PROPER
WP 3 - SUSTAINABLE ASSESSMENT OF MEASURES AND TREATMENT SYSTEMS FOR ROAD RUNOFFS
Task 3.1. Literature Review on Blue-Green Treatment Solutions

Conference of European Directors of Roads (CEDR)

Aalborg ● January 2019

DELIVERABLE 3.1

Title

PROPER – WP 3. Sustainable assessment of measures and treatment systems for road runoffs
Task 3.1. Literature Review on Blue-Green Treatment Solutions

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Abstract

This reports represents the project deliverable 3.1 and concerns the results from task 3.1 of the CEDR Proper Project – Literature Review on Blue-Green Treatment Solutions. The report intends to guide practitioners working with the selection and design of road runoff treatment systems through the maze of structural technologies that have been implemented to date. Its approach is generic, involving matching the characteristics of road runoff pollutants to treatment processes that can be brought into play to mitigate impacts. It presents a broad overview of available treatment systems and practices to support the user in selecting the most appropriate treatment solution for a particular site or scenario.

It concludes that, in cases where road runoff treatment is needed, solutions applying decentralized infiltration or filtration are generally preferable. Where such systems are not an option, centralized treatment can be applied, where solutions applying filtration or infiltration tend to be the most efficient ones.

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Acronyms and glossary

AMPA – aminomethylphosphonic acid

BMP – Best Management Practice

CEDR – Conference of European Directors of Roads

EMC – Event Mean Concentration

IDF – Intensity; Duration; Frequency

PAH – Polycyclic Aromatic Hydrocarbons

SMC – Site Mean Concentration

SUDS – Sustainable Urban Drainage Systems

TSS – Total Suspended Solids

1. Introduction

It is the objective of this work package to give detailed information of the functionality and performance of a range of blue-green solutions. It intends to create a guide that contains an overview of relevant blue-green solutions, leading to a tool that helps stakeholders choose the most appropriate system in a specific situation.

Blue-green runoff drainage systems – in the UK known as SUDS (Sustainable Urban Drainage Systems) and in the USA called stormwater BMPs (Best Management Practices) – refer to a range of both structural technologies and nonstructural measures that reduce impacts of stormwater runoff on receiving waters. A central characteristic of a such system is its ability to mimic the predevelopment hydrology. In general, structural measures offer opportunities to combine removal of pollutants from runoff with a reduction of the flooding and erosion impacts often associated with runoff flows. The nonstructural measures include a wide range of approaches, including regulations, management, and public education, with the purpose of reducing the dispersal (or migration) of pollutants into the environment.

The objective of this report is to guide practitioners working with the selection and design of road runoff treatment systems through the maze of structural technologies that have been implemented to-date. Its intention is to help practitioners identify and appropriately select the best solutions to protect Europe's water resources from the adverse impacts which may be associated with road runoff (See CEDR PROPER D2.1 for a comprehensive overview of receiving water impacts). The report is not intended as a design guideline but does nevertheless provide some guidance on design of specific solutions. Its approach is a generic one, where the physical, chemical, and biological characteristics of road runoff pollutants are related to the physical, chemical, and biological treatment processes that can be brought into play to mitigate impacts. From this starting point it leads the reader to a generic selection of appropriate treatment systems and practices. It is the hope of the authors that this approach will allow the user to select the best solution for the issue at hand – recognizing that one solution does not fit all situations, and that each solution must be optimized towards local conditions.

The report focusses on structural solutions that allow combining runoff detention with pollutant retention. It covers filtration systems, infiltration systems (e.g. infiltration basins and trenches), retention ponds, constructed wetlands, transfer systems (e.g. swales and filter strips) and alternative surface materials (e.g. porous asphalt). It addresses low-impact development approaches relevant for road systems and how these can be implemented and operated. The report gives an overview on the treatment efficiency of common blue-green drainage systems and treatment solutions to manage road runoff.

2. Fundamentals of road runoff pollutant management

Road runoff can contain a multitude of problematic substances with a wide range of characteristics and concentrations. At the same time, runoff volumes can vary drastically with time (both within an individual event and on a seasonal to annual basis), and so does the runoff's pollutant content. Furthermore, no two sites are identical, having different boundary conditions such as pollutant source strength, runoff conditions, climate, and the demands posed by the receiving environment. The solutions to retain the pollutants must hence be versatile and bring adequate physical, chemical and biological processes into play. At the same time they must be robust, affordable and have a low maintenance demand. In some cases the footprint of the treatment facility is also an issue while it is of little importance in other contexts.

This chapter presents the fundamental physical, chemical and biological aspects relevant for design of treatment solutions for road runoff. It focuses on relevant processes within physics, chemistry and biology, taking into account both equilibrium and dynamic conditions. Treatment processes typically occur in a multiphase system comprising water, solid and gas phases. The chapter addresses the partitioning between phases and the exchange of substances between phases.

Work package 1 of the PROPER project, "Prediction of Pollutant Loads and Concentrations in Road Runoff" has addressed the topic of road runoff pollutants types and concentrations and has as such set the upstream boundary conditions for the treatment solutions. The present report does hence not address the specific pollutants but covers what are suitable categorizations in terms of their management. Work package 2 of the PROPER project, "Assessing the vulnerability of European water bodies for road runoffs during building and operating of roads" has reviewed data on the impacts of road runoff within receiving water environments and has hence set the downstream boundary conditions for the treatment solutions and consequently the need for treatment.

2.1 Flow and pollutant characteristics

2.1.1 Flow characteristics

Stormwater runoff from roads is an intermittent phenomenon as surface runoff only occurs during rain or snowmelt events. Additionally, precipitation patterns are characterized by highly variable intensities and durations. These patterns may include extended dry periods when a treatment facility will not receive any runoff. Alternatively, the pattern of precipitation events may encompass episodes of high intensity / short duration events, or a combination of the two in varying proportions. In cold climates, substantial runoff volumes are associated with snow melt events. In terms of design, this means that runoff can be viewed as a stochastic phenomenon which best can be described by statistical parameters.

2.1.1.1 Inflow: Intensity, duration, frequency

Rain intensities are traditionally described by 3 parameters: Intensity; Duration; Frequency (IDF). These are commonly combined into IDF-curves meant to characterize the rainfall of a given region (Figure 1). However, while these curves do give an idea about the rainfall statistics, they have to be used with some care. They have in most cases been constructed from long series of historical rain data with the purpose of designing the capacity of drainage pipes. For this purpose they typically have been constructed by applying a dry period of 1 hour to separate storm events. This is adequate for designing pipes as drainage pipes typically are emptied within that hour and two consecutive rain events hence can be viewed as being independent of each other. However, when designing stormwater detention systems, a dry weather period of 1 hour will not ensure independency of two events as the detention volumes of the treatment facilities commonly have much longer emptying times. For design purposes, this issue will lead to detention volumes becoming too small, probably by 15-20%, when applying IDF curves for design of stormwater detention.

