less than 5% of the particles were smaller than 10 µm, which is in line with other reported studies (Cadle and Williams 1978, Broeke et al. 2008). See **Figure D1A**. No particles in the size range <0.1 µm were generated above background concentrations, and in the size range of 0.5 µm – 20 µm, the particle generation was also no greater than background concentrations except during acceleration/deceleration or steering (Kreider et al. 2010). The average particle size of 72 µm measured in-line during the simulation test corresponded well with the particle size distribution of the bulk TWP collected during the on-road tests, which had a median particle size of 83 µm. Similar observations were also made by Smolders and Degryse (2002), who found that roadside tyre debris <100 µm had a mean diameter of 65 µm for cars and 80 µm for trucks. However, there is a chance that the smaller particulate size fractions could be underrepresented in such studies. Broeke et al. (2008) recommended to use 5% of PM as PM_{10} (<10 µm) and 20% of PM_{10} as $PM_{2.5}$ (<2.5 µm) based on available literature. Hence, a best guess estimate of the size distribution of tread wear particles for selected size bins is shown in **Table D2**.

Table D2 *Size distribution of tread wear particles for selected size bins based on the work by Kreider et al. (2010) and recommended ratios of PM10 and PM2.5 by Broeke et al. (2008) shown in* ***Figure D1A****.*

Size bin	Volume%
50-350 µm	85
30-50 µm	8
10-30 µm	2
<10 µm	5

Looking at the number size distribution in **Figure D1B**, Kreider et al. (2010) observed two distinct peaks, at 5 µm and 25 µm, with the former being tallest. Similar simulation studies have been conducted by others finding bimodal PM_{10} number size distributions with peaks at 2-3 µm and 8-9 µm (Gustafsson et al. 2008), 0.3-0.4 µm and 4-5 µm (Aatmeeyata et al. 2009) and 1.0 µm and 5-8 µm (Panko et al. 2009). Hence, generally speaking and with a high degree of uncertainty, the majority of tyre wear particles are in the low micro scale range, but the main mass of tyre wear appears to be in the range of 50-100 µm.

A number of studies have also reported the generation of very small (<1.0 µm) and ultrafine (<0.1 µm) particles from the tyre road interface. Though, still under debate (Pierson et al. 1974, Grigoratos and Martini 2014), unimodal particle number distribution peaks at 15-50 nm (Dahl et al. 2006, Gustafsson et al. 2008), 30-90 nm (Panko et al. 2009) and 10-80 nm (Mathissen et al. 2011) have been reported. Even if the mass of this particle fraction is very low compared to the total released tyre wear mass, these airborne particles may potentially be much more potent than their larger counterparts due to their high surface-to-volume ratios and mobility in biota.

Moreover, Cadle and Williams (1979) showed that airborne tyre wear particles ranged in size from 0.01 µm to 30 µm, but, from the above discussion, the majority of the particle mass will not be airborne for long under still conditions.

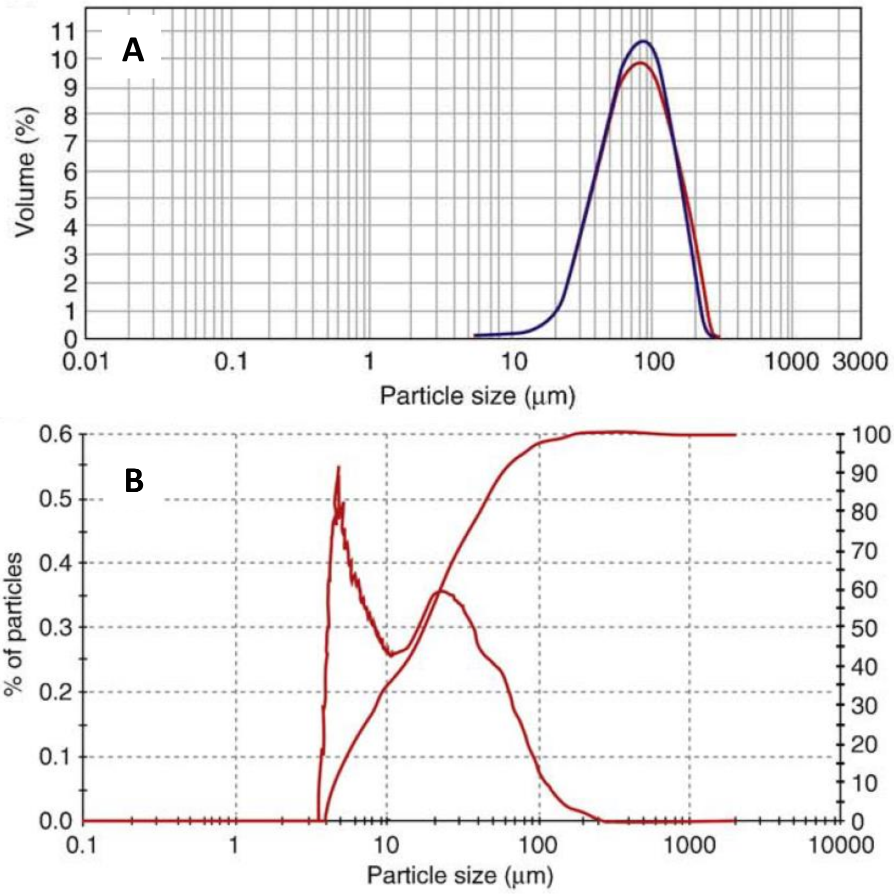

Figure D1 *<u>Volume size distribution</u> (**A**) and <u>number size distribution</u> (**B**) of tread wear particles (TWP) as determined by transmission optical microscopy of samples collected during a run road simulation tests with summer friction tyres on standardized asphalt. Reprinted from Kreider et al. (2010) with permission from Elsevier.*

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Appendix E. Hazardous compounds associated with road and tread wear

Compound group	**Compound**	**Kreider et al. (2010)**	**Kreider et al. (2010)**	**Kreider et al. (2010)**
		RP	**TWP**	**TP**
Used in tyre manufacturing	Zinc	4000	3000	9000
	Silicon	86	87	54
	Sulphur	9000	5000	12
Other metals	Aluminium	33,9	28,2	470
	Antimony	N.D.	130	76,5
	Arsenic	122	N.D.	N.D.
	Beryllium	N.D.	N.D.	N.D.
	Bismuth	N.D.	N.D.	86,8
	Boron	53,7	N.D.	N.D.
	Cadmium	N.D.	N.D.	N.D.
	Calcium	27,6	65,3	1010
	Chromium	N.D.	N.D.	N.D.
	Cobalt	N.D.	N.D.	N.D.
	Copper	188	634	21,5
	Iron	33	27,7	224
	Lead	49,7	N.D.	N.D.
	Magnesium	10,8	14,5	65,8
	Manganese	509	607	N.D.
	Nickel	40,8	52,6	N.D.
	Potassium	8840	5810	242
	Selenium	N.D.	N.D.	N.D.
	Silver	N.D.	N.D.	N.D.
	Sodium	7140	4750	N.D.
	Titanium	2810	1390	29,9
	Vanadium	60,6	49,6	N.D.
PAHs	Acenaphthene	4,08	0,04	0,13
	Naphthalene	6,10	0,20	1,18
	Phenantherene	53,40	1,66	1,21
	Pyrene	54,84	4,77	0,06
	Acenaphthalene	0,14	0,15	1,24
	Anthracene	7,36	0,10	0,11
	Benzo(a)Anthracene	38,65	0,18	2,87
	Benzo(a)pyrene	12,51	0,28	N.D.
	Benzo(b)fluoranthene	7,40	0,37	0,92
	Benzo(g,h,i)perylene	4,04	3,22	1,77
	Benzo(k)fluoranthene	7,40	0,02	0,92
	Chrysene	17,72	0,36	2,95
	Dibenzo(a,h)anthracene	2,56	0,10	0,87
	Fluoranthene	82,13	0,98	1,62
	Fluorene	1,76	0,07	0,25
	Indeno-1,2,3(c,d)pyrene	5,36	0,21	N.D.
	Total	305,45	12,71	16,10

Appendix F. Current analytical challenges related to tyre wear particle characterisation

Various techniques have been used to collect particles from tyre wear and other non-exhaust sources, either under real-world test conditions or in the laboratory using specialised testing machines.

Real-world conditions

Road dust can be sampled by e.g. sweeping (Pollard 1997), using a dry (Hildemann et al. 1991, Rogge et al. 1993) or wet (Orr and Deletic 2000) vacuum sweeper or using a passive dust downfall collector (Snilsberg 2008). The collected material from sweeping is typically sieved to remove coarse grit. The main challenge with this methodology is to distinguish between particles originating from tyre wear and other non-exhaust particle sources (e.g. brake wear), but the finer particle fractions are also potentially lost due to spreading by wind or vehicle-generated currents.

Tyre wear can be collected directly from the tyre as done by e.g. Kreider et al. (2010), using aspiration systems with a slot-type capture hood attached to the rear left tyre hub of a car and to the rear left axle of a truck positioned as close as possible to the exit of the contact patch area (see **Figure F1**). Contrary to most studies, which have focused on the airborne particles, the applied suction was made strong enough (Cadle and Williams 1978) to collect also the coarser particle fractions. The mass of rubber in the collected particles was estimated using density measurements and the ash content of the particles (with the loss during annealing indicating the organic content of the tyre wear particles). Since resuspention of already present tyre wear particles on the road surface is an inherent challenge in tests (Boulter 2006), molybdenium (Mo) was used as an element tracer specific to the test tyre (Kreider et al. 2010). A challenge reported by others, is that fine tyre wear particles, when resuspended, become electrically charged and adhere to the walls of the sampling equipment, making it difficult to make a representative collection of the finer size fractions (Thorpe and Harrison 2008).

Figure F1. *Photograph of an on-road tyre wear collection system using an aspiration system with a slot-type capture hood attached to the rear left axle of a truck. Reprinted from Kreider et al. (2010) with permission from Elsevier.*

Laboratory road simulation tests

A range of different test equipment have been designed and used for running road simulation tests under controlled conditions. For a description of some of these, see Snilsberg (2008). Also Kreider et al. (2010) did road simulation tests in parallel with the above mentioned on-road tests to allow for collection of TWP from specific tyre types without interference from other road surface contaminants such as brake dust, vehicle exhaust, oil/grease, salts, soil, vegetation, etc. The TWP was collected using a device similar to that which was installed on the passenger car and truck. Also in these simulation tests, loss of the finer particle fractions due to electrostatic effects when resuspended, is a potential error (Thorpe and Harrison 2008).

Particle size analysis and distributions

A number of techniques and methodologies have been applied to describe the size distribution of tread wear particles[79]. However, it is a challenge to do a direct proper comparison of the results obtained with all these different systems as they all have their particular inherent limitations related to e.g. particle size ranges, scattering and influence of particle shape. Moreover, in studies focusing on airborne particulate matter, it is common to relate to the particles' aerodynamic diameter, hence considering it as a completely smooth sphere with a density of 1 kg per litre, to relate its diameter to its terminal settling velocity in air falling under the influence of gravity. As illustrated in **Figure F2**, this will hide or supress differences in physical shape and exaggerate the actual size of the particle if the density is larger than 1 kg/l.

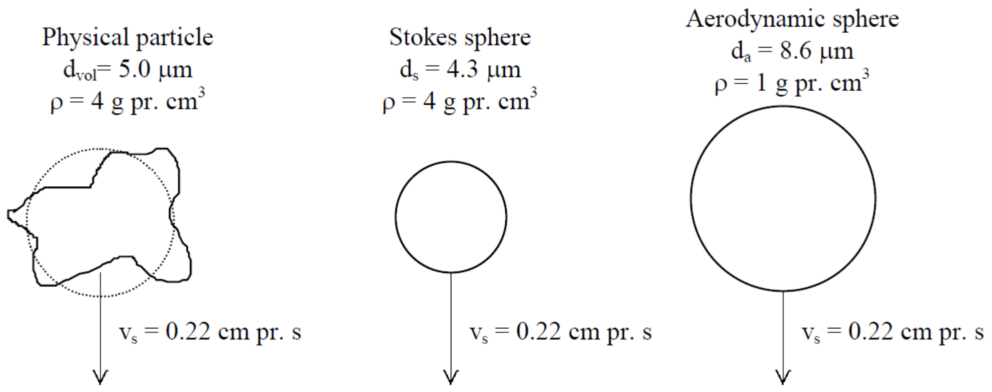

***Figure F2.** Stokes and aerodynamic diameters for an irregularly shaped particle (Fauser 1999).*

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[79] Examples are transmission optical microscopy and laser diffraction (Kreider et al. 2010), Engine Exhaust Particle Sizer (EEPS) (Mathissen et al. 2011), Electrical Low-Pressure Impactor (ELPI) (Sanders et al. 2003), optical particle counter (von Uexküll et al. 2005), cascade impactor (Kupiainen et al. 2003), Aerodynamic Particle Sizer (APS) (Lijima et al. 2007), APS combined with Scanning Mobility Particle Sizer (APS-SMPS) (Kukutschová et al. 2011), Micro-Orifice Uniform Deposit Impactor (MOUDI) (Harrison et al. 2012) and GRIMM analyser (Wahlstrom et al. 2010).

Appendix G. Factors affecting tyre wear

There are many factors that are believed to influence tyre wear (Boulter 2006):

a) tyre characteristics
- size (radius/width/depth)
- tread depth
- presence of studs
- construction
- pressure and temperature
- contact patch area
- chemical composition
- accumulated mileage
- set-up

b) road surface characteristics
- material (bitumen/concrete)
- texture pattern and wavelength
- porosity
- condition
- wetness
- surface dressing

c) vehicle characteristics
- weight
- distribution of load
- location of driving wheels
- engine power
- electronic braking systems
- suspension type
- state of maintenance

d) vehicle operation
- speed
- linear acceleration
- radial acceleration
- frequency and extend of braking and cornering

Some researchers have tried to quantify the impact of certain specific aspects on the tyre wear, but it should be expected that these are dependent not only on how the tests are conducted, but also on the local conditions during the tests and therefore not directly transferrable to other localities or conditions. Some examples are described briefly in the following:

Driving behaviour

Although some studies have indicated increased tread wear with increasing vehicle speed[80] (e.g. Dannis 1974 and Sakai 1996), urban driving with usually more acceleration and braking, and more corners and bends has been shown to result in higher tread wear per km driven within urban areas than within rural areas or on highways (Dannis 1974, Stalnaker et al. 1996, LeMaitre et al. 1998, Luhana et al. 2004). However, there is little data available to properly substantiate this. Some of the extreme values[81] are probably not realistic anymore due to advances in technology and improved properties of tyres (such as wear resistance and grip). Broeke et al. (2008) have suggested to use a factor 2 to compensate between urban driving and driving elsewhere.

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[80] Increased vehicle speed has been shown to decrease the mean particle diameter of the tyre wear, and this may partially explain the increased PM_{10} production reported by some studies (Luhana et al. 2004).