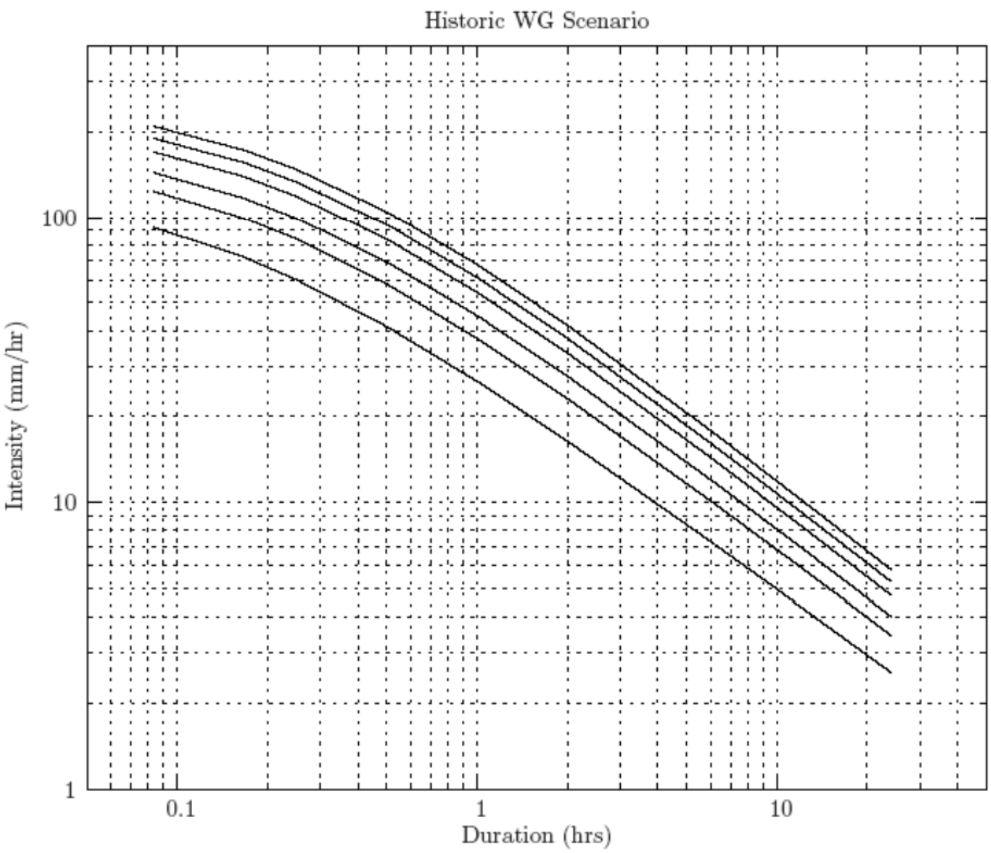

Figure 1. Intensity; Duration; Frequency (IDF) curves IDF-relationships for London, United Kingdom; 2, 5, 10, 25, 50, and 100 years return periods according to MTO (1997)

The issue is illustrated in Figure 2 where the outflow from a 10 ha drainage area is simulated. The rain series behind the data is from Denmark and covers a period of 3 days at the end of a November-month. For the design of pipes (generation of IDF curves), this rainy period would be interpreted as 8 independent events. However, for stormwater detention with low outflow rates from the detention volume, it should probably be viewed as 2 or maybe 3 events as the short inter-event periods during the storms will not have allowed the detention volume to empty out. A way around this issue is to run fully dynamic simulations applying either a hydrodynamic model or a simplified model targeted the design of stormwater facilities.

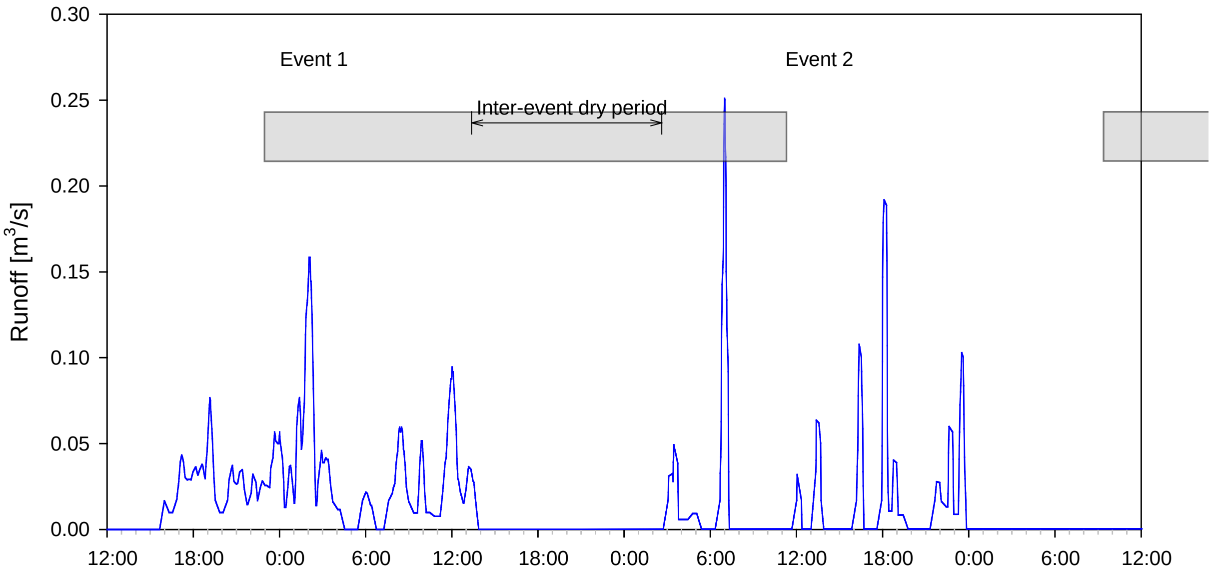

Figure 2 Events and inter-event dry periods. An example of simulated outflow from a 10 ha drainage area

In some cases, treatment facilities do not only receive runoff during rain events or from snowmelts. Pipes in the drainage area might be leaking and, where groundwater levels are high, this can cause infiltration. Direct inflow from road drainage might also occur, and pipes from the surrounding land can be misconnected to the drainage network or the facility itself. The extent of this infiltration/inflow cannot be theoretically predicted but a number of methods for its measurement have been developed for urban sewer systems conveying wastewater (e.g. Pawlowski et al., 2014; Shelton et al., 2011). This phenomenon has received little attention for urban stormwater sewers and road drainage systems. Infiltration/inflow is consequently commonly ignored when addressing treatment systems for road runoff. However, where infiltration/inflow has a significant extent, it will increase the hydraulic load on a facility and hereby reduce its treatment efficiency. This might be best illustrated by an example: One hectare of impervious area will in many European climates yield in the order of 5000 m^3 of runoff per year. A continuous infiltration/inflow contribution of just 0.16 L/s will give a similar amount and hence double the hydraulic load on a facility.