[81] In tests simulating both 'city' and 'motorway' driving conditions, Stalnaker et al. (1996) found that city driving, which included large numbers of turns, accounted for 63% of the tyre wear, even though it represented only 5% of the distance driven or 32 times greater than that of motorway driving. Dannis (1974) measured 490 mg tyre wear per km per tyre when taking bends in 50 km/h compared to 24 mg tyre wear per km per tyre when driving at 120 km/h on highways.

Similarly, an aggressive driving style will tend to result in more rapid and uneven tyre wear than a 'smooth' driving style (Luhana et al. 2004, Boulter 2006, Councell et al. 2004). Hence, a “driver’s age and/or sex factor” may also be adequate, but there exist no data to indicate its size.

Tyre characteristics

When running road simulation tests with all new tyres, Sakai (1996) found that after a running-in distance of approximately 300 km, the tyre wear rate (g/km) was 75% of the initial wear rate, but became almost constant thereafter. Furthermore, when not having used the tyres for three months, an additional running-in distance of 150 km was required.

High wear rates may occur as a result of steering system misalignment and incorrect tyre pressure. Other factors include worn or damaged suspension parts, overloading, incorrect steering geometry and track setting, and the improper matching of rims and tyres (Luhana et al. 2004). With low-mileage cars, there is also the danger that the tyre wall can degrade before the tread wears away, especially if the tyres are exposed to strong sunlight and moving air (Luhana et al. 2004).

The treads of winter friction tyres have a softer rubber mix (reduced SBR/PBR ratio; see **Table B1** in **Appendix B**) than summer tyres to give them proper grip on cold pavement. Hence, late exchange of winter tyres exposing them to prolonged periods with warmer asphalt, will significant impact tyre wear.

The use of studded tyres significantly increases road dust production, particularly PM_{10}, but all this increase in road particles seems to originate from the asphalt and not from tyre treads (Gustafsson et al. 2008). There also seems to be a strong correlation between vehicle speed and wear when using studded tyres (Gustafsson et al. 2008, Johansson et al. 2007, Snilsberg 2008).

Vehicle characteristics

Typical emission tyre wear factors reported for light-duty vehicles are summarised in **Figure G1**. During “normal driving” a wear factor of 100 mg/vkm seems appropriate. For heavy-duty vehicles reported emission tyre wear factors has been in the range of 189-1403 mg per vehicle kilometre (see **Table G1**), depending on the vehicle configuration (e.g. number of axles and load) (Boulter 2006).

On a front-wheel drive (FWD) vehicle, the front wheels are used both for traction and steering, while the rear wheels are only responsible for rear axle control and load carriage. Luhana et al. (2004) reported that front tyres on a FWD vehicle accounted for 69–85 % of total vehicle tyre wear.

Table G1. *Reported emission tyre wear factors for heavy-duty vehicles.*

Reference	Type of vehicle	Tyre wear factor (mg/vkm)
Baumann and Ismeier (1997)	Heavy-duty vehicles	189
	Articulate lorries	234
	Buses	192
Gebbe et al. (1997)	Heavy-duty vehicles	539
Garben et al. (1997)	Heavy-duty vehicles	Ca. 800
EMPA (2000)	Heavy-duty vehicles	Ca. 800
SENCO (1999)	Large goods vehicles	1403

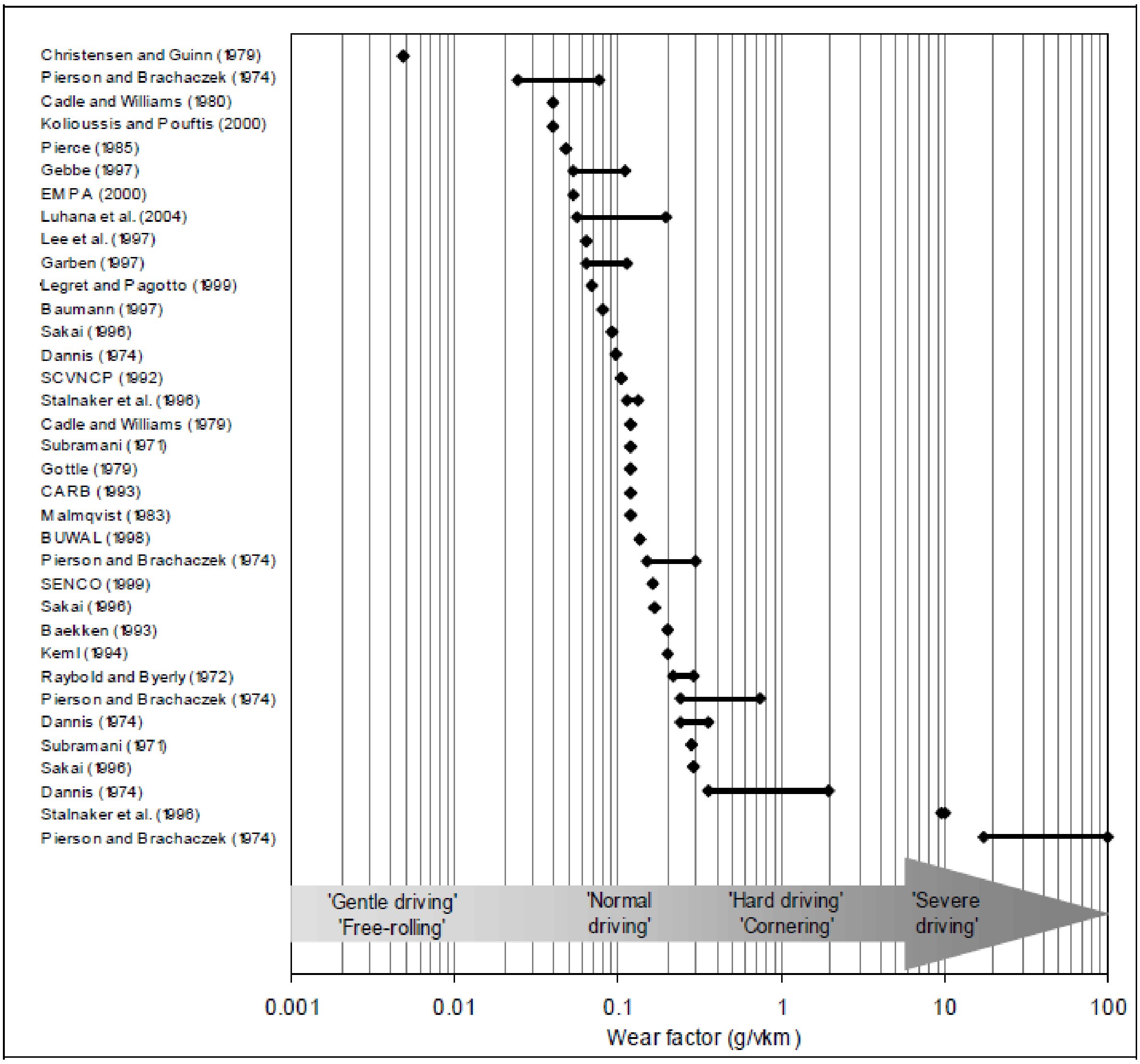

Figure G1. *Emission tyre wear factors for light-duty vehicle tyres assuming four wheels per vehicle (Boulter 2006; adopted from Councell et al. 2004). References can be found in Boulter 2006.*

Road surface characteristics

Since the micro-texture of the road surface directly influences the frictional forces on the tyre tread, it also has a huge impact on the overall tyre wear. Lowne (1970) observed a large variation in the degree of tyre wear as a result of different road surfaces, where the wear on rough, harsh surfaces was approximately 3 times as severe as that on smooth, polished surfaces. However, this has been shown to be difficult to study, since both controlled laboratory simulation studies and on-road studies have their inherent limitations and the influence from other factors are difficult to supress (Luhana et al. 2004, Boulter 2006, Grigoratos and Martini 2014).

LeMaitre et al. (1998) observed 50 % higher tyre wear during dry conditions than when the road was wet. They also found that winter tyre wear was 40 % higher than summer tyre wear, though Pirelli (2000) reported 90% longer tyre life when the outside temperature decreased from 15°C to 0°C.

Appendix H. Estimated annual releases of PMB caused by studded tyres

The annual releases of SBS in road wear, $E_{RW,SBS}$ caused by studded tyres can be estimated by multiplying the specific studded tyre road emission factor, EF_{ST} with the annual travelled distance done with studded tyres on roads containing PMB.

$$E_{RW,SBS} = \sum_i D_{PMB,i} \cdot f_{ST,i} \cdot f_{w,i} \cdot f_{SBS,i} \cdot EF_{ST,i} \qquad \text{(H1)}$$

Where:

- $D_{PMB,i}$ is the annual travelled distance for all vehicles on roads with pavements containing PMB in the road wear layer in area i (million vehicle km),
- $f_{ST,i}$ is the fraction of cars using studded tyres in area i (-),
- $f_{w,i}$ is the fraction of the year considered winter and period for using studded tyres in area i (-),
- $f_{SBS,i}$ is the SBS weight-fraction of the road wear in area i (-), and
- i is an area in which all the above parameters are assumed identical.

According to the National Road Authority map service (https://www.vegvesen.no/vegkart/) the total length of public county and state roads[82] where PMB has been used (L_{PMB}) is 2,770 km, assuming that all bitumen is modified with SBS (or similar) polymers. However, to calculate a more precise travelled distance (D_{PMB}) we need to couple road lengths within rather narrow AADT ranges. Unfortunately, this is a rather laborious job to do for the PMB roads using the otherwise excellent map service. According to Aurstad et al. (2016), PMB is primarily used with skeletal and asphalt on the more heavily trafficked roads (≥3,000 AADT). As an estimate, we have therefore extracted data for selected AADT ranges for all roads ≥3,000 AADT and multiplied the average AADT-value in each AADT range with the total length of roads (L_{all}) in the same AADT range to calculate D_{all} (travelled distance on roads with all types of bitumen). This value is then multiplied with the PMB correction factor (f_{PMB}) to obtain D_{PMB}:

$$D_{PMB} = D_{all} \cdot f_{PMB} \qquad \text{(H2)}$$

$$f_{PMB} = \frac{L_{PMB}}{L_{all}} \qquad \text{(H3)}$$

The results are summarised in **Table H1**. However, the usage of studded tyres has decreased considerably, and in the 2016/2017 winter season it was 12-13% in the greater Oslo area and around Bergen[83] (primarily due to the introduction of a studded tyre tax), while it was approximately 50% on average in the rest of Norway. The calculations of D_{PMB} and $E_{RW,SBS}$ for the greater Oslo area, Bergen, the rest of Norway and all of Norway combined are shown in **Table H1**.

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[82] Municipal roads are not included.

[83] https://vegnett.no/2017/03/nordmenn-pigger-fortsatt-av/

The following additional assumptions were made:

- The wear layer of pavement typically contains approximately 5% bitumen and the concentration of the polymer SBS in the bitumen average 5%, resulting in f_{SBS} = 0.0025.
- The road wear factor for studded tyres on pavement with PMB, EF_{ST} = 7.5 g/vkm.
- All roads ≥3,000 AADT have applied PMB in the pavement
- The studded tyre season lasts five months (November-March); f_w = 0.42.

In total the estimated annual SBS release from ≥3,000 AADT roads in Norway is estimated to be approximately 28 tonnes.

Table H1. *Estimated release of SBS in road wear caused by studded tyres in Norway. The boundaries of the greater Oslo area and the Bergen area are shown in* ***Figure H1****.*

	Norway	**Greater Oslo area**		**Bergen**		**Other areas**	
AADT range	**km**	**km**	**mill. vkm/y**	**km**	**mill. vkm/y**	**km**	**mill. vkm/y**
3,000 – 5,000	3365	146	213	91,9	134	3127	4566
5,000 – 7,000	1596	86,8	190	48,7	107	1461	3198
7,000 – 9,000	933	79,3	232	32,8	96	821	2397
9,000 – 11,000	685	63,9	233	30,9	113	590	2154
11,000 – 13,000	436	46,6	204	28,5	125	361	1581
13,000 -15,000	348	29,6	151	24,7	126	294	1501
15,000 – 20,000	397	30,2	193	27,6	176	339	2167
20,000 – 30,000	287	34,8	318	23,7	216	229	2085
30,000 – 40,000	89,9	5,28	67	5,92	76	78,7	1005
40,000 – 50,000	64,4	14,6	240	15,0	246	34,8	572
50,000 – 60,000	41,2	7,12	143	1,43	29	32,7	655
60,000 – 70,000	18,5	9,47	225			9,03	214
70,000 – 80,000	17,2	13	356			4,20	115
80,000 – 90,000	10,7	10,7	332			0	
90,000 – 100,000	4,16	4,16	144			0	
100,000 – 110,000	0,75	0,75	29			0	
Total	8,294	582	3,270	331	1,444	7 380	22,210
PMB roads	2,770	582		99		2,089	
Ratio PMB roads	0.33	1.0		0.30		0.28	
Road wear (tonnes/year)	11,224		1,225		175		9,823
$E_{RW,SBS}$: **SBS release (tonnes/year)**	**28.1**	**3.1**		**0.4**		**24.6**	

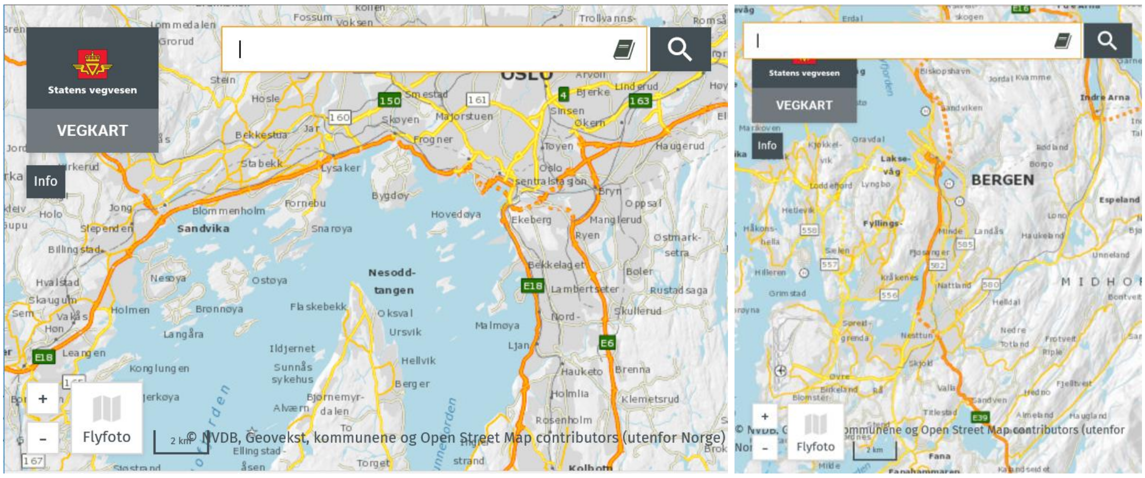

Figure H1. *The boundaries of the Greater Oslo area (left) and Bergen area (right) used in the estimates. The maps are copied from www.vegvesen.no/vegkart.*

Appendix I. Resuspension of airborne microplastic particles during dry weather

Resuspension of microplastic particles during dry weather

Road dust may be suspended or resuspended in the atmosphere as a result of vehicle-generated turbulence as air is squeezed from beneath the tyre, by tyre shear caused by rotation, and by the action of the wind (Luhana et al. 2004). Nicolson and Branson (1990) studied the importance of traffic-generated resuspension from induced turbulence and tyre shear by measuring surface concentrations of fluorescently dyed spherical silica particles with a density of approximately 1 g/ml and four nominal particle sizes (5 µm, 10 µm, 12 µm and 20 µm; i.e. more or less equal to their aerodynamic diameter). They found that both turbulence-induced and tyre shear-induced resuspension became more difficult with decreasing particle size, but that this was more evident with the former, and that large fractions of the deposited material were removed after the single passage of a vehicle (**Figure I1**). There was a clear dependence of resuspension on vehicle speed (**Figure I2**). They argued that the particles remaining on the road surface after a number of vehicle passes are likely to be associated with depressions in the road surface, but that this amount is unlikely to be large and will reduce quickly with increasing vehicle speed. For a busy, fast road, therefore, resuspension is likely to be controlled by the rate of incorporation of deposited material with soil or dust that may be translocated onto the road surface. Such incorporation may be most rapid when the surface is moist such that resuspension factors resulting from turbulence or tyre shear might be greatest immediately after a road becomes dry (Nicolson and Branson 1990).

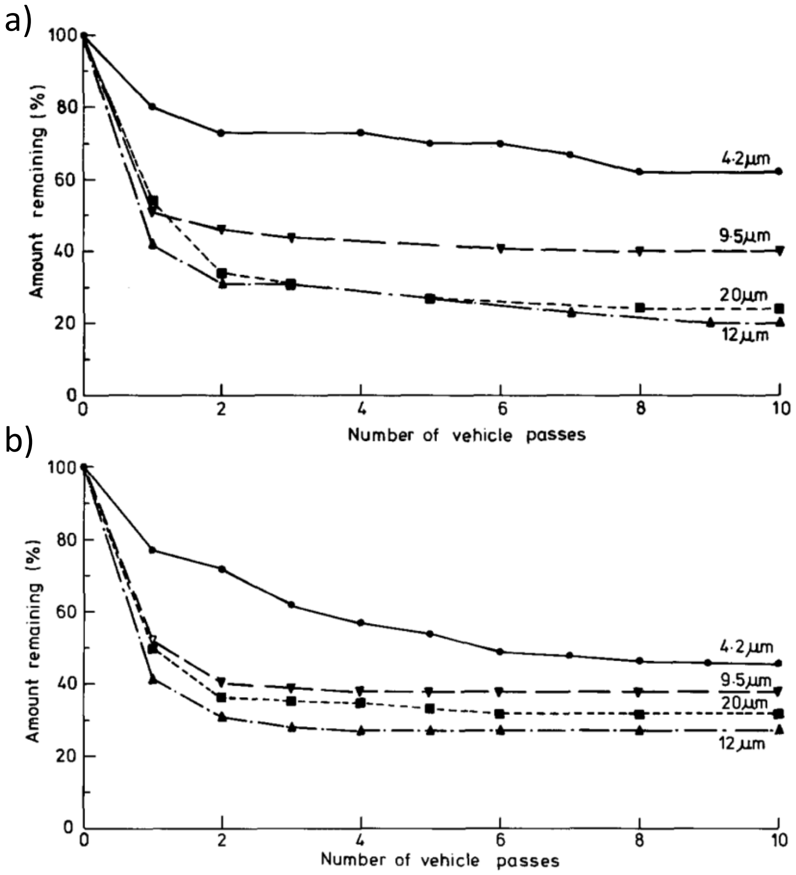

Figure I1. *The resuspension of fluorescent particles due to turbulence (a) and tyre shear (b) generated by a medium size car at 64 km/h (Nicolson and Branson, 1990).*

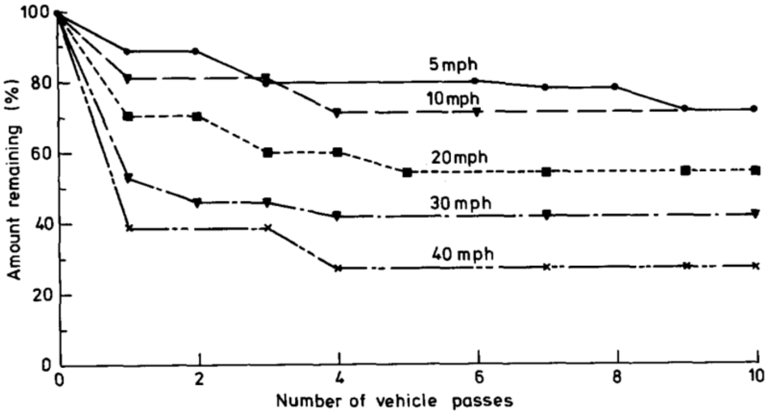

Figure I2. *Resuspension of 12 µm particles due to turbulence generated by a medium size car at various speeds (Nicolson and Branson, 1990)*

Appendix J. Estimated settling velocities of TWP

The settling velocity (V_p; m/s) of discrete[84] particles in water with laminar flow (i.e. no vertical mixing) can be described by Navier-Stokes equation:

$$V_p = \frac{{d_s}^2 \cdot (\rho_s - \rho_w) \cdot g}{18 \cdot \nu \cdot \rho_w} \qquad \text{(J1)}$$

Where

- d_s is the particle's Stokes diameter or effective diameter (m),
- ρ_w is the density of the surrounding water (1000 kg/m^3),
- ν is the kinematic viscosity (m^2/s),
- g is the acceleration of gravity (9,81 m/s^2), and
- ρ_s is the density of the particle (kg/m^3).

The kinematic viscosity decreases with increasing temperature and increases somewhat with salinity. A detailed description of the relationship between the dynamic and kinematic viscosities ($\mu = \nu \cdot \rho_w$) is given by Sharqawy et al. (2010), and based on tabulated viscosity values for selected temperatures (T; 0, 10, 20 and 30 °C) and salinities (S; 0, 10, 20, 30 and 40 ‰) Vogelsang and Bjerkeng (2014) fitted a function describing their relationship[85]:

$$\nu = \frac{1.789625 + 0.0010201 \cdot S^{1.16035}}{1 + 0.0350 \cdot T + 0.000201 \cdot T^2 - 0.000027 \cdot S \cdot T} \cdot 10^{-6} \qquad \text{(J2)}$$

We used equation H1 to calculate the settling velocities of particles with selected effective diameters within the TWP size distribution range and typical densities (1.7-2.3 g/cm^3) as shown in **Table J1**. At 10°C a TWP with the average particle size (by mass) of ca. 80 µm and a density of 1.7 g/cm^3 settles one meter in approximately 9 min. The particle size has a profound impact on the settling velocities as particles with a diameter of e.g. 2.5 µm will spend many days before settling the same distance. Also the density of the particle has a large impact, given by the difference between the density of the particle and that of pure water. The clean tread particle with a typical density of 1.15 g/cm^3 need 4.7 times longer time to settle than a TWP with a density of 1.7 g/cm^3.

It should be noted that laminar flow, which is a prerequisite for equation H1 to be valid, will hardly be present during massive runoff if measures to retain and limit the volumetric load of the treatment unit.

Increasing water salinity as a consequence of road salting has a slight negative effect on the calculated settling velocities [86], however, since increased salt concentrations will decrease the strength and width of the electrical double layer around the particles, the particles may aggregate to larger flocs that may drastically increase the settling velocities (Sutherland et al. 2014). This is a rather complex process that is difficult to predict as it is dependent on many variables.

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[84] Meaning that they don't influence each other, which is usually the case in road runoff.

[85] The maximum relative deviation is 0.2%.

[86] 11% increase in settling time when increasing from 0.001 psu (freshwater) to 35 psu (seawater).

Table J1. *Calculated necessary time to settle 1 m in a laminar water flow.*

Particle size	**Density**						
	1.7 g/cm^3				**1.15 g/cm^3**	**2.0 g/cm^3**	**2.3 g/cm^3**
	Temperature						
	0°C	**4°C**	**10°C**	**20°C**	**10°C**		
	Calculated time (min) to settle 1 m						
2.5 μm	12,500	10,900	9,100	7,000	43,000	6,400	4,900
10 μm	782	684	570	437	2,700	399	307
30 μm	87	76	63	49	295	44	34
50 μm	31	27	23	17	106	16	12
80 μm	12.2	10.7	8.9	6.8	42	6.2	4.8
300 μm	0.87	0.76	0.63	0.49	3.0	0.44	0.34

Appendix K. Trap efficiency of gully pots

When determining the trap efficiency of gull pots, Karuranatne (1992) and Butler and Karuranatne (1995) used the settling velocity described in **Appendix J** in their equation, but included a correction factor α to take the expected turbulence in the gully pot during rain events into account:

$$\varepsilon = \alpha \cdot \sum_i \frac{V_i}{V_i + Q/A_g} \qquad [4.1]$$

Where:

- V_i is the settling velocity of particle *i* with diameter d_i (m/s),
- Q is the flow rate into the gully pot (m^3/s), and
- A_g is the cross section of the gully pot (m^2).

Stokes' law is applicable under laminar flow (no turbulence), but inside a gully pot during rain events turbulence effects cannot be neglected. The correction factor α was therefore introduced to avoid overestimation of the settling velocity. Butler and Karuranatne (1995) set this value to 0.6, but Bolognesi et al. (2008) showed that this factor was dependent on the size of the particles and suggested the use of the following expression:

$$\alpha = 0.8574 \cdot e^{-1.7602 \cdot d_i} \qquad [4.2]$$

We have used these equations to calculate the expected trap efficiencies of gully pots for given volumetric ladings between 0.005 m^3/s and 0.025 m^3/s for particles with densities of 1.7 g/cm^3 and 2.1 g/cm^3. See **Table K1**. If the assumed particle size distribution given in **Table 2.2** is used as basis, and averaging the trap efficiencies over the different particle size ranges, the estimated combined trap efficiencies are as shown in **Table K2**.

Table K1. *Tarp efficiencies of gully pots for particles with densities of 1.7 g/cm^3 and 2.1 g/cm^3 for given volumetric ladings between 0.005 m^3/s and 0.025 m^3/s.*

		1.7 g/cm^3					**2.1 g/cm^3**				
		Q (m^3/s)					Q (m^3/s)				
		0.005	0.010	0.015	0.020	0.025	0.005	0.010	0.015	0.020	0.025
d	**α**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**
µm	-	-	-	-	-	-	-	-	-	-	-
1	0.86	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.5	0.85	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.84	0.004	0.002	0.001	0.001	0.001	0.006	0.003	0.002	0.002	0.001
30	0.81	0.032	0.017	0.011	0.008	0.007	0.050	0.026	0.017	0.013	0.010
50	0.79	0.083	0.043	0.029	0.022	0.018	0.124	0.066	0.045	0.034	0.028
80	0.74	0.179	0.099	0.068	0.052	0.042	0.256	0.147	0.103	0.079	0.064
250	0.55	0.613	0.442	0.345	0.283	0.240	0.713	0.554	0.453	0.383	0.332

Table K2. *Trap efficiencies of gully pots for specific particle ranges if based on assumed particle size distribution of TWP in road runoff.*

		1.7 g/cm^3					**2.1 g/cm^3**				
		Q (m^3/s)					Q (m^3/s)				
		0.005	0.010	0.015	0.020	0.025	0.005	0.010	0.015	0.020	0.025
Size range	Vol%	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**	**ε**
1-2.5 µm	1	1.4E-06	7.1E-07	4.7E-07	3.5E-07	2.8E-07	2.2E-06	1.1E-06	7.4E-07	5.6E-07	4.5E-07
2.5-10 µm	4.0	8.2E-05	4.1E-05	2.7E-05	2.1E-05	1.6E-05	1.3E-04	6.4E-05	4.3E-05	3.2E-05	2.6E-05
10-30 µm	1.8	3.4E-04	1.7E-04	1.1E-04	8.6E-05	6.9E-05	5.2E-04	2.7E-04	1.8E-04	1.3E-04	1.1E-04
30-50 µm	8.2	4.7E-03	2.4E-03	1.6E-03	1.2E-03	9.9E-04	7.1E-03	3.7E-03	2.5E-03	1.9E-03	1.6E-03
50-80 µm	35	0.046	0.025	0.017	0.013	0.010	0.066	0.037	0.026	0.020	0.016
80-350 µm	50	0.20	0.14	0.10	0.08	0.07	0.24	0.18	0.14	0.12	0.10
Total	100	**0.25**	**0.16**	**0.12**	**0.10**	**0.08**	**0.32**	**0.22**	**0.17**	**0.14**	**0.12**

Appendix L. Rainfall Intensity-duration-frequency (IDF) curves for Oslo - Blindern

Table L1. *Recurrence intervals and precipitation intensities for precipitation events with duration from 5-1440 min for Oslo – Blindern for the period 1968-2014 (met.no).*

Recurrence interval (year)	**Precipitation intensity (L/s*ha)**										
	Duration (min)										
	5	10	15	20	30	45	60	180	360	720	1440
2	187	140	114	98	77	60	49	21	12.0	8.0	4.8
5	253	189	158	138	109	86	70	28	15.8	9.7	5.8
10	297	222	188	164	130	103	84	33	18.3	10.8	6.4
20	338	254	216	189	150	120	97	37	21	11.9	7.0
25	352	264	224	197	156	125	101	38	22	12.2	7.1
50	393	295	252	222	176	141	114	43	24	13.3	7.7
100	433	325	279	246	195	157	127	47	26	14.3	8.3
200	474	356	306	270	215	174	140	51	29	15.4	8.8