2.1.1.2 Outflow: Flow attenuation

Many roads discharge water to hydraulically sensitive water bodies, typically smaller streams and rivers. In such cases it can be necessary to detain the runoff for some time and release it at a rate that does not cause flooding or erosion of the water body. In this context it is important to remember that flow attenuation is aimed at mitigating hydraulic impacts, as opposed to pollutant removal / treatment. Common treatment systems like retention ponds and constructed wetlands do, for example, function perfectly fine at a high discharge rate as long as the hydraulics of the systems has been designed appropriately (Kadlec and Wallace, 2009).

2.1.2 Pollutant variability

Stormwater pollutant concentrations vary during an event, between events, and between sites. Variations can be quite substantial and are often measured by orders of magnitude (Clary and Jones, 2017). The variation during an event occurs because pollutants that have accumulated on road surfaces during dry weather conditions are washed off during the storm. The lighter material tends to be washed off rapidly at the start of the event, while the heavier materials take longer to be conveyed from the road surface to the treatment facility. The result is a phenomenon often called “first flush”. This phenomenon has been studied in quite some detail and is commonly taken into consideration for treatment system design (e.g. Aryal et al., 2017; Yang et al., 2018; Zhao et al., 2018). However, in practice it is difficult to define if and to what extent first flush occurs, and in a design situation it cannot be realistically predicted (Metadier et al., 2012) as it is not only a function of the antecedent dry period and the wet weather conditions but can also be influenced by the in-pipe drainage behaviour of runoff as it is drained to a treatment system.

Variations between events are typically characterized by an Event Mean Concentration (EMC). EMC is defined as a concentration that characterizes an event in terms of a flow-weighted mean value, in other words EMC equals the total mass of a substance for an event divided by the associated volume of runoff water. Variations of EMCs in stormwater are typically orders of magnitude and it is problematic to establish a clear cause-effect relationship between EMCs and, for example land use, traffic intensity or antecedent dry period (Metadier et al., 2012; Madarang et al., 2014). Variations between sites are typically characterized by a site mean concentration (SMC). Contrary to the terminology used, SMC is a concentration that characterizes a site in terms of a median value – and not the mean value – based on an evaluation of a number of EMCs at a particular site. Like EMCs, SMCs tend to vary by orders of magnitude and it is in practice problematic to predict SMC values for a specific site from catchment characteristics or traffic intensities (Hvitved-Jacobsen et al., 2010).

In conclusion, in practice it is not possible to robustly predict runoff concentrations during a specific event nor associated EMC / SMC values for an identified site. However, it is possible is to estimate most probable SMC values for a cohort of sites of specific characteristics. This work is undertaken in Task 1.2 of the PROPER project “Critical review of existing tools to predict road runoff pollution loads and concentration”. This review suggests that runoff concentrations (whether pre- or post-treatment) can only be assessed in terms of most probable values. Specific outlet concentrations of a specific facility cannot – as yet – be theoretically predicted, but most probable mean outlet concentrations from a cohort of similar management solutions can.

2.1.3 Pollutant characteristics

Pollutants can be characterized in many ways, depending on the required use of the data. For example, it is common to divide organic and inorganic constituents into groups related to their environmental impacts or to somewhat arbitrary ‘pollutant families’. Such pollutant grouping is a pragmatic approach used widely in not only a road runoff context. However, grouping of pollutants could be undertaken differently e.g. in relation to physico-chemical characteristics and it is hence important to be aware that in terms of treatment, similarities among substances from different groups might well be more pronounced than is the case for substances within a conventionally identified group. Common groups are for example:

- Biodegradable organic matter
- Nutrients
- Heavy metals
- Organic micropollutants
- Solids (suspended solids)
- Pathogenic microorganisms

A different way of grouping pollutants is to view the substances in terms of their physical, chemical and biological properties and behavior in an environmental system. In many ways this is a more appropriate grouping when addressing treatment solutions as it is those properties that determine the behavior of a substance and its susceptibility to removal by one or more processes within a particular treatment system. Relevant bio-physico-chemical groupings could be based on various aspects such as:

- Dissolved versus particulate materials (and associated particle size distribution)
- Propensity to precipitate
- Sorption
- Degradability (microbial or photo-mediated)
- Potential for bioaccumulation
- Volatility
- Acute versus chronic impacts

In addition to these groups, a number of other runoff characteristics are important for the treatment processes:

- Redox conditions in terms of dissolved oxygen concentrations and redox potentials when dissolved oxygen is absent
- Conductivity as an overall measure of the content of ionic substances. For example, chloride as an indicator for deicing agents
- pH to specify the acidity or basicity of the water
- Alkalinity as this determines the buffer capacity of the water. Alkalinity in stormwater is typically associated with particularly the carbonate system and levels of water hardness
- Temperature as this affects physical, chemical and biological process rates

2.1.3.1 Dissolved versus particulate materials

A major way of distinguishing between pollutants is to identify whether they occur in the particulate or dissolved phase. Particulates range from colloidal particles (colloids) to macroscopic particles. Colloids are so small that their movement in a liquid is completely governed by thermal energy. They consist of a number of associated molecules and are significantly larger than most single molecules. Particles are termed colloids as long as they stay suspended in a liquid and do not settle out even though their density differs from the density of the liquid. There is no clear boundary between what is a dissolved substance, a colloid, and a macroscopic particle. As the particle size increases, particle movement becomes governed by gravitational forces and the particles settle or float in a liquid. In terms of treatment, the settling behavior of particles is of major interest as much of the pollutants in road runoff are either particulate or associated with particles.

Fine particles and colloids can coagulate due to attractive forces e.g. van der Waals attraction forces. These forces result from the nonpermanent induced dipoles within a colloidal particle or molecule. Various external conditions affect the stability of the coagulated particles, especially the water's pH, ionic strength, temperature, and turbulence. Generally colloids in road runoff are negatively charged (Hvitved-Jacobsen et al., 2010) and coagulation hence requires an initial step where a positively charged coagulant, for example iron, aluminium or natural polymers, initiate the formation of larger particles. Upon coagulation, the formed particles tend to flocculate – a process affected by the turbulence of the liquid and its viscosity. In summary, coagulation and flocculation can allow colloids to come together so that the agglomerated material ultimately can settle in the liquid or be filtered out by a porous media.