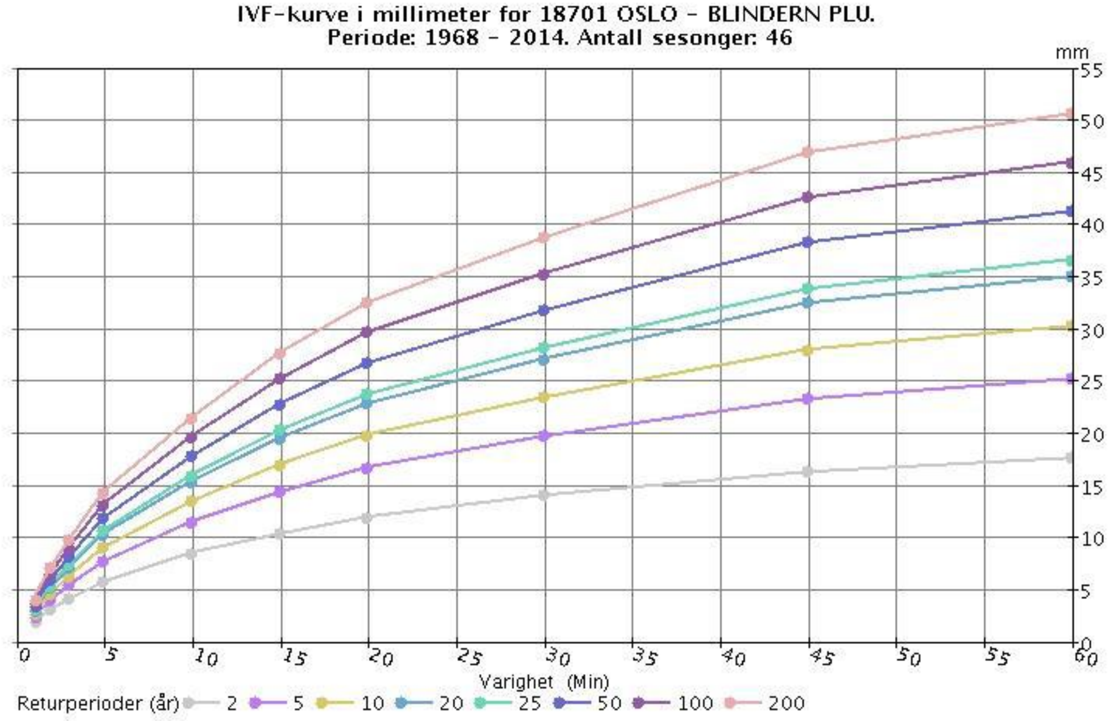


Figure L1. *IVF curves for Oslo – Blindern for the period 1968-2014 for 1-60 min precipitation events (met.no).*

Appendix M. Wet weather accumulation and road runoff

Brodie (2007) developed a ‘parsimonious’ model of non-coarse particle (<500 µm) loads in stormwater runoff from impervious surfaces. The model started with rainfall energy principles identified from the Rainfall Detachment Index (RDI) (see below) and was progressively refined to allow for surface particle accumulation during wet weather and also the effect of very small storm events. The model produced cumulative loads that were generally within 10% of the measured total.

RDI utilizes 6-minute rainfall intensities (I_6) and is a variant to the well-known Rainfall Erosivity Index (EI_{30}) used in soil erosion estimation. RDI is given by:

$$RDI = \frac{\sum I_6^2 \cdot Peak\ I_6^2}{D}$$

The definitions of $\sum I_6^2$ and $Peak\ I_6^2$ are shown in Table L1. D is the duration of the storm in hours.

Table M1. *Definition of rainfall energy parameters (Extracted from Brodie (2007).*

Parameter	**Basis**	**Symbol**	**Units**
Peak 6 minute Rainfall intensity squared	Maximum rainfall intensity during 6 minute time increment squared	Peak I_6^2	mm^2/hr^2
Sum of 6 minute Rainfall intensity squared	Sum of rainfall intensity at 6 minute increments squared during time period within storm when rainfall intensity exceeded 0.25 mm/hr	$\sum I_6^2$	mm^2/hr^2

A more detailed description of the model and the work by Brodie can be found in his thesis (Brodie 2007).

The below Figures are extracted from Brodie and are referred to in the main text of this report.

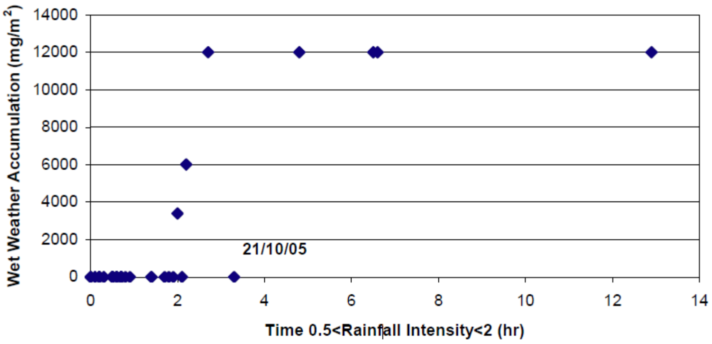
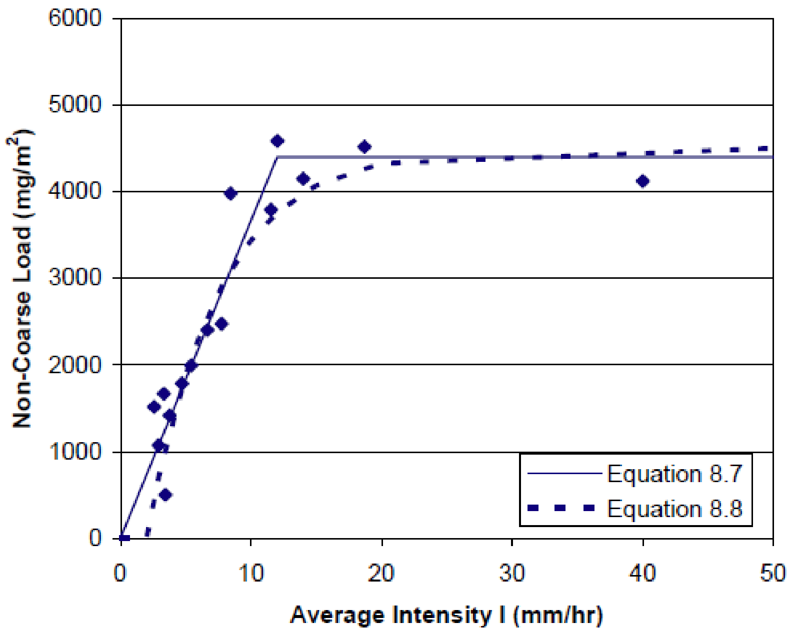


Figure 9.13 Plot of wet weather fine particle load (mg/m^2) on road surface used in refined mass balance analysis against the duration that rainfall intensity is within the range of 0.5 to 2mm/hr for December 2004 to January 2006 storm data



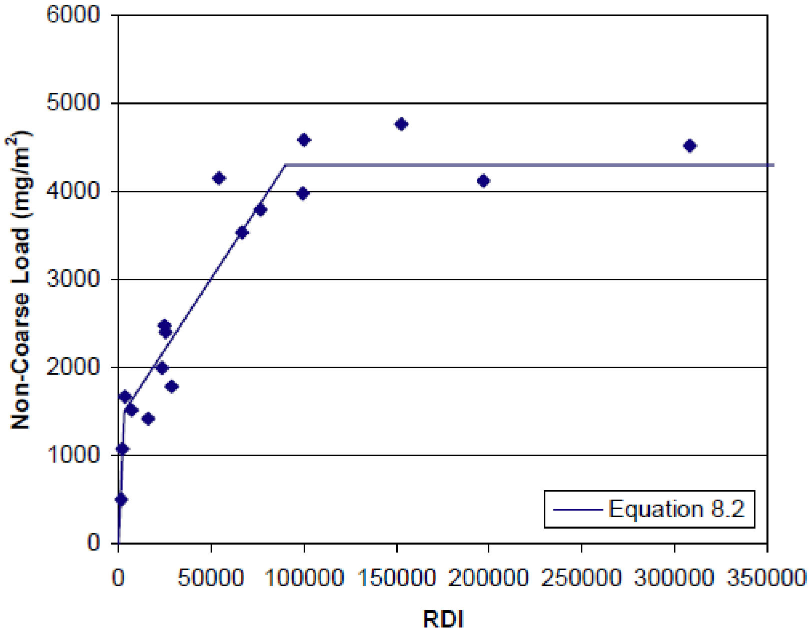
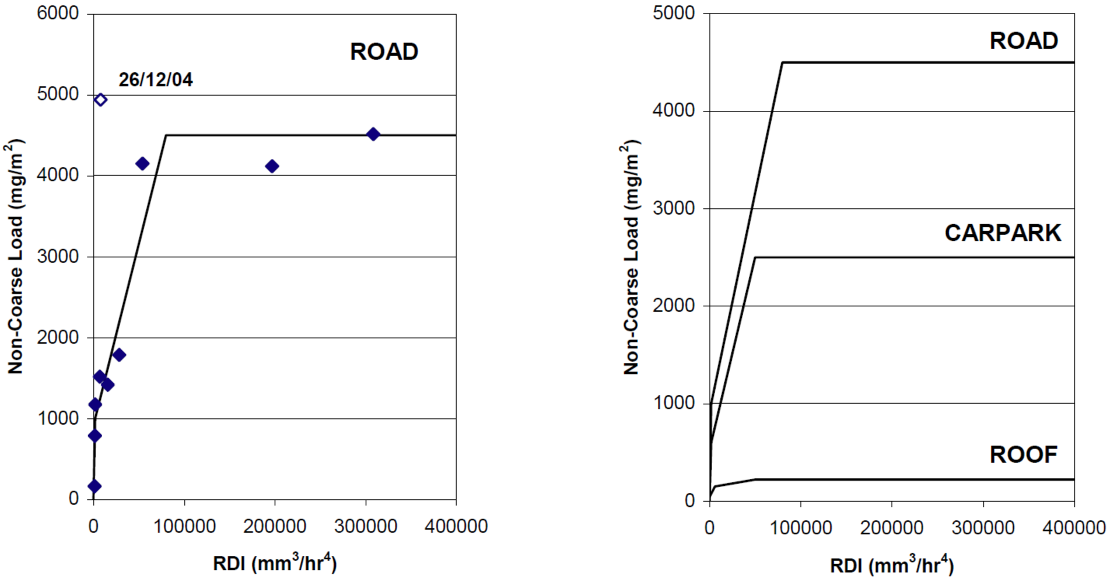


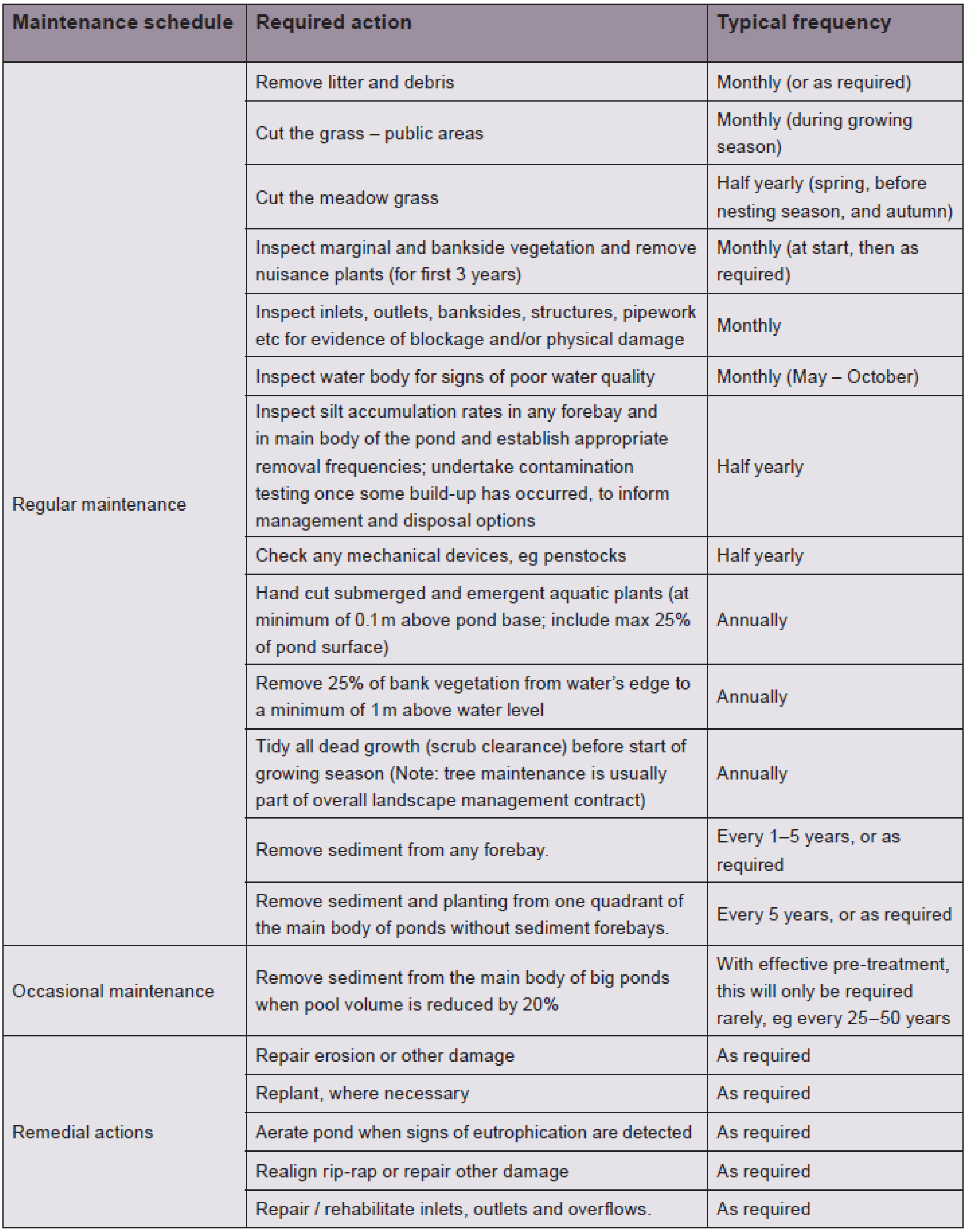
Figure 8.18 Road Non-Coarse Particle loads plotted against I and RDI using selected December 2004 to January 2006 data and showing fitted regression curves



- **Figure 8.3 Roof, carpark and road Non-Coarse Particle loads plotted against RDI based on December 2004 to February 2005 data. Fitted piecewise linear curves are also shown**

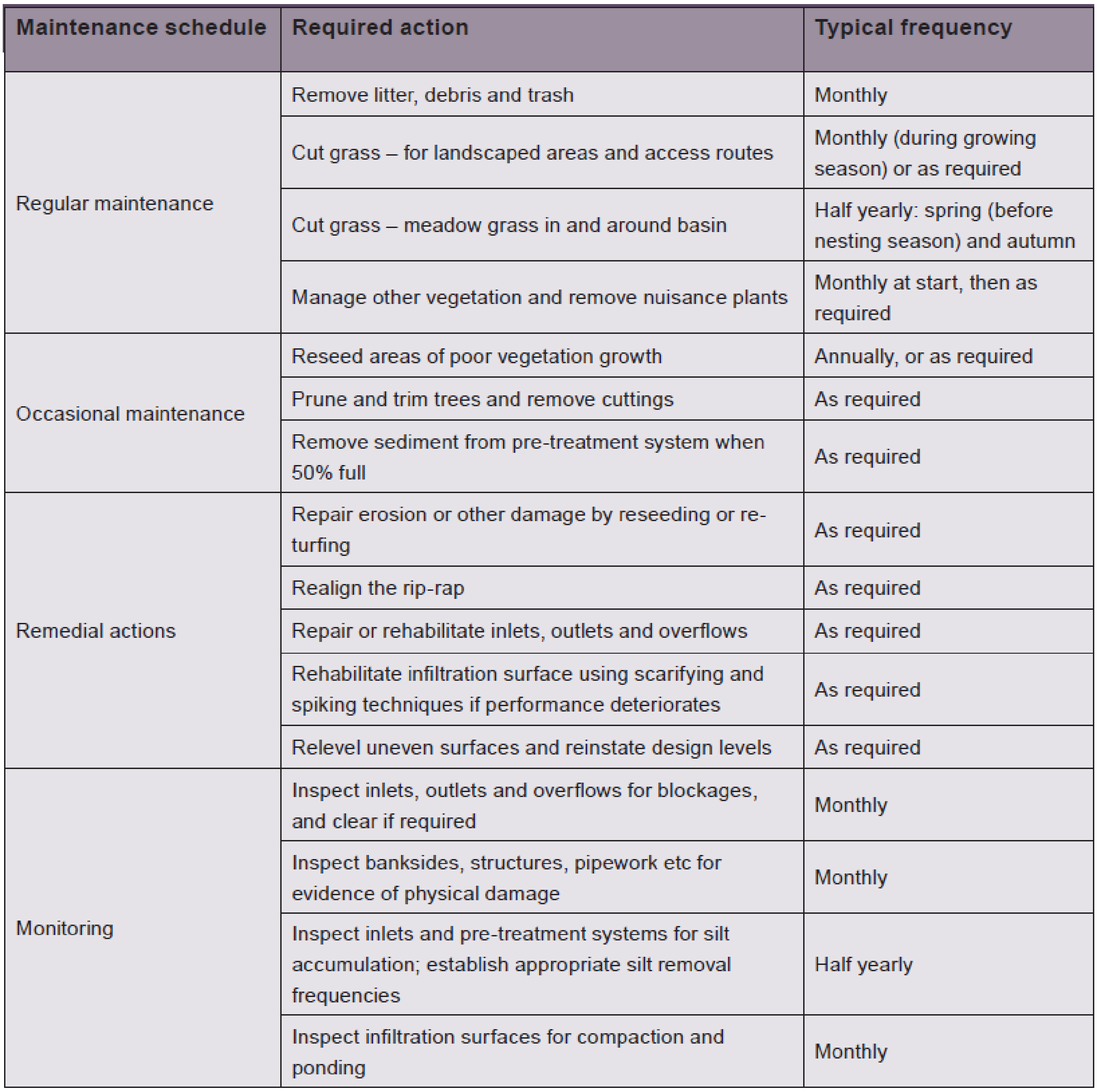
Appendix N. SuDS maintenance needs

Table N1. *Expected maintenance needs for* ***ponds and wetlands*** *(copy of table 23.1 in Woods Ballard et al. 2015 with courtesy of CIRIA).*



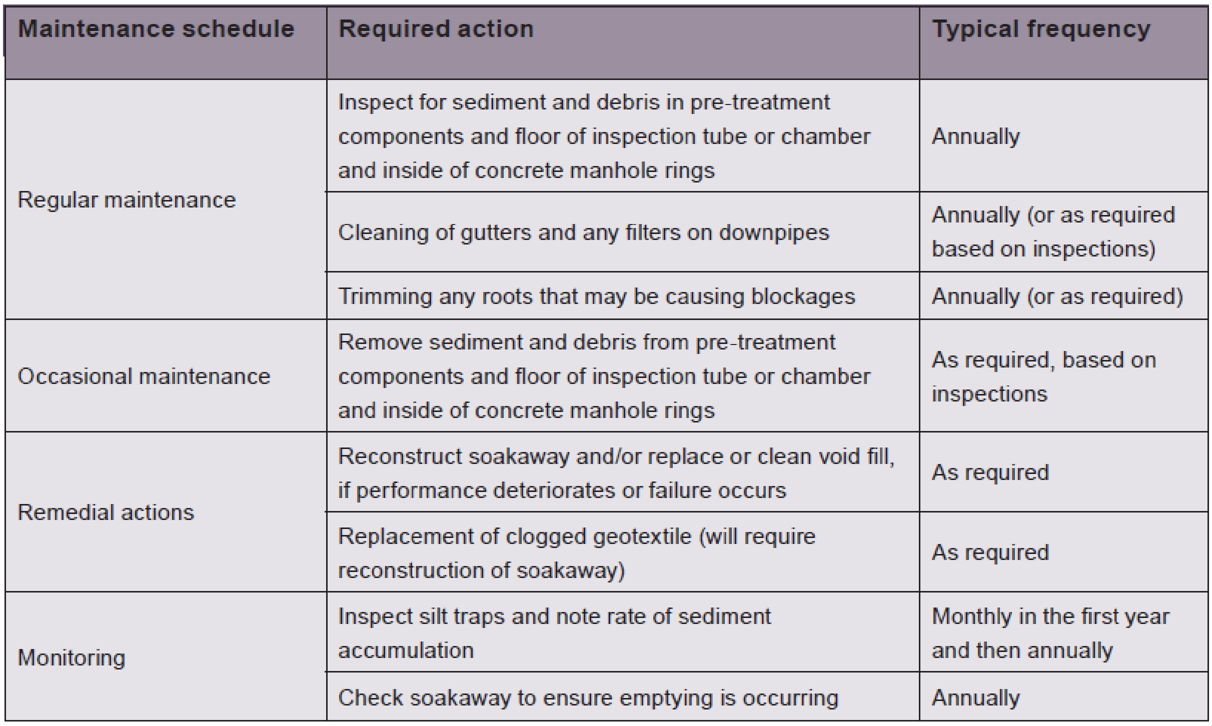
Maintenance schedule	Required action	Typical frequency
Regular maintenance	Remove litter and debris	Monthly (or as required)
	Cut the grass – public areas	Monthly (during growing season)
	Cut the meadow grass	Half yearly (spring, before nesting season, and autumn)
	Inspect marginal and bankside vegetation and remove nuisance plants (for first 3 years)	Monthly (at start, then as required)
	Inspect inlets, outlets, banksides, structures, pipework etc for evidence of blockage and/or physical damage	Monthly
	Inspect water body for signs of poor water quality	Monthly (May – October)
	Inspect silt accumulation rates in any forebay and in main body of the pond and establish appropriate removal frequencies; undertake contamination testing once some build-up has occurred, to inform management and disposal options	Half yearly
	Check any mechanical devices, eg penstocks	Half yearly
	Hand cut submerged and emergent aquatic plants (at minimum of 0.1 m above pond base; include max 25% of pond surface)	Annually
	Remove 25% of bank vegetation from water's edge to a minimum of 1 m above water level	Annually
	Tidy all dead growth (scrub clearance) before start of growing season (Note: tree maintenance is usually part of overall landscape management contract)	Annually
	Remove sediment from any forebay.	Every 1–5 years, or as required
	Remove sediment and planting from one quadrant of the main body of ponds without sediment forebays.	Every 5 years, or as required
Occasional maintenance	Remove sediment from the main body of big ponds when pool volume is reduced by 20%	With effective pre-treatment, this will only be required rarely, eg every 25–50 years
Remedial actions	Repair erosion or other damage	As required
	Replant, where necessary	As required
	Aerate pond when signs of eutrophication are detected	As required
	Realign rip-rap or repair other damage	As required
	Repair / rehabilitate inlets, outlets and overflows.	As required

Table N2. *Expected operation and maintenance needs for* ***infiltration basins*** *(copy of table 13.2 in Woods Ballard et al. 2015 with courtesy of CIRIA)*



Maintenance schedule	Required action	Typical frequency
Regular maintenance	Remove litter, debris and trash	Monthly
	Cut grass – for landscaped areas and access routes	Monthly (during growing season) or as required
	Cut grass – meadow grass in and around basin	Half yearly: spring (before nesting season) and autumn
	Manage other vegetation and remove nuisance plants	Monthly at start, then as required
Occasional maintenance	Reseed areas of poor vegetation growth	Annually, or as required
	Prune and trim trees and remove cuttings	As required
	Remove sediment from pre-treatment system when 50% full	As required
Remedial actions	Repair erosion or other damage by reseeding or re-turfing	As required
	Realign the rip-rap	As required
	Repair or rehabilitate inlets, outlets and overflows	As required
	Rehabilitate infiltration surface using scarifying and spiking techniques if performance deteriorates	As required
	Relevel uneven surfaces and reinstate design levels	As required
Monitoring	Inspect inlets, outlets and overflows for blockages, and clear if required	Monthly
	Inspect banksides, structures, pipework etc for evidence of physical damage	Monthly
	Inspect inlets and pre-treatment systems for silt accumulation; establish appropriate silt removal frequencies	Half yearly
	Inspect infiltration surfaces for compaction and ponding	Monthly

Table N3. *Expected operation and maintenance needs for* ***soakaways*** *(copy of table 13.1 in Woods Ballard et al. 2015 with courtesy of CIRIA)*



Maintenance schedule	Required action	Typical frequency
Regular maintenance	Inspect for sediment and debris in pre-treatment components and floor of inspection tube or chamber and inside of concrete manhole rings	Annually
	Cleaning of gutters and any filters on downpipes	Annually (or as required based on inspections)
	Trimming any roots that may be causing blockages	Annually (or as required)
Occasional maintenance	Remove sediment and debris from pre-treatment components and floor of inspection tube or chamber and inside of concrete manhole rings	As required, based on inspections
Remedial actions	Reconstruct soakaway and/or replace or clean void fill, if performance deteriorates or failure occurs	As required
	Replacement of clogged geotextile (will require reconstruction of soakaway)	As required
Monitoring	Inspect silt traps and note rate of sediment accumulation	Monthly in the first year and then annually
	Check soakaway to ensure emptying is occurring	Annually

Appendix O. Minutes from workshop

Workshop 25.9.2017 (kl. 10-14) i Miljødirektoratets lokaler på Helsfyr

Mikroplast og renseteknologi for veistøv i overvann - *referat*

Miljødirektoratet, Norsk institutt for vannforskning (NIVA) og Transportøkonomisk institutt (TØI) arrangerte denne workshopen om mikroplast i veiavrenning og teknologier for å rense ut veistøv. Workshopen var en del av et nystartet prosjekt finansiert av Miljødirektoratet. Hensikten med workshopen var å skape en arena for idémyldring og kunnskapsutveksling rundt sentrale tema med en målsetting om å sikre et godt kunnskapsgrunnlag og at alle viktige momenter blir vurdert i det videre prosjektarbeidet.

Dette referatet oppsummerer det som kom ut av gruppearbeidet under workshopen. Som deltakerlisten i Vedlegg 1 viser, var de tre gruppene godt representert med aktører med ulike roller og faglige erfaringer. **Takk til alle for alle innspill og bidrag til gode diskusjoner!**

Dette er et **første utkast til referat**, og vi håper på tilbakemeldinger og synspunkter på det som står her. Referatet sendes også ut til de inviterte som dessverre ikke hadde anledning til å være med på workshopen. Vi håper på innspill og kommentarer også fra dere!

Under gruppearbeidene var det et særskilt fokus på faktorer som bidrar til frigivelse, spredning og tilbakeholdelse av mikroplastpartikler, og faktorer som er med på å bestemme valg av ulike renseløsninger. For å systematisere de mange faktorene som ble trukket fram er disse blitt kategorisert som vist i **Tabell 1**. Disse kategoriene er brukt i den videre presentasjonen av resultatene.

***Tabell 1.** Kategorisering av faktorer identifisert under workshopen.*

Kategori	Beskrivelse	Faktorer
Partikkelkarakteristika	Omfatter partiklenes form, størrelse og egenvekt i tillegg til egenskaper som påvirker i hvilken grad de brytes ned videre eller binder seg til hverandre eller til andre partikler og tilstedeværende miljøgifter	• Geometrien til partiklene • Partikkelstørrelse og -sammensetning • Sekundær slitasje • Partiklenes tetthet/densitet (synke/flyte) • Svelling (både tetthet og størrelse) • Porøsitet • Klumper partiklene seg sammen? (partiklene danner kaker) • Binding til eventuelle andre typer partikler/humus • Bindingsegenskaper til aktuell miljøgift og plastpartikkel (tilstandsform)

Kategori	Beskrivelse	Faktorer
		• Hydrofobisiteten til gummi/plast-overflaten • Aldring av gummipartiklene
Kjøreadferd og trafikkbelastning	Omfatter både kjøremønster trafikkmengder, og kjøretøy-sammensetningen.	• Trafikkbelastning, ÅDT • Kjøremønster, kjørestil • Kjørehastighet, skiltet fart • Oppbremsing • Start og stopp • Tungtransport og masseforflytning (busser, traktorer, lastebiler) • Kollektivtransport (påvirker trafikkmengde) • Tyngde på kjøretøy • Sprut av veivann • Svikt i kjøretøy (ulykker, bilbrann)
Dekk	Omfatter dekkenes sammensetning og egenskaper	• Gummikvalitet, gummiblanding • Gummiens adsorpsjonsevne • Ute temperatur påvirker dekkene • Fyllstoffer • Additiver • Dekkegenskaper (hardhet og friksjon) • Alder på dekk (nye vs gamle) • Sommerdekk vs piggfrie vinterdekk • Tidspunkt for skifte fra sommer til vinterdekk • Piggdekk vs piggfritt • Årsak til slitasje
Vei	Omfatter type veidekke dets egenskaper, samt veiens utforming	• Type asfalt • Kvalitet på vei/asfalt (ruhet, friksjon i veibanen) • Tilsetningsstoffer i veidekket • Veimerkingsmaterialet (tetthet) • Kurvatur • Veiutforming (start-stopp, kryss, lys, rundkjøringer) • Type vei (RV, EV, kommunal og med/uten veimerking) • Vei vs tunnel • Årsak til slitasje
Veidrift	Omfatter drift og rengjøring av veier og tunneler	• Sandstrøing • Salting • Støvbinding (pga. luftkvalitet) • Veirengjøring • Vifter i tunneler • Feiing
Vær og klima	Omfatter alle typer vær- og klimafenomener	• Nedbørsmengde og -intensitet (regn og snø/snøsmelting)