2.1.3.2 Precipitation

Truly dissolved substances might be directly precipitated as compounds of low water solubility. Or they might be precipitated by complex formation with compounds of low water solubility. The latter is probably the most common phenomenon. An example is iron(III)hydroxide (ferric hydroxide), which also can lead to complex formation with various ligands, including some of the dissolved substances. Formation of metal complexes is for example a mechanism for getting heavy metals out of solution. The degree of complexation and hence removal of dissolved substances will depend strongly on the speciation of the metal. Detailed information on this can for example be gained from speciation and phase diagrams that are based on thermodynamic data or from computer programs which predict speciation. Speciation of metals depend strongly on pH and redox potential. For example, iron(III)-complexes often bind a wide range of substances. When conditions favor reduction of iron(III) to iron(II), previously bound substances may be released back into solution. This phenomenon is, for example, seen during eutrophication-induced oxygen depletion where anaerobic sediments release previously bound metals and phosphorous (e.g. Vink et al., 2017).

The precipitation-products are colloids and will behave as such, meaning they can coagulate and flocculate and ultimately settle out of the water column. They will do so together with naturally occurring colloids. Addition of, for example, iron salts will hence lead to removal of not only substances that react directly with the iron but also of substances associated with other colloids, which then are removed by coagulation/flocculation.

2.1.3.3 Sorption

A number of substances exhibit partitioning between solid and liquid phases. Partitioning between phases is a complex phenomenon, depending on the substance itself (the sorbate) and the solid phase to which it is sorbed (the sorbent). It does, though, also depend on environmental conditions such as pH, ionic strength, and competing sorbates. For stormwater pollutants, the most important sorbents belong to the groups of organic particles and clay minerals (Arias-Estevez et al., 2008). Technical sorption materials such as limestone, zeolite, activated carbon, olivine, and so on are also effective to sorb a wide range of substances.

A vast number of studies have addressed the sorption of various pollutants to a diversity of matrices under a range of conditions, see for example Delle Site (2002). For many practical applications it has been assumed that there is a correlation between a substance's hydrophobicity measured by its K_{OW} value (octanol-water partitioning coefficient) and its ability to sorb in natural systems such as stormwater treatment facilities. This assumption gives, however, only an indication of the relative degree of magnitude of sorption and not an exact value (e.g. Bollmann et al., 2015; Styszko et al., 2014).

2.1.3.4 Degradability

Some substances are readily degradable by microorganisms while others are not. Most organic micropollutants are degraded by co-metabolism, where the degradation of the pollutant depends on the presence of a primary substrate (Lolas et al., 2012; Fischer and Majewsky et al, 2014; Gonzalez-Gil et al., 2017). In co-metabolism, an enzyme produced to catalyse the degradation of a metabolic substrate is also capable of degrading an organic micropollutant. In some cases, simultaneous catabolism can also play a role, where an organism derives energy from the degradation of both substrates. Similar to primary substrates, the degradation of many organic micropollutants will depend on the redox conditions, especially on the availability of oxygen. Many substances are degraded to varying degrees under both aerobic and anaerobic conditions, albeit typically by different species of micro-organisms. An example is the group of PAHs (polycyclic aromatic hydrocarbons) where the preferred degradation route is by molecular oxygen, but in anaerobic conditions degradation can also take place by organisms reducing sulphate, nitrate and metal compounds as well as by methanogens (Nzila, 2018).

Some substances are readily degraded without the intervention of microorganisms. Oxidative processes and hydrolysis can occur, for example, through light (photodegradation) (e.g. Minelgaite et al., 2017; Wang et al., 2017). Other forms of chemical degradation do also occur, for example by heat, acids, alkalis, salts, galvanic forces, etcetera. Which specific degradation process is actually responsible is seldom known specifically, photodegradation is commonly seen as one of the major mechanisms responsible.

Both biological and chemical degradation can cause the formation of breakdown products which also may be environmentally problematic, an issue which is well-known for, amongst others, pesticides. For example the formation of aminomethylphosphonic acid (AMPA) during glyphosate degradation (e.g. Imfeld et al., 2013).

2.2 Unit processes in road runoff treatment

2.2.1 Retention of particles

Stormwater treatment solutions bring many of the previously described processes into play in varying combinations, with different systems offering differing potentials for identified processes to occur. They all take advantage of the fact that the majority of the pollutants in road runoff are associated with particles – both macroscopic and colloidal – and that an effective detainment of particles (and associated pollutants) will yield an effective treatment. Part of the organic substances associated with the retained particles will undergo further degradation processes within the accumulated deposits (the sediments). Some organic substances and most inorganic substances will simply accumulate and build up over time. Ultimately they will have to be dug up and disposed of.

2.2.1.1 Sedimentation

Sedimentation is commonly described using Stokes law. While Stokes law for the settling of particles is not physically wrong, it does have severe limitations in terms of fully describing processes within a stormwater management facility. Its assumptions – namely that particles must be spherical and rigid, the viscosity of the fluid is the predominant limitation on acceleration, there is no interaction with other particles or substances in the water, and that the water is not in motion – are in practice seldom valid. In practice it tends to only give reasonable estimates for particles in the range of probably some 40 – 100 µm and hence only targets a very limited part of the relevant size range (Hvitved-Jacobsen et al., 2010). Other theories do exist for the settling of particles within turbulent conditions. However, due to the wide diversity of particle sizes and shapes, the coagulation, flocculation and stability of aggregated particles, as well as the complex macroscopic hydraulics, these models also are challenged when it comes to real systems. In addition hereto, the exact boundary conditions in terms of particle sizes, particle shapes, particle density, inflow patterns, wind induced mixing, and so on, are unknown at the detailed level (Andradottir, 2017). Hence with the need to describe sedimentation using empirical expressions emerges. This typically boils down to surface loadings or volumetric loadings combined with guidelines on how to design the specifics of a certain sedimentation system, for example a retention pond.

2.2.1.2 Erosion and resuspension

Particles once deposited should stay deposited. However, this is not always the case as changes in hydraulic conditions may lead to erosion and resuspension of previously settled material. The erosive conditions might be caused by large inflows or by wind creating internal flows in the water column (Bentzen et al., 2009). Resuspension can also occur at the outlet of a facility if the local velocity causes critical sheer stresses to be exceeded. As with sedimentation, these processes are in practice difficult to describe deterministically as there are too many unknowns and unknowables. For example the degree to which the sediments are cohesive, where sediments actually deposit, plant growths protect sediments from resuspension, and so on. Also here design in practice therefore boils down to empirical guidelines.

2.2.1.3 Filtration

Filtration is an effective approach to retain particles. Its efficiency depends on the media through which it occurs as well as the characteristics of the particles contained in the water that is being filtered. Whenever liquids containing fine particles pass through a porous media, the particles contained in the liquids will clog the upper layer of the media. The layer formed is often referred to as the colmation layer (e.g. Hiscocka and Grischek, 2002; Veličković, 2005). This phenomenon is illustrated in Figure 3, where water containing fine particles are filtered through a coarser medium.

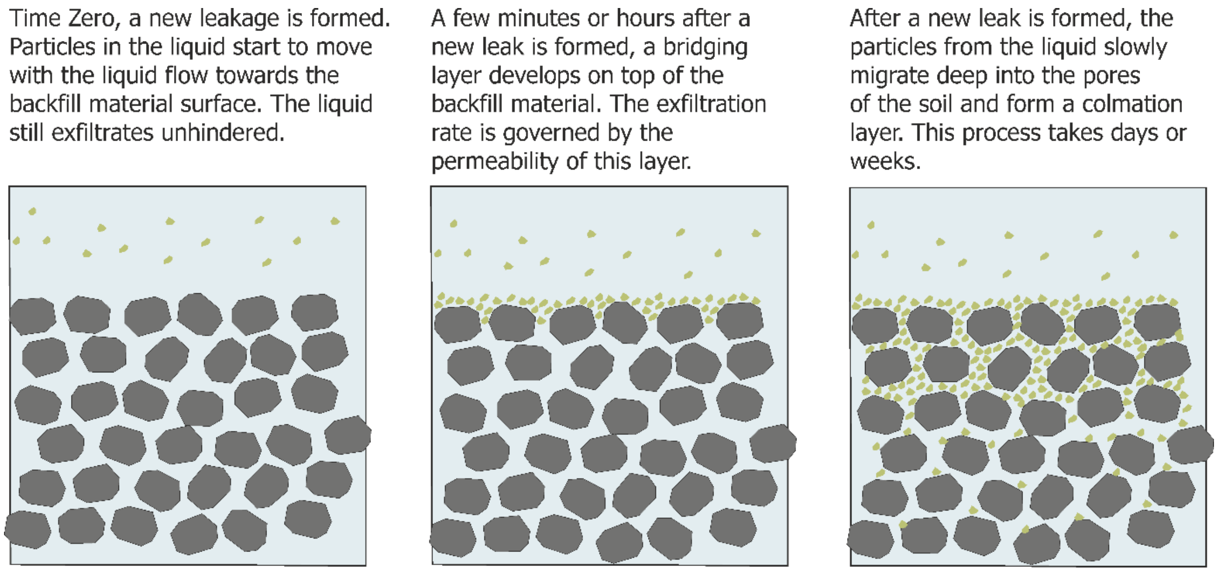

Figure 3 Colmation of a porous media

The clogging causes the formation of a colmation layer, which subsequently will govern the hydraulic capacity of the filter surface, and which also will define the active pore size of the filter material. Ultimately this leads to filter surfaces being able to retain particles significantly finer than the pore size of the virgin filter material. This phenomenon is well-known from various contexts where it has been shown to significantly enhance the ability of a soil to retain pollutants (Vollertsen and Hvitved-Jacobsen, 2003, Dizer et al., 2004; Levy et all, 2011; Harvey et al., 2015).However, this gain does come at the cost of a reduced hydraulic capacity.

Very fine particles and colloids may remain mobile within soil pore spaces. Whilst the exact size of particles that can do this is not well-defined, they are typically within the colloid range. The understanding of this process is though still rather limited (Grayling et al., 2018).

2.2.2 Retention of dissolved substances

A minor fraction of the pollutants in road runoff is truly dissolved as single molecules or ions. These will stay in equilibrium with the solid phases of the system, where they can be permanently retained or detained for shorter periods. While detained, some organic substances might be degraded and some substances might change from a loose binding to the matrix to a strong and irreversible binding, potentially becoming part of the mineral or inert organic matter structure.

2.2.2.1 Sorption

Sorption can be divided into two phenomena, namely adsorption and absorption.

Adsorption is the adherence of substances onto the surface of a particle. The interactions between a substance in solution and a solid surface are governed by forces across the liquid–solid interface. The substance partitions according to the intermolecular forces, creating either electron-pair bonds or permanent and mutually induced dipoles, binding the substance to the solid. Details on sorption mechanisms can be found in many textbooks on physicochemistry, for example Atkins and de Paula (2014).

Absorption covers the phenomenon where a substances penetrates into a different phase such as a liquid or solid – contrary to adsorption where it is bound to its surface. One can pragmatically view absorption as an uptake of a substance into a different phase, e.g. from the water phase into a solid phase (dissolved substances can to some degree move in a solid phase, for example a polymeric phase like plastics).

Adsorption is an equilibrium process with a constant ratio between the concentration adsorbed on the solid (C_{solid}) and the concentration in the liquid (C_{water}):

$$K_{s,w} = \frac{C_{solid}}{C_{liquid}}$$

$K_{s,w}$, also often called K_d, is termed the partitioning coefficient. Besides depending on the substance and the solid, its actual value will depend on conditions in the water phase like C_{liquid}, pH, ionic strength and redox conditions, and on the surface area of the solid phase. For organic substances, the K_{ow} of the substance (its octanol-water partitioning coefficient) is often used as a rough estimate on how well it will sorb to an organic matrix. The higher the value, the better the sorption.

Often sorption is described by sorption isotherms linking water phase and solid phase concentrations. The most common isotherms models applied to describe sorption equilibrium are the Freundlich isotherm, the Langmuir isotherm and the linear isotherm.

Adsorption is not always an instantaneous process and may require minutes to hours to run to completion (e.g. Wium-Andersen et al., 2012). Adsorption kinetics relevant for a process in road runoff treatment are typically well-described by 2nd order rate expressions including both the sorbent and the sorbate.

2.2.2.2 Plant uptake

Plants (macrophytes) do take up some pollutants from the surroundings, but plant uptake is in general not an viewed as an important process for the overall removal of pollutants from stormwater (Istenic et al., 2012; Stephansen et al., 2014). It is commonly assumed that the primary role of macrophytes, being they emergent or submerged, for treatment in a road runoff treatment system is to stabilize sediment beds and hereby reduce the risk of resuspension, and to reduce turbulence in the water phase and hereby enhance sedimentation (Brix, 1999).

2.2.3 Degradation of pollutants

Pollutants can be degraded in the water phase of a treatment facility, on biofilms growing on its solid surfaces, and in its sediments. Degradation in the water phase is most likely to be a result of photodegradation (section 2.1.3), as the amount of suspended biomass in the water phase of stormwater management facilities typically is low. Biological degradation is probably mainly related to the occurrence of microbiological populations within both biofilms and sediments. This may be facilitated by temporary sorption processes, allowing a substance to stay longer in a system and at higher concentrations. Investigations from other soil and sediment related environments indicate that sediments can constitute environments where biological degradation of for example biocides and pesticides can proceed under both aerobic and anaerobic conditions (Pesce et al., 2010; Robles-González IV et al., 2008).