Kategori	Beskrivelse	Faktorer
		• Nedbørshyppighet • Tørrvær • Flomutsatthet • Temperatur • Vindutsatthet • Årstidsvariasjoner • Klimaendring
Omgivelser	Omfatter alt som befinner seg i rimelig nærhet langs veien, både over og i bakken	• Vegetasjon (tetthet, høyde) • Bygninger (tetthet, høyde) • Helningsgrad langs vei • Grunnforhold • Harde overflater • Absorpsjon langs veiskulder • Giftstoffer i omgivelsene • Nærhet til vassdrag, vannveier • Ømfintlig område/resipient
Bortledningssystem for veivann	Omfatter alt som har med bortledning av veivann, både på overflaten og under overflaten (infiltrasjon, rørsystem)	• Avrenningsveier • Avrenningsforhold • Fordrøyning • Partikkelavrenning • Jordtype ift. transportegenskap • Overvann/grøftesystem • Fellesavløpssystem (AF-system)
Design renseløsninger	Omfatter hvordan renseløsningene er designet og tenkt å fungere, alene eller i et større system	• Størrelse/plassbehov/infrastruktur • Utforming • Utforming rist • Fleksibilitet (i utforming) • Modulbasert • Mulighet for ettermontering • Flere løsningstyper for ulike typer situasjoner • Kan kombineres med ekstra renseprosesser • Synergieffekt mellom ulike løsninger • Standardisering • Bærekraftighet • "Grønnhet"/attraktivitet • Lukket system • Desentralisert renseløsning
Belastning og effekt av renseløsninger	Omfatter hvordan renseløsningene belastes og hvordan dette påvirker dem	• Dimensjonering • Belastning (L/s) • Oppholdstid • Stabil vannstrøm gjennom enhet • Strømningsmønster (turbulens) gjennom enhet

Kategori	Beskrivelse	Faktorer
		• Mengde annen type forurensing (mulighet klogging) • Robusthet (mot gjentetting) • Renseeffekt
Drift og vedlikehold av renseløsninger	Omfatter drift, kontroll og vedlikehold av renseløsningene	• Enkelhet, driftsvennlighet • Lett fysisk tilgang for vedlikehold • Behov for oppfølging • Kontroll og drift • Overvåkning/sensor • Vedlikeholdsbehov, -hyppighet • Tømmehyppighet • Levetid
Erfaringsbase	Omfatter i hvilken grad renseløsningene er dokumentert å fungere og er tilgjengelige	• Historiske data • Dokumenterte løsninger • Tilgjengelighet • Pilotprosjekter
Økonomi	Omfatter alle økonomiske aspekter knyttet til investeringer, drift og vedlikehold	• Økonomi til vedlikehold • Kostnad/pris • Tilgjengelig økonomi
Administrativt	Omfatter administrative forhold og offentlige insentiver	• Samspill mellom veiforvalter og avløpsvirksomhet • Høye dokumentasjonskrav • Insentiver • Økonomiske virkemidler; forurenser betaler, verdisetting av natur/økosystemtjenester

Gjennomgang av resultatene fra gruppearbeidene

Det ble tatt utgangspunkt i de seks ulike hovedtemaene vist i **Tabell 2**. Til hvert hovedtema ble det stilt et sett med spørsmål hver enkelt og gruppen samlet sett skulle ta stilling til. For noen av spørsmålene var det lagt opp til en egen gruppeprosess for å få til dette. Denne er nærmere beskrevet i **Vedlegg 2**. Gjennom gruppeprosessen ble først de ulike faktorene identifisert, deretter ble deres innbyrdes viktighet vurdert, og til slutt ble kunnskapsstatus knyttet til hver enkelt faktor vurdert. I den følgende presentasjonen av resultatene fra gruppearbeidene er **viktigheten** vist som et vektet snitt mellom «0» (helt uviktig) til «3» (veldig viktig) og **kunnskapsstatus** vist som et vektet snitt mellom «0» (fraværende) til «2» (tilstrekkelig). For å angi hvor kunnskapsbehovet er størst er viktigheten multiplisert med kunnskapshullet (beregnet som «2» minus «kunnskapsstatus»; f.eks. hvis kunnskapsstatus var satt lik 1,5 blir kunnskapshullet 2-1,5=0,5, og hvis viktigheten var satt til «2,5» blir kunnskapsbehovet 0,5x2,5 = 1,25). For lett å kunne sammenligne verdiene for de ulike faktorene er det brukt et horisontalt stolpediagram internt i tabellene med grønne stolper for kolonnen med «viktighet», gule stolper for «kunnskapsstatus» og røde stolper for «kunnskapsbehov».

Gruppeprosess! (Foto: Mona E. Dadkhah)

Tabell 2. *Hovedtemaer for arbeidet i de ulike gruppene under workshopen.*

Hovedtema	Gruppe
Karakterisering av mikroplastpartiklene	Gruppe 1
Spredning av mikroplastpartikler	Gruppe 1
Effekt av sandfang	Gruppe 2 og gruppe 3
Hvor mye går til sentralt RA? Slam vs utslipp?	Gruppe 2
Erfaringer med eksisterende rensetekniske løsninger	Gruppe 2 og gruppe 3
Erfaringer med alternative rensetekniske løsninger	Gruppe 2 og gruppe 3

Hovedtema: Karakterisering

Oppgave	Innspill
Faktorer som påvirker frigivelsen av mikroplastpartikler • Hotspots – hvor forventes høyest konsentrasjon? • Sesongvariasjoner	Innspillene er oppsummert i **Tabell 3**. Veibelastning (ÅDT) og faktorer knyttet til dekkenes kvalitet ble ansett som viktigst, men kjøremønster og kvaliteten på veien viktig. Kunnskapsbehovet ble vurdert å være størst knyttet til betydningen av dekkenes kvalitet. Under diskusjonen ble følgende nevnt: • Partikler produsert ved bremsing har kanskje annen størrelse enn ved svingning, høy hastighet vs lav fart. Tunge biler produserer andre type partikler enn lette biler.
Faktorer som påvirker størrelsen og tettheten til partiklene	Identifiserte faktorer er listet opp i **Tabell 4**. Det ble ikke gjort noen innbyrdes vekting av faktorene eller vurdering av kunnskapsstatus. Under diskusjonen ble følgende spesielt trukket fram: • Tetthet til opphavsmaterialet. • Gummipartikler (tetthet større enn 1) suger til seg Hg/metaller, det samler seg opp på partiklene. • Tetthet under eller over 1. «Fusjonerer» med annet, aggregerer. • Forvitring av partikler endrer tettheten. • Trafikk knuser/kverner veistøvpartikler og endrer størrelsen
Utfordringer knyttet til kvantifisering av mikroplastpartikler	Kvantifisering av mikroplast er en utfordring ved at målemetoden gir føringer for hva du vil finne både i forhold til kjemisk sammensetning og størrelse. Dette henger igjen sammen med hvordan mikroplast blir definert.
Faktorer som påvirker innholdet av miljøgifter i mikroplastpartiklene	Identifiserte faktorer er listet opp i **Tabell 5**. Det ble ikke gjort noen innbyrdes vekting av faktorene eller vurdering av kunnskapsstatus.
Samlet vurdering	Det er store utfordringer med å definere hva som er plast og kvantifiseringen av plast i veistøv. Det er mange faktorer som påvirker og mye ukjente prosesser.

***Tabell 3.** Faktorer som påvirker frigivelsen av mikroplastpartikler. Vektingen av «viktighet» er gjort på bakgrunn av alle 9 som deltok i gruppearbeidet.*

Kategori	Faktor	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Bortledningssystem for veivann	Avrenningsveier, hardgjorte overflater	0,2	-	-
	Vei, infrastruktur (type vei, grøfter, sandfang)	?	-	-
Dekk	Bilgummikvalitet, dekkvalitet	1,7	0,5	2,5
	Dekkegenskaper	1,1	-	-
	Dekkvalitet (nye vs gamle)	1,1	1	1,1
	Gummilegering	1,7	0,5	2,5
	Piggdekk vs piggfritt	0,8	-	-
	Sommerdekk vs piggfrie	0,4	0,5	0,7
	Temperatur (vinterdekk osv.)	1,2	1	1,2
	Tidspunkt for skifte fra sommer til vinterdekk	?	-	-
Kjøreadferd og trafikkbelastning	Bremser vs dekk	?	-	-
	Busser, traktorer, lastebiler	0,3	-	-
	Kjøremønster/kjørestil	1,0	-	-
	Kollektivtransport (påvirker trafikkmengde)	0,3	-	-
	Skiltet fart/hurtighet	0,6	-	-
	ÅDT	2,0	2	0,0
Omgivelser	Helningsgrad	?	-	-
	Stigningsgrad på strekningen (vei/tunnel)	?	-	-
Vei	Kvalitet på vei/asfalt (abrasive?)	1,1	1	1,1
	Type asfalt	?	-	-
	Veiutforming (start og stopp)	0,6	-	-
Veidrift	Omgivelser, rengjøring, vannveger	0,6	-	-
	Veidrift; sandstrøing vs salting	1,0	1,5	0,5
	Veivask	0,9	1	0,9
Vær og klima	Nedbør (snø, regn)	1,2	1	1,2

***Tabell 4.** Faktorer som påvirker størrelsen og tettheten til partiklene*

Kategori	Faktor
Dekk	Additiver
	Alder på dekk
	Dekktemperatur
	Dekktype (pigger, piggfrie, sommer)
	Fyllstoffer
	Type gummi
Kjøreadferd og trafikkbelastning	Svikt i kjøretøy
Partikkelkarakteristika	Aldring av gummipartiklene
	Sekundær slitasje
	Svelling (både tetthet og størrelse)
Vei	Asfaltens ruhet, friksjon i veibanen
	Veimerkingmaterialet (tetthet)
	Årsak til slitasje

Tabell 5. *Faktorer som påvirker innholdet av miljøgifter i mikroplastpartiklene*

Kategori	Faktor
Dekk	Dekkets adsorpsjonsevne
	Innhold i dekk
Kjøreadferd og trafikkbelastning	Tungtransport og masseforflytning
Omgivelser	Giftstoffer i omgivelsene
	Medium (jord, vann,…)
Partikkelkarakteristika	Aldring av partikler
	Bindingsegenskaper til aktuell miljøgift og plastpartikkel (tilstandsform)
	Mikroplastpartiklenes overflateegenskaper (porøsitet, 4-X?)
	Tettheten >1 (synker) eller <1 (flyter i vann)
Vei	Tilsetningsstoffer i veidekket
Veidrift	Veisalting
	Veivasking/-drift

Hovedtema: Spredning

Oppgave	Innspill
Faktorer som påvirker spredningen via luft • Sesongvariasjoner • Veiutforming • Partikkelkarakteristika • Nedbør, smelting • Veivedlikehold	Identifiserte faktorer er listet opp i **Tabell 6**. Det ble ikke gjort noen innbyrdes vekting av faktorene eller vurdering av kunnskapsstatus. Mange av faktorene er overlappende med faktorer for avrenning da det er to komplementære prosesser. Det som ikke fjernes fra veien med vann er tilgjengelig for å spres i luft og motsatt. Følgende ble trukket fram under diskusjonen: • Plastpartikler blir ikke målt i luft i dag da regelverket går på partikkel masse (PM) og ikke kjemisk sammensetning. • Men godt utgangspunkt å bruke kunnskap vi har fra veistøv. • Fra kjemisk sammensetning ved reseptor modellering får man ofte dekk som partikkelkilde, med også en større eller mindre del som ikke er kvantifisert eller kun kvantifisert som veistøv. • Definisjon er viktig, hva er mikroplast?
Faktorer som påvirker spredningen via avrenning • Veiutforming • Partikkelkarakteristika • Nedbør, smelting • Veivedlikehold	Innspillene er oppsummert i **Tabell 7**. Et bredt spekter av faktorer ble vurdert som tilnærmet like viktige; partikkelkarakteristika, nedbør, adsorpsjon til veiskulder, bortledningssystem for veivann og vedlikehold av sandfang o.l. Kunnskapsbehovet ble vurdert som størst knyttet til bortledningssystemet, men det er også behov for mer kunnskap knyttet til partikkelkarakteristika og betydningen av nedbør og sesongvariasjoner. Det ble vurdert til at man hadde lite kunnskap om de fleste prosessene direkte knyttet til mikroplast og mer kunnskap om miljøgifter og veistøv generelt. Det er mulig at man kan dra nytten av den kunnskapen, men det er også forventet at mikroplasten vil kunne oppføre seg annerledes. Det gjelder for de fleste av faktorene.

	Under diskusjonen ble følgende spesielt trukket fram: • sprut>avrenning • Belastning på ulike veier, groper i vei, helling etc. gjør at noen sandfang blir mer belastet slik at vedlikeholds behov vil kunne variere mye. • Modellering av bilgummipartikler, mangler en del inputdata, • Flom tilsier at vannmengdene er så store at avløp og drenering ikke klarer å ta unna. Spredningen vil dermed være veldig ulik sammenlignet med normal situasjonen.
Faktorer som vanskeliggjør en kvantifisering av spredningen	Følgende faktorer ble trukket fram: • Spørsmål knyttet til definisjon av mikroplast: Hva er mikroplast? Hva skal man kalle det, polymer? Egenskap vs kjemisk sammensetning. Ikke viktig å skille mellom naturgummi eller plast; naturgummi går inn i definisjonen, siden den har plast-liknende egenskaper. Nedre partikkelstørrelse operasjonelt definert (gitt av cut-off på utstyr), men PM <2,5 ikke godt kvantifisert i dag. • Generelt en problemstilling om enheter; masse vs antall partikler og/eller størrelse. • Vanskelig å kvantifisere mikroplast i miljøprøver, og spesielt kloakkslam, da signalene blir skult/maskert av forstyrrende elementer i slammet («matriks-effekt»).
Samlet vurdering	

Tabell 6. *Faktorer som påvirker spredningen via luft*

Katogori	Faktor
Dekk	Dekkets egenskaper; gummi
	Dekktype; pigg, sommer, piggfri
Kjøreadferd og trafikkbelastning	Hastighet
	Trafikktype
	Trafikkvolum
Omgivelser	Bygninger (tetthet, høyde)
	Vegetasjon (tetthet, høyde)
Partikkelkarakteristika	Geometrien til partiklene
	Partikkelstørrelse/tetthet
Vei	Asfalttype
Veidrift	Renhold
	Vedlikehold av veg
	Vegdrift
	Vifter i tunneler (renhold)
Vær og klima	Vindutsatt?
	Vær; tørrvær?

Tabell 7. *Faktorer som påvirker spredningen via avrenning. Vektingen av «viktighet» er gjort på bakgrunn av alle 9 som deltok i gruppearbeidet.*

Kategori	Faktor	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Bortledningssystem for veivann	Avløp, sandfang, fordrøyning	1,8	0,5	2,7
	Jordtype ift transportegenskap	1,8	1,5	0,9
	Overvann/grøftesystem	1,8	0,5	2,7
Drift og vedlikehold av renseløsninger	Vedlikehold av sandfang/oppsamlingskum o.l.	1,9	2	0,0
Kjøreadferd og trafikkbelastning	Sprut av veivann	0,8	1,5	0,4
Omgivelser	Absorpsjon langs veiskulder	1,8	1,5	0,9
	Nærhet til vassdrag	0,9	1,5	0,4
	Terreng; helningsgrad langs veien	0,4	2	0,0
	Vegetasjon (hindrer spredning)	1,0	0,8	1,2
Partikkelkarakteristika	Binding til eventuelle andre typer partikler/humus	1,8	1,5	0,9
	Hydrofobisiteten til gummi/plast-overflaten	1,8	1	1,8
	Klumper partiklene seg sammen? (partiklene danner kaker)	1,8	1	1,8
	Størrelse på partiklene	1,8	1	1,8
	Tettheten; synke/flyte	1,8	1	1,8
Veidrift	Feiing	1,0	1,5	0,5
	Vedlikehold av vei, kvalitet av vei	0,4	1	0,4
Vær og klima	Nedbør; mengde og intensitet; flomutsatt eller ikke	1,7	1	1,7
	Årstidsvariasjoner	0,9	0	1,8

Hovedtema: Effekt av sandfang

Oppgave	Innspill
Hvilke faktorer påvirker effekten av sandfang som barriere	Innspillene fra gruppe 2 er oppsummert i **Tabell 8**. De faktorene som ble ansett som viktigst var sandfangets utforming og dimensjonering, belastning og strømningsmønsteret og oppholdstiden inne i sandfanget, samt tømmefrekvens og økonomi satt av til vedlikehold. Mange av disse faktorene er også innbyrdes påvirket eller avhengige av hverandre. Utformingen av risten i forkant av sandfanget er også viktig. Samtidig ble kunnskapsbehovet knyttet til nesten alle disse faktorene vurdert som betydelig, da fem av dem skåret >5 poeng av 6 mulige poeng. Følgende ble trukket fram under diskusjonen i **Gruppe 2**: • Usikkert om salt har en positiv eller negativ effekt på fjerningen. Salt kan påvirke på overflateladningen til partiklene og dermed føre til aggregering. • Sandfang kan kombineres med andre teknikker, men vi vet ikke effekten på fjerningen av mikroplast. • Vi kjenner ikke optimal/nødvendig oppholdstid for å holde tilbake mikroplast. • Det er mange ulike utforminger av sandfang, men det er ikke kjent hvilke som er best egnet til fjerning av mikroplast

	- Noen studier har sett på betydningen av tømmefrekvens for tilbakeholdelse av partikler i sandfang, men disse har hatt fokus på sand. Følgende faktorer ble trukket fram under diskusjonen i **Gruppe 3**: - Partikkelbelastning - Partikkelstørrelse - Volum sandfang, større sandfang? - Fordrøyning i sandfang - Vannmengde og vannhastighet/turbulens - Følsomt for tilstedeværelse av olje og fett? - Vedlikehold/tømming - Måling av fyllingsgrad og vedlikehold - Feiing - Snøsmelting - Bør ha dykket utløp
Hvilke mikroplastpartikler kan forventes å bli holdt tilbake?	Rensing av mikroplastpartikler som stammer fra bildekk i sandfang er trolig lav. Sandfang er effektiv på partikler i området ned mot 0,3 - 0,5 mm. Mikroplastpartikler fra bildekk er ofte i størrelsesorden <0,1 mm. Tilbakeholdelse/rensing vil kunne skje ved at partiklene aggregerer.
Samlet vurdering	Sandfang slik de er utformet i dag er lite egnet for å holde tilbake mikroplastpartikler.

Tabell 8. *Hvilke faktorer påvirker effekten av sandfang som barriere. Vektingen av «viktighet» er basert på snittet av de som hadde gitt poeng for hver enkelt faktor.*

Katogori	Faktor	Antall svart	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Belastning og effekt av renseløsninger	Belastning (L/s)	4	2,3	2	0,0
	Dimensjonering	4	2,8	0	5,5
	Oppholdstid	5	2,4	0	4,8
	Strømningsmønster (turbulens)	5	3,0	2	0,0
Bortledningssystem for veivann	Avrenningsforhold	2	2,0	1	2,0
	Partikkelavrenning i nedbørfeltet	4	1,8	1	1,8
Design renseløsninger	Desentralisert renseløsning	3	2,7	2	0,0
	Kan kombineres med ekstra renseprosesser	4	1,5	2	0,0
	Utforming	4	3,0	0	6,0
	Utforming rist	3	2,3	1	2,3
Drift og vedlikehold av renseløsninger	Drift & vedlikehold	5	3,0	0	6,0
	Tømmehyppighet	4	3,0	0	6,0
	Vedlikehold; lett tilgang fysisk	4	1,0	2	0,0
Partikkelkarakteristika	Partikkelstørrelse, -sammensetning	5	2,6	0	5,2
Veidrift	Salt	3	1,3	0	2,7
Vær og klima	Nedbørintensitet	4	1,8	2	0,0
Økonomi	Økonomi til vedlikehold	3	3,0	2	0,0

Hovedtema: Hvor mye går til sentralt RA? Slam vs utslipp?

Oppgave	Innspill
Hvilke faktorer har mest å si for et nasjonalt estimat for tilførsler til sentrale renseanlegg?	Innspillene er oppsummert i **Tabell 9**. Tilstedeværelsen av et fellessystem for avløp og overvann for bortledning av veivann ble ansett som enkeltfaktoren av størst betydning, men også faktorer som bidrar til mikroplastpartikler i veiavrenningen (oppbremsing, ÅDT, kjørehastighet) og nedbørshyppighet ble naturlig nok vektet høyt. Det største kunnskapsbehovet ble vurdert å være knyttet til betydningen av kjøreadferden, piggdekkbruk og veiens kurvatur, men også betydningen av sandfang og vedlikehold av overvannsløsninger er viktig å få belyst.
Faktorer som vanskeliggjør en kvantifisering av de nasjonale tilførslene	To faktorer ble trukket spesielt fram: • Manglende kunnskap om hvilke områder/veier som drenerer til AF-systemet og hvilke som ikke gjør det. • Manglende kunnskap om hvor mye som fanges opp/forsvinner i nærområdet. • Et veldig grovt estimat kan muligvis beregnes ut fra antall sandfang, hvor de ligger og hvor mye avløpsvann som går gjennom disse.
Hvilke rensetrinn har mest å si for at mikroplastpartiklene blir fanget opp?	Alle rensetrinnene med partikkelfjerning kan i utgangspunktet bidra til fjerningen av mikroplastpartikler. Dette gjelder siling med mikrosil og sedimentering med og uten kjemisk felling og i tilknytning til slamsepareringen i aktivslamprosessen. Lang oppholdstid er bestemmende ved sedimentering, men kjemisk felling vil i betydelig grad kunne bedre fjerningen (øker sedimenteringshastigheten). Sistnevnte er sannsynligvis avhengig av hvilke fellingskjemikalier som brukes og overflateegenskapene til mikroplastpartiklene. Effekten er også avhengig av hvilke partikkelstørrelsesfraksjoner som er lagt til grunn.
Samlet vurdering	Det er store usikkerheter knyttet til hvor mye av mikroplastpartiklene i veiavrenningen som ender opp i AF-systemet. På renseanleggene er det mange ulike renseprosesser som kan bidra til fjerningen, men det er usikkert i hvilken grad de fine mikroplastpartiklene i veiavrenning fanges opp.

Tabell 9. *Hvilke faktorer har mest å si for et nasjonalt estimat for tilførsler til sentrale renseanlegg? Vektingen av «viktighet» er basert på snittet av de som hadde gitt poeng for hver enkelt faktor.*

Kategori	Faktor	Antall svart	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Bortledningssystem for veivann	AF-system	2	3,0	2	0,0
Dekk	Andel piggfrie dekk	4	2,0	0,5	3,0
Drift og vedlikehold av renseløsninger	Vedlikehold lokale overvannsløsninger	3	1,7	0,5	2,5
Kjøreadferd og mengde	Kjørehastighet	4	2,3	0,5	3,4
	Oppbremsing	4	2,8	1	2,8
	ÅDT	4	2,5	0,7	3,3
Lokale overvannsløsninger	Lokale overvannsløsninger	3	1,7	1	1,7
	Sandfang	6	1,8	0,2	3,3
Vei	Kurvatur	4	2,0	0,5	3,0
	Type asfalt	3	2,0	0,2	3,6
Veidrift	Feiehyppighet	1	?	?	-
	Salting pga luftkvalitet	3	0,3	0	0,7
Vær og klima	Nedbørshyppighet	3	2,3	1,5	1,2

Hovedtema: Erfaringer med eksisterende rensetekniske løsninger

Oppgave	Innspill
Hvilke faktorer har betydning for valget av renseløsning for veiavrenning langs hovedveier utenfor byene?	Innspillene fra Gruppe 3 er oppsummert i **Tabell 10**. Et bredt spekter av faktorer ble vurdert som viktige for valget av renseløsninger der vannmengde, trafikkbelastning, partikkelkarakteristika (størrelse og tetthet), renseløsningens fleksibilitet, robusthet og bærekraft samt behov og kostnader knyttet til drift og vedlikehold ble vektet høyest. Kunnskapsbehovet ser ut til å være størst knyttet til betydningen av renseløsningenes fleksibilitet, robusthet og bærekraft, samt trafikkbelastningen og resipientens følsomhet. Det er også behov for økt kunnskap om betydningen av samspillet mellom veiforvalter og avløpsvirksomheten.
Hvilke faktorer har betydning for valget av renseløsning for veiavrenning inne i urbane områder med betydelig plassbegrensning?	Innspillene fra Gruppe 2 er oppsummert i **Tabell 11**. Faktorene som ble vektet høyest (≥2,7) var forhold knyttet til drifts- og vedlikehold av renseløsningen (enkelhet, driftsvennlighet, robusthet og nødvendig frekvens for vedlikehold) og mulighet for ettermontering i tillegg til renseløsningens renseeffekt (ikke mht. mikroplastpartikler). Kunnskapsbehovet ser ut til å være størst knyttet til renseeffekten (for mikroplastpartikler) og betydningen av drifts- og vedlikehold, dette også sett i lys av ulike årstider. Under diskusjonen ble følgende spesielt nevnt: • Kunnskap om løsninger som kan fjerne partikler er tilgjengelig, men lite dokumentasjon knyttet til fjerningen av mikroplast (og salt) fra veivann.

	• Rensetiltak er i dag primært satt inn for rensing av vaskevann fra tunneler, men lite for annet veivann (med unntak av sandfang).
Hvilke renseløsninger, som brukes i Norge i dag, fungerer som en barriere mot mikroplastpartikler?	Renseløsninger basert på infiltrasjon i kombinasjon med fordrøyning og sedimentasjon er sannsynligvis de som best fungerer som en barriere mot mikroplastpartikler. Dette er godt dokumentert for partikler generelt, men ikke for mikroplastpartikler.
Hvilke faktorer påvirker effekten av renseløsningene som barriere	Innspillene fra Gruppe 3 er oppsummert i **Tabell 12**. Igjen var det et bredt spekter av faktorer ble vurdert som viktige for renseeffekten mot mikroplastpartikler der de som ble ansett som aller viktigst (≥2,6) var partikkelstørrelsen, vannmengden i forhold til dimensjonering, samt tilstrekkelig oppholdstid og stabil vannstrøm, godt vedlikehold og økonomi. Det å ha gjennomført pilotprosjekter virker også positivt.
Samlet vurdering	Riktig design og dimensjonering, samt å sørge for tilstrekkelig vedlikehold (inkludert økonomi for dette) er sentralt for at renseløsningene skal fungere. Kunnskapen om hvilke løsninger som fungerer mot mikroplastpartikler er begrenset, men det er grunn til å anta at det først og fremst er infiltrasjonsløsningene som fungerer best til dette formål av dagens renseløsninger.

Tabell 10. *Hvilke faktorer har betydning for valget av renseløsning for veiavrenning <u>langs hovedveier utenfor byene</u>? Vektingen av «viktighet» er basert på snittet av de som hadde gitt poeng for hver enkelt faktor.*

Kategori	Faktor	Antall svart	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Administrativt	Samspill mellom veiforvalter og avløpsvirksomhet	6	1,7	0	3,3
Belastning og effekt av renseløsninger	Mengde annen type forurensning (mulighet klogging)	8	1,8	2	0,0
	Vannmengde	5	3,0	1	3,0
Design renseløsninger	Fleksibilitet, robusthet og bærekraft	6	2,8	0	5,7
Drift og vedlikehold av renseløsninger	Grad av oppfølging	7	2,4	2	0,0
	Kostnad, levetid, drift og vedlikehold	7	2,6	1	2,6
	Vedlikeholdsbehov	6	2,5	2	0,0
Erfaringsbase	Historisk data	5	1,8	1	1,8
Kjøreadferd og mengde	Trafikkbelastning	6	2,7	0	5,3
Omgivelser	Grunnforhold	5	1,8	2	0,0
	Ømfindtlig område/resipient	3	2,3	0	4,7
Partikkelkarakteristika	Partikkeldensitet	6	2,7	1	2,7
	Partikkelstørrelse	7	2,7	1	2,7
Vei	Type vei / med eller uten veimerking	4	2,3	1	2,3

Tabell 11. *Hvilke faktorer har betydning for valget av renseløsning for veiavrenning <u>inne i urbane områder med betydelig plassbegrensning</u>? Vektingen av «viktighet» er basert på snittet av de som hadde gitt poeng for hver enkelt faktor.*

Kategori	Faktor	Antall svart	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Belastning og effekt av renseløsninger	Renseeffekt	6	2,7	0,3	4,5
Design renseløsninger	"Grønnhet"/attraktivitet	5	2,0	1,8	0,4
	Fleksibilitet i utforming	3	2,3	1,8	0,5
	Flere løsningstyper for ulike typer situasjoner	2	2,0	-	-
	Modulbasert	4	2,0	1,8	0,4
	Mulighet for ettermontering	3	2,7	-	-
	Robust utforming (mot gjentetting)	6	3,0	1	3,0
	Standardisert	5	2,2	2	0,0
	Størrelse/plassbehov	4	2,5	2	0,0
Drift og vedlikehold av renseløsninger	Enkelhet, driftsvennlighet	5	3,0	1	3,0
	Robusthet	4	3,0	1	3,0
	Vedlikeholdshyppighet	6	3,0	1	3,0
Erfaringsbase	Dokumenterte løsninger	5	2,0	1,5	1,0
	Tilgjengelighet	3	2,3	2	0,0
Omgivelser	Resipient	4	2,5	2	0,0
	Terrengfall	3	2,0	1,8	0,4
Veidrift	Salt	3	1,0	0,3	1,7
Vær og klima	Årstider	4	2,0	0,5	3,0
Økonomi	Pris	6	1,7	1,5	0,8

Tabell 12. *Hvilke faktorer påvirker effekten av renseløsningene som barriere? Vektingen av «viktighet» er basert på snittet av de som hadde gitt poeng for hver enkelt faktor.*