Few detailed studies exist on the degradation of specific pollutants in stormwater treatment systems. In general studies on such systems have mainly focused on the overall efficiency of these systems to retain pollutants, with attention invested in understanding the underlying biological and chemical degradation mechanisms of specific substances. Most is probably known on micropollutants such as pesticides, where both the sediments and the plants have been found to play a role in the attenuation and degradation of pesticides in stormwater wetlands (Maillard and Imfeld, 2014). During the vegetative phase of their study, they found that plants enhanced pesticide removal while the pesticides again were released during senescence. The mechanisms behind this behaviour was not clear, but might be related to sorption/desorption of the involved substances. Imfeld et al. (2013) showed that the removal of glyphosate and AMPA varied substantially over the year due to characteristics of the runoff and the biological activity in the studied wetland. However, these studies were both made on wetlands dedicated to treating vineyard runoff, and pesticide concentrations were hence likely several orders of magnitudes higher than what can realistically be expected in road runoff.

There are a few indirect studies indicating that PAHs are degraded in stormwater ponds. A Danish survey covering 70 retention ponds receiving highway runoff showed that PAH in sediments of stormwater ponds typically was in the same range as in the sediments of reference lakes. They found concentrations in the range of 0-2 $\mu g\ g^{-1}$ (dry sediments) (Grauert et al., 2012a; Grauert et al., 2012b). A similar conclusion was drawn by Stephansen (2014) when studying PAH in stormwater ponds and natural shallow lakes. The study concluded that the short-chained PAHs were low in both systems, while the long-chained PAHs persisted in the stormwater ponds. Assuming that highway runoff caries a higher load of PAH than does the water to the natural lakes, these observations imply that short-chain PAHs must to some degree have been degraded in the stormwater ponds.

For soil-based infiltration systems, Tedoldi et al. (2016) reviewed the mechanisms for retention and degradation of micropollutants. They found that for example hydrocarbons tend to stay in the upper 10 to 30 cm of the soils. This could indicate that the hydrocarbons to some extend do get degraded in such system. A study from the USA on rain garden soil (LeFevre et al., 2012) showed that carbohydrates were partly degraded in such soil and that a population of specialized microorganisms able to do this degradation had developed.

2.2.4 Dilution and equalization of pollutions before discharge

The time-scale of the impacts caused by a pollutant is important for how treatment should address the mitigation of that pollutant. If for example a pollutant has an acute toxic impact on the receiving environment but only occurs infrequently in the runoff, for example pesticides, attenuation and dilution is an appropriate approach to manage such event. The same is the case for managing of accidental spills, which can cause quite severe localized damage. Accidents are, however, infrequent and do seldom contribute substantially to the annual pollution load of a region. Attenuation and dilution can hence be an appropriate mitigation method. However, if the impact is cumulative, for example that of most heavy metals, it is important to bring down the annual load, while peak concentrations are of lesser or no importance.

Most of the pollutants in road runoff cause accumulate impacts and a main goal of road runoff treatment solutions is hence to reduce the annual load to the environment. But for accidental spills, peak concentrations commonly are of little or no consequence in this respect. Looking at treatment efficiencies, it is hence of limited value to study the efficiency of a system to mitigate a single runoff event. Instead the long-term load-reduction to the environment should be addressed.

3. Solutions for road runoff treatment

This chapter outlines the main concepts of stormwater management practices intended for managing and treating runoff from roads, service areas and tunnels. Detailed sizing of the solutions is not addressed but the reader is referred to the specialized literature on this topic, such as national or regional manuals and guidelines and text books (e.g. Hvitved-Jacobsen et al., 2010). Costs of installation, operation and maintenance are also referred to within local literature as these costs are site and region specific.

Many of the solutions to manage road runoff are similar to those used in urban areas for management of urban stormwater runoff, but optimized towards managing runoff from roads. The ideal treatment solution prevents hydraulic impacts on local water bodies and pollutant impacts on the receiving environment. Avoiding or minimizing hydraulic impacts can be achieved by attenuation of peak flows prior to discharge to surface waters or by infiltrating the water. In terms of hydrology, the latter is often preferable as road runoff infiltration can mimic the pre-development situation of the drainage area.

Treatment can be achieved in several ways, where some solutions mainly target particulate pollutants while others also target part of the dissolved fraction. The most efficient solutions tend to be those that filter the road runoff through a soil matrix where particulates are removed down to small particle sizes. The efficiency of the filtration depends on the particle sizes (and size distributions) of the filter material and the pollutants. It also depends on the degree to which flow short circuiting (preferential flow patterns) is avoided, as short circuits allows untreated water to pass through the filter matrix. It is also noteworthy that the particulates of the road runoff will form a colmation layer which might ultimately govern how efficient the filter operates (a phenomena with similarities to cake filtration (Tien, 2006)).

Depending on the chemical properties of the soil (the filter matrix) and of the pollutant, the matrix can also sorb dissolved pollutants. The likely retainment of a dissolved pollutant will depend on characteristics of the matrix (the sorbent) and the dissolved substance (the sorbate). The efficiency of the sorption depends on the chemical composition of the sorbent but also on physical aspects such as contact time. Contact in the filter should be in the order of tenth of minutes to hours to allow the sorption process to run to completion (Wium-Andersen et al, 2012; Khorsha and Davis, 2017). In general terms, the ability of a matrix to sorb metals can be expected to increase with its content of clay minerals, iron, aluminum content, and with its pH. The ability of a sorbent to immobilize an arbitrary organic sorbate can be expected to increase with its organic matter content. The degree of sorption can be estimated through K_{ow} value of the sorbate. For example would one expect that a filter is efficient towards PAHs as they generally have high K_{ow} values. Furthermore, one would expect the PAH chrysene to sorb better to a road runoff filter than the PAH anthracene as their respective K_{ow} values are 5.73 and 4.45. Such a filter would be of limited value towards e.g. benzene which has a K_{ow} of 2.13.

Combining the above understanding of the filtering process, the overall efficiency of a filter will depend on the soil (the matrix), the pollutants, the runoff water, and the surface loading. All other being equal, a filter with low hydraulic conductivity which receives a low surface loading will be the more efficient. At the same time, it is desirable to implement simple and easy-to-operate filtration solutions which require little maintenance.

When infiltration or filtration is not an option, solutions depending on sedimentation will also produce good results, for example using wet retention ponds or artificial wetlands. Here larger particles settle out while smaller particles and colloids adsorb to surfaces. The removal process in small sedimentation tanks is well-described by a simple mechanical sedimentation process (e.g. as described by Berbee et al., 1996). However, when particles become small and close to the density of water, and retention times are days or weeks, gravimetric sedimentation is no longer a valid method to describe retention. Here more complex phenomena take over, such as flocculation, adherence to surfaces, ballasted sedimentation (where heavier particles and lighter particles adhere and together allow the lighter particle to sink), and similar. These phenomena tend to make the efficiency of large sedimentation basins such as retention ponds better than should be expected from simple sedimentation theory alone.

For all treatment systems, some pollutants simply accumulate as they are non-biodegradable (e.g. heavy metals) while others will undergo some sort of chemical and biological degradation (e.g. PAH). The degree to which pollutants degrade will depend on redox and moisture conditions, where aerobic processes tend to be able to remove pollutants to lower levels and at a faster rate than anaerobic processes.

Maintenance is another aspect which must be kept in mind. With poor maintenance even the most efficient system will at some point fail. There are, though, substantial differences in the amount of maintenance that is required by the different management technologies. In general one can assume that low tech solutions with large footprints require less maintenance than high tech solutions with small footprints. The exact amount and type of maintenance will depend not only on the type of facility, but also on a number of construction and environmental details, and should hence be considered from case to case.

3.1 An overview of common treatment solutions

3.1.1 Infiltration into road embankment / shoulder

Decentralised infiltration into road embankments (road shoulder) or ditches meets the above listed parameters of a filtration soil having a low surface loading and a simple operation. Due to its simplicity and efficiency, it should be the solution of choice whenever other conditions allow.

Stormwater can be infiltrated into the road embankments as long as the soil permeability is adequate and the groundwater levels sufficiently below the infiltration surface. Such infiltration has much similarity to infiltration in filter strips and swales, and allows management of the runoff for most runoff events (Boivin et al., 2008). One benefit of this solution is that the runoff water is kept close to where it falls, hence only causing less modification of the hydrological conditions compared to the pre-development situation. Such approach to managing road runoff is an important component in road runoff management in for example Switzerland and Germany (Werkenthin et al., 2016; Piquet et al., 2008, 2009). Using embankments for infiltration, it is of course paramount to ensure that the water does not pond and ultimately risk failure of the embankment (Polemio and Lollino, 2011; Pereira et al., 2015). It is hence essential that the hydraulic conductivity of the soils is sufficient to allow sufficient long-term infiltration rates. Such rates are difficult to obtain and must hence be deducted from soil properties such as porosity using grain size parameters, the degree of soil compaction, and for natural soils, the degree of over-consolidation (Allen, 2017). Due to the above, it can be desirable to use an artificial soil, e.g. a well-defined sand, as the top-layer of the embankment. Hereby the risk of preferential flow paths is also minimized (Pazeller et al., 2017).

3.1.2 Swales

A swale is a shallow vegetated tract of land that conveys stormwater. Most swales are dry, but they can also be designed as wet swales. In many cases a substantial part of the runoff will infiltrate in a dry swale, reducing both runoff volumes and pollutant content. Good pollutant removal efficiency of a dry swale requires that the slope of the swale is rather low and that it is well drained. Where the gradient of the land and the permeability of the soil allows full infiltration of the runoff, swales yield high pollutant removal, while it is poor for steep gradients and impermeable soils (Bäckström et al., 2006).

Swales are usually shallow grassed or vegetated linear, depressed channels located close to the source of the runoff. Swales are constructed with the purpose to transfer stormwater by leading the surface water overland from the drained surface area to a discharge system (storage) or receiving waters. Swales will collect the runoff water and provide temporary storages and thereby reduce peak flows. The runoff will flow along the length of the swale and into it. The swales are often constructed to be shallow, relatively wide, have shallow side slopes and a flat bottom. This means that for most of the time the water flows slowly in a thin layer through the grass or other vegetation, which is located along the bottom and sides of the channel. If the gradient of the swale is low, the subsoil has an adequate permeability and the distance to the groundwater is sufficient (1-1½ m), swales can infiltrate much or even all of the water they convey, hereby yielding treatment similar to road shoulder infiltration or infiltration basins. The infiltration area of a swale is typically significantly larger than that of an infiltration basin serving the same road area. Both the life expectancy and the treatment efficiency can hence be expected superior.

If the gradient of the swale is steep, check dams are installed along the bottom of the swale to reduce the erosion of soil and damaging of vegetation. A check dam is a small device constructed of gravel bags, sandbags, rocks, fiber rolls or another product placed across the swale. In addition to slowing the water velocity the check dams have the ability to encourages sediments to settle.

The vegetation of swales must be flood-tolerant and erosion-resistant. It will act as a filter medium removing pollutants that are transported within runoff, before the water will filtrate through soil layers. A dry swale is only holds water during wet weather. The collected stormwater will be drained away from the swale within hours or days. Wet swales may occur by design or accident if the water table is close to the ground surface, thereby the wet swale will acts as a long linear shallow wetland with similar treatment performance (MPCA, 2008). If infiltration to the groundwater is not permissible, the swale can be lined with an impermeable lining (Suds Wales, 2018; Lake Superior Streams, 2018; Rainscaping Iowa, 2014).

Swale maintenance is mainly a matter of managing the vegetation to ensure a pleasing appearance and keep trees and bushes at bay. Likewise a control of clogging is necessary, because sedimentation will stick to the ground of the swale. Like many other solutions, bioswales can be well integrated in the landscape. The linear structure of the swales makes them very suitable to treat runoff water from motorways, residential roadways or from parking lots.

3.1.3 Infiltration trenches

Infiltration trenches are shallow trenches filled with gravel or stones (Figure 4). The road runoff is directed into the trench via typically a grassed swale and temporarily stored in the void spaces of the trench filling material before infiltrating into the surrounding soil. The design of an infiltration trench follows a similar procedure as that of an infiltration basin. Both infiltration techniques effectively remove pollutants, reduce runoff volumes and can help replenish local groundwater. The main difference is that an infiltration trench typically serves a smaller road area than does an infiltration basin.

Infiltration trenches are commonly used for drainage areas less than 4 ha, and often serve just the road along which they are placed. The depth of an infiltration trench ranges typically between 1 and 2.5 m (Keblin et al., 1998). The sides and the bottom of the trenches should be lined with filter fabric, furthermore there can be a layer of filter fabric 0.15 – 0.30 m below the ground surface to prevent the flow from clogging most of the storage media.

Due to the narrow shape of a trench it requires minimal land use and can be effectively adapted into the roadside landscape. An infiltration trench requires to be covered with grass or have surrounding grassed strips to protect the infill by large sediments. A trench must be regularly maintained to function properly, at least twice a year and ideally every other month. If appropriate pretreatment is provided, the maintenance requirements of a trench will minimize and a trench may last as long as 10-15 years before major reconstruction (Keblin et al., 1998).