Kategori	Faktor	Pos./Neg.	Antall svart	Viktighet (snitt)	Kunnskaps-status (0-2)	Kunnskaps-behov
Administrativt	Høye dokumentasjonskrav	Negativ	7	2,1	1	2,1
Belastning og effekt av renseløsninger	Dimensjonering	Negativ	5	2,6	2	0,0
	Feil dimensjonering/ klogging	Negativ	4	2,0	1	2,0
	Nedbørsmengde/ vannmengde	Negativ	5	2,8	1	2,8
	Oppholdstid	Positiv	6	2,7	2	0,0
	Stabil vannstrøm	Positiv	7	2,6	2	0,0
	Turbulens	Negativ	6	2,0	2	0,0
Design renseløsninger	Lukket system	Positiv	6	2,3	0	4,7
	Plass / infrastruktur	Negativ	6	2,5	2	0,0
	Synergieffekt mellom ulike løsninger	Negativ	6	2,0	1	2,0
Drift og vedlikehold av renseløsninger	Dårlig kontroll og drift	Negativ	4	2,5	1	2,5
	Godt vedlikehold	Positiv	5	3,0	2	0,0
	Manglende vedlikehold	Negativ	5	3,0	2	0,0
	Overvåkning/sensor	Positiv	5	2,2	0	4,4
Erfaringsbase	Pilotprosjekter	Positiv	6	2,8	0	5,7
Partikkelkarakteristika	Aggregering med andre partikler	Positiv	5	2,4	0	4,8
	Partikkelstørrelse	Positiv	7	2,7	0	5,4
Vær og klima	Klimaendring	Negativ	4	3,0	1	3,0
Økonomi	Tilgjengelig økonomi	Negativ	5	2,6	1	2,6

Hovedtema: Erfaringer med alternative rensetekniske løsninger

Oppgave	Innspill
Hvilke andre renseløsninger kan være aktuelle langs hovedveier utenfor byene? Hva er de viktigste begrensingene til disse?	Følgende er i hovedsak en oppsummering av diskusjonen i Gruppe 3, men med enkeltinnspill fra Gruppe 2: Aktuelle løsninger som ble nevnt: • Infiltrasjon med sedimentering i forkant • Våtmark • Laguner • Filterbasseng med dren i bunn • Lukkede nedgravde sedimentasjonsbasseng med infiltrasjon • Filtergrøft med dren i bunn • Seriekoblede sandfang med infiltrasjonsgrøft • Regnbed med rensing av veivann • Forbehandling og etterpolering i rensedam • Langtidssedimentering i lukket system • Membran bioreaktor (MBR) og vakuum-roterende membran/diskfilter (VRM), eventuelt tilsatt aktivkull • Mediafiltere • Finrister (screens)

	• Mekanisk separering • Filtrering gjennom geotekstiler • Kjemisk felling • Desentraliserte avløpsløsninger • Pumping videre til sentralt renseanlegg • Biofiltere • Mobile renseenheter • Flotasjon; HDF/DAF • Filtrasjonsgrøfter Løsninger knyttet til veivasking: • Flere el-drevne biler til veivasking • Utvikling av filter til multi-use Andre momenter som ble nevnt: • Viktig å bruke sidearealene langs veiene • Grøfterens ønsker minst mulig vekst (reduserer behov), men ikke optimalt mht. renseeffekt/tilbakeholdelse av forurensninger • I framtiden kanskje det kan settes krav til sammensetning av jordmassene i veigrøftene for å sikre infiltrasjon • Trær fungerer som rensing, men det er et siktkrav langs hovedveiene • Desentraliserte løsninger best (der mulig)
Hvilke andre renseløsninger kan være aktuelle inne i urbane områder med betydelig plassbegrensning? Hva er de viktigste begrensingene til disse?	Følgende er i hovedsak en oppsummering av diskusjonen i Gruppe 3, men med enkeltinnspill fra Gruppe 2: • Urealistisk å rense "alt" overvann i bykjernen/sentrumsområdene. Det ville kreve mange kompakte og høyteknologiske løsninger som vil være altfor kostnadskrevende. Løsningen er å ha gode og velfungerende fellessystemer, samt avskjæring av overflateavrenning fra tak, bygårder etc. hvor man tar i bruk fordrøyning/infiltrering der det er mulig. Det vil gi bedre kapasitet i fellessystemet og muligheten for å rense vegvann i renseanleggene. • Viktig at man har gode feie- og renholdsrutiner av gater og veier • Viktig at sandfang driftes og vedlikeholdes. Imidlertid ble det påpekt at sandfang trolig IKKE kan rense mikroplastpartikler. • Det er ønskelig å kunne teste ut pilotanlegg for rensing • Det er ønskelig at det etableres en erfaringsdatabase over ulike løsninger. Det finnes imidlertid en base i USA som inneholder store mengder data http://www.bmpdatabase.org/index.htm . Klima2050 er i tillegg i gang med å etablere http://www.ovase.no/
Samlet vurdering	Det finnes en lang rekke alternative løsninger for rensing av veivann utenfor byene, men foreløpig lite dokumentasjon av disse mht. effekt på mikroplastpartikler. I byene vil det være aktuelt å kombinere flere tiltak for å begrense mengden som må renses: • Gode feie- og renholdsrutiner • Avskjære avrenning fra mindre forurensede flater

	• Fordrøyning og infiltrasjon for å kontrollere den volumetriske belastningen på rensesystemene, enten disse er sentraliserte eller desentraliserte Uttesting av aktuelle løsninger i pilotskala vil være viktig for å skaffe nødvendig dokumentasjon.

Vedlegg 1 – Gruppeinndeling under workshopen «Mikroplast og renseteknologi for veistøv i overvann» 25.9.2017

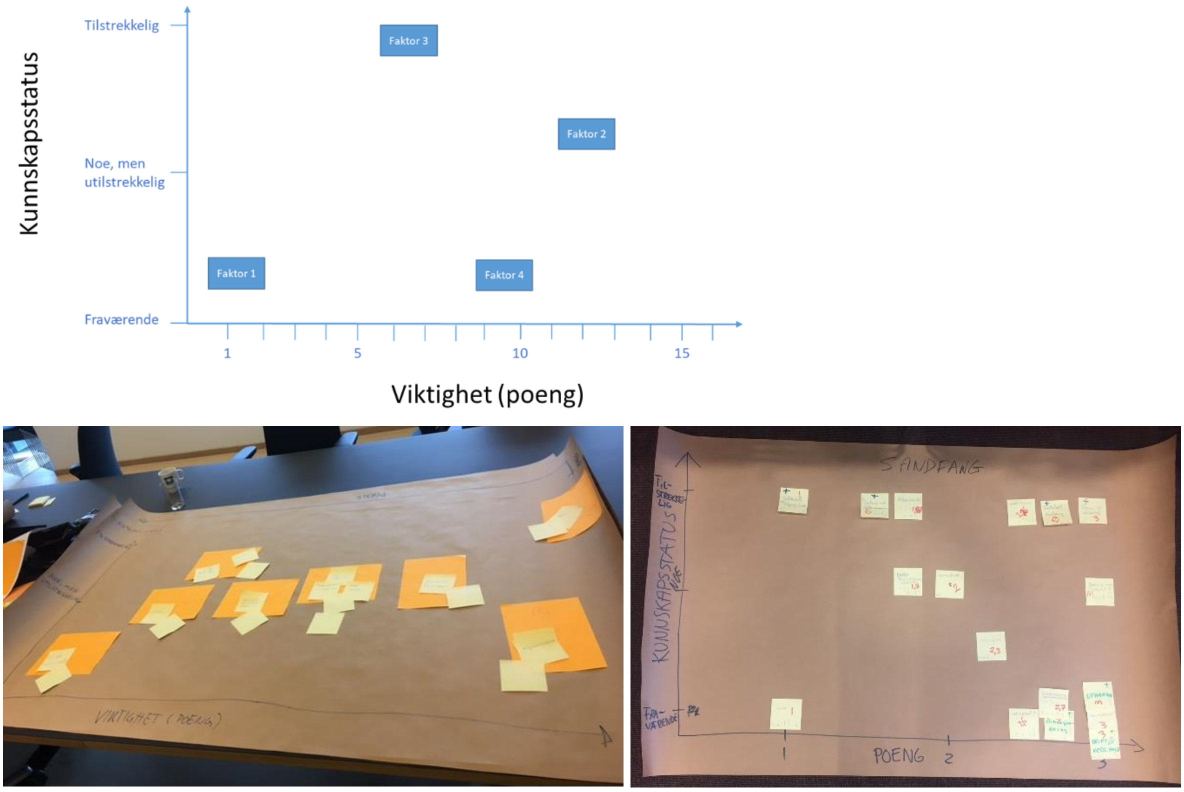
Gruppe	Navn	Tilhørighet	Rolle
Gruppe 1 – Karakterisering og spredning	Ingrid Sundvor	TØI	Moderator
	Sissel Brit Ranneklev	NIVA	Referent
	Claire Coutris	NIBIO	FoU
	Hans Kristian Daviknes	Bymiljøetaten	Problemeier
	Lene Sørlie Heier	Statens vegvesen	Problemeier
	Erik Joner	NIBIO	FoU
	Elisabeth Lundsør	Norconsult AS	Konsulent
	Benjamin Alcock	SINTEF Materialer og nanoteknologi	FoU
	Elisabeth Rødland	Statens vegvesen	Problemeier
	Karl Idar Gjerstad	Statens vegvesen	Problemeier
	John Norberg	Trafikverket (Sverige)	Problemeier
Gruppe 2 – Rense-teknologier	Christian Vogelsang	NIVA	Moderator
	Mona Eftekhar Dadkhah	NIVA	Referent
	Sogge Johnsen	Basal	Leverandør
	Arne Haarr	Norsk Vann	Interesse-organisasjon
	Heidi Kristensen	Bymiljøetaten	Problemeier
	Svein Ole Åstebøl	COWI AS	Konsulent
	Kjersti Kronvall	Statens vegvesen	Problemeier
	Muhammad Umar	NIVA	FoU
Gruppe 3 – Rense-teknologier	Sondre Meland	NIVA	Moderator
	Trine-Lise Torgersen	Miljødirektoratet	Referent
	Jes Vollertsen	Aalborg Universitet	FoU
	Magne Stokka	Rambøll	Konsulent
	Fredrik Myhre	WWF Verdens naturfond	Interesse-organisasjon
	Per Møller-Pedersen	Storm Aqua AS	Leverandør
	Harald Fjære	Huber Norge NUF	Leverandør
	Simon Haraldsen	FMOA	Problemeier
	Kamal Azrague	Sintef Byggforsk	FoU
	Jaran Raymond Wood	Leca Norway	Leverandør

Vedlegg 2 – Anvendt gruppeprosess under workshopen «Mikroplast og renseteknologi for veistøv i overvann» 25.9.2017

De tre gruppene fikk i oppgave å identifisere og vurdere betydningen av faktorer knyttet til en rekke problemstillinger knyttet til mikroplast i veiavrenning. Problemstillingene er vist lenger nede. For de problemstillingene som er markert med blå skrift skulle gruppene gå gjennom en egen gruppeprosess, som var tenkt gjennomført som følger:

1. Individuelt (5 min): Hvilke faktorer har betydning? Én faktor på hver Post-it-lapp!
2. Plenum (5 min): Sammenstilling; fjerne duplikater. Noen som mangler?
3. Individuelt (5 min): Hvor viktig er hver enkelt faktor? Angi poeng på hver lapp;
    - fra «0» (helt uviktig) til «3» (veldig viktig).
    - «?» hvis man ikke har noen formening
4. Plenum (5 min): Oppsummering av poeng og plassering på tallinje (x-akse)
5. Plenum (10 min): Vurdering av kunnskapsstatus for hver enkelt faktor
    - Fra «0» (fraværende) til «2» (tilstrekkelig)

Dette ble gjort på litt ulik måte i de forskjellige gruppene, men alle over samme lest. Se **Figur A** under. På grunn av tidspress ble ikke alle de blå problemstillingene håndtert på denne måten.



Figur A. *Øverst: Prinsippskisse for resultatet av gruppeprosessen. Nederst: Eksempler på resultat fra gruppeprosessene.*

Gruppe 1

Karakterisering

1) Faktorer som påvirker frigivelsen av mikroplastpartikler
    - Hotspots – hvor forventes høyest konsentrasjon?
    - Sesongvariasjoner
2) Faktorer som påvirker størrelsen og tettheten til partiklene
3) Utfordringer knyttet til kvantifisering av mikroplastpartikler
4) Faktorer som påvirker innholdet av miljøgifter i mikroplastpartiklene

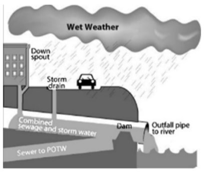
Spredning

1) Faktorer som påvirker spredningen via luft
    - Sesongvariasjoner
2) Faktorer som påvirker spredningen via avrenning
    - Veiutforming
    - Partikkelkarakteristika
    - Nedbør, smelting
    - Veivedlikehold
3) Faktorer som vanskeliggjør en kvantifisering av spredningen

Gruppe 2 og 3

Effekt av sandfang

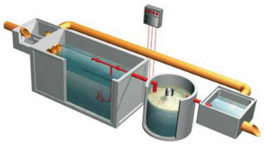
1) Hvilke faktorer påvirker effekten av sandfang som barriere
    - Negativt: rød lapp
    - Positivt: grønn lapp
2) Hvilke mikroplastpartikler kan forventes å bli vil holdt tilbake?



Hvor mye går til sentralt RA? Slam vs utslipp?

1) Hvilke faktorer har mest å si for et nasjonalt estimat for tilførsler til sentrale renseanlegg?
2) Faktorer som vanskeliggjør en kvantifisering av de nasjonale tilførslene
3) Hvilke rensetrinn har mest å si for at mikroplastpartiklene blir fanget opp?

Gruppe 2 og 3



Erfaringer med eksisterende rensetekniske løsninger

1) Hvilke faktorer har betydning for valget av renseløsning for veiavrenning langs hovedveier utenfor byene?
2) Hvilke faktorer har betydning for valget av renseløsning for veiavrenning inne i urbane områder med betydelig plassbegrensning?
3) Hvilke renseløsninger, som brukes i Norge i dag, fungerer som en barriere mot mikroplastpartikler?
4) Hvilke faktorer påvirker effekten av renseløsningene som barriere
    - Negativt: rød lapp
    - Positivt: grønn lapp
5) Hvilke andre renseløsninger kan være aktuelle langs hovedveier utenfor byene? Hva er de viktigste begrensingene til disse?
6) Hvilke andre renseløsninger kan være aktuelle inne i urbane områder med betydelig plassbegrensning? Hva er de viktigste begrensingene til disse?

NIVA: Norges ledende kompetansesenter på vannmiljø

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NIVA
Norsk institutt for vannforskning

Gaustadalléen 21 • 0349 Oslo
Telefon: 02348 • Faks: 22 18 52 00
www.niva.no • post@niva.no