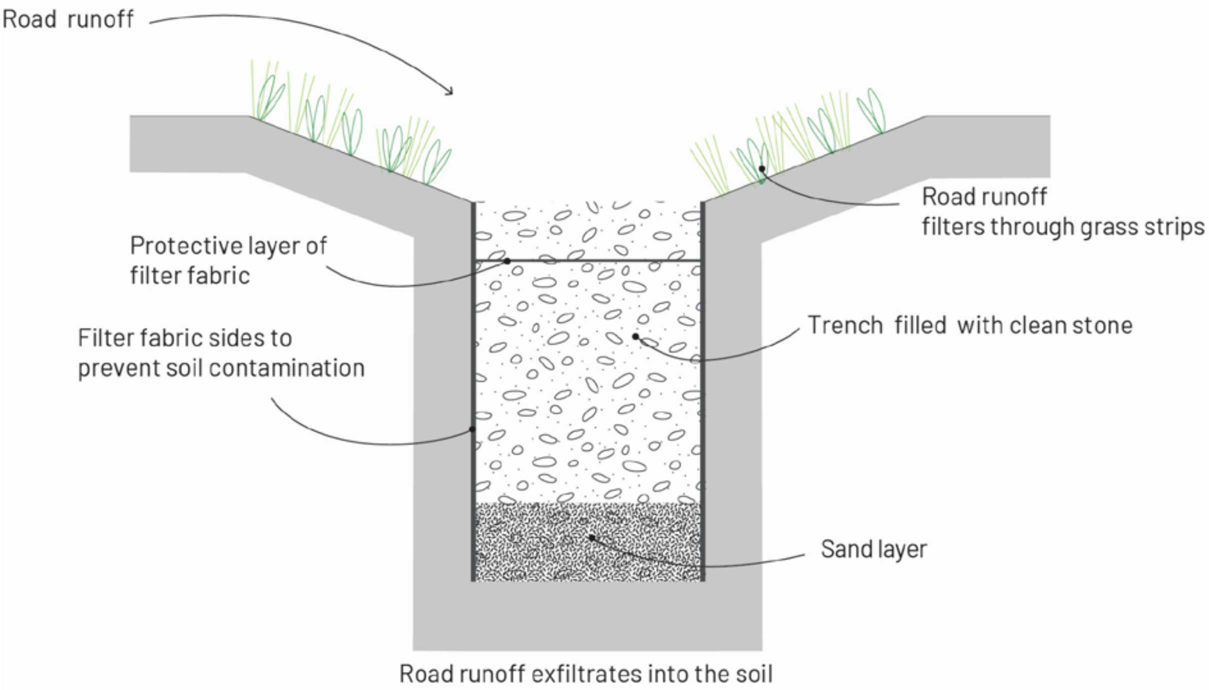

Figure 4 Infiltration trench

3.1.4 Soakaways

A soakaway is an underground pit that stores runoff from smaller areas and allows it to gradually infiltrate into the soil. Soakaways can be grouped and linked together to drain large areas such as highways and motorways. The design of soakaways are often square or longitudinal pits either filled with stones, plastic units or other inert materials with a large void NWRM (2014). Soakaways are a smaller variation of an infiltration trench and operate in the same way. Soakaways, do not require the same amount of space in length and width as infiltration trenches. Soakaways are easy to integrate into a site, but offer no biodiversity value as they function as an underground storage facility and water runoff should not appear on the surface.

3.1.5 Porous pavement

A porous pavement can be a cost-effect solution for many road drainage purposes. It consist of a special made asphalt, porous concrete, concrete grid pavement or plastic modular blocks pavement. The porous surface collects rainwater directly as it falls and reduce the amount of road or parking area runoff by capturing the runoff in a stone reservoir layer until it either infiltrates into the soil or continuous in filtered form to a drainage system (filter system). A porous pavement is traditionally only considered practical in areas with low traffic, such as parking areas, access roads, driveways and sidewalks. Higher traffic increases the risk of early clogging. Porous pavements provide significant reductions in surface road runoff, up to 90 percent of rainfall is retained within this solution (FHWA, 1996).

Concrete grid pavement can hold heat in the pattern voids in hot climates, which decrease the viability of growing grass within the voids. Plastic modular blocks are better suited to growing grass in hotter climates. Porous pavement systems can be effective in colder climates, if the stone reservoir is located below the frost line. Porous pavements should not be used for gas stations or other places where there is a high potential for spills.

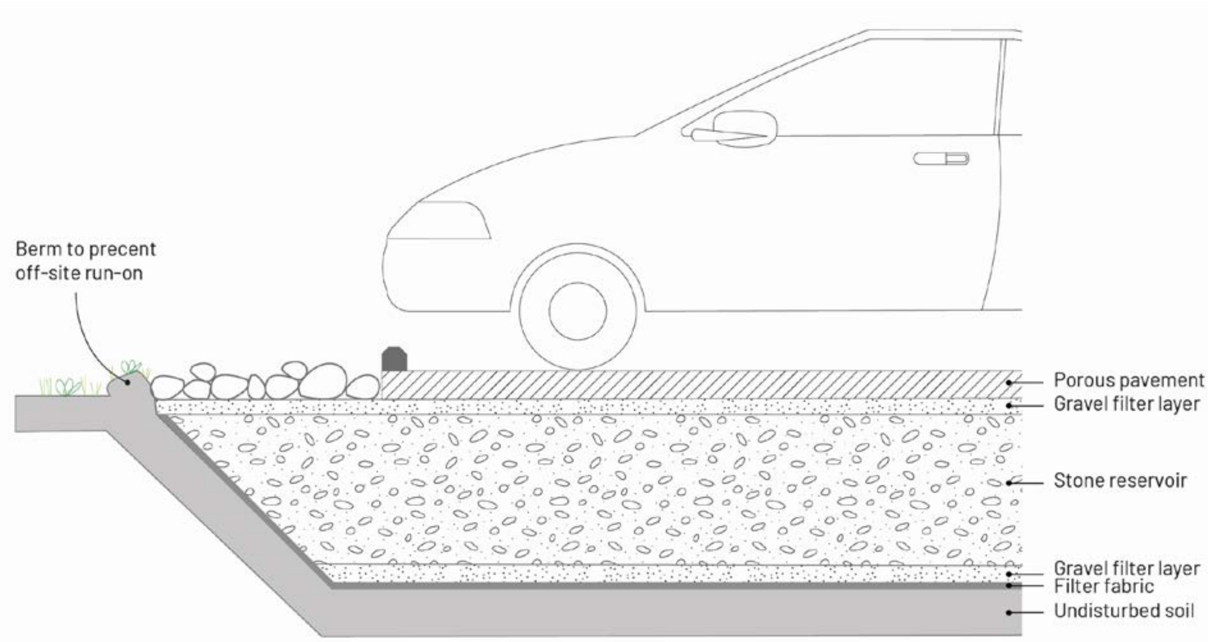

Figure 5 Permeable pavement

3.1.6 Filtration systems

A filtration system is basically an infiltration systems equipped with an underdrain over an impermeable base, collecting the treated runoff water before it percolates to the groundwater. Such a system is shown in Figure 6 for an infiltration trench or similar construct and in Figure 7 for a swale. In both cases the water is intercepted by a drain pipe and conveyed to a surface recipient. Similar solutions can be designed for infiltrations basins, soakaways and porous pavements. The treatment efficiency of such system will depend on the filter material applied, where coarse materials yield limited treatment and fine materials give good treatment.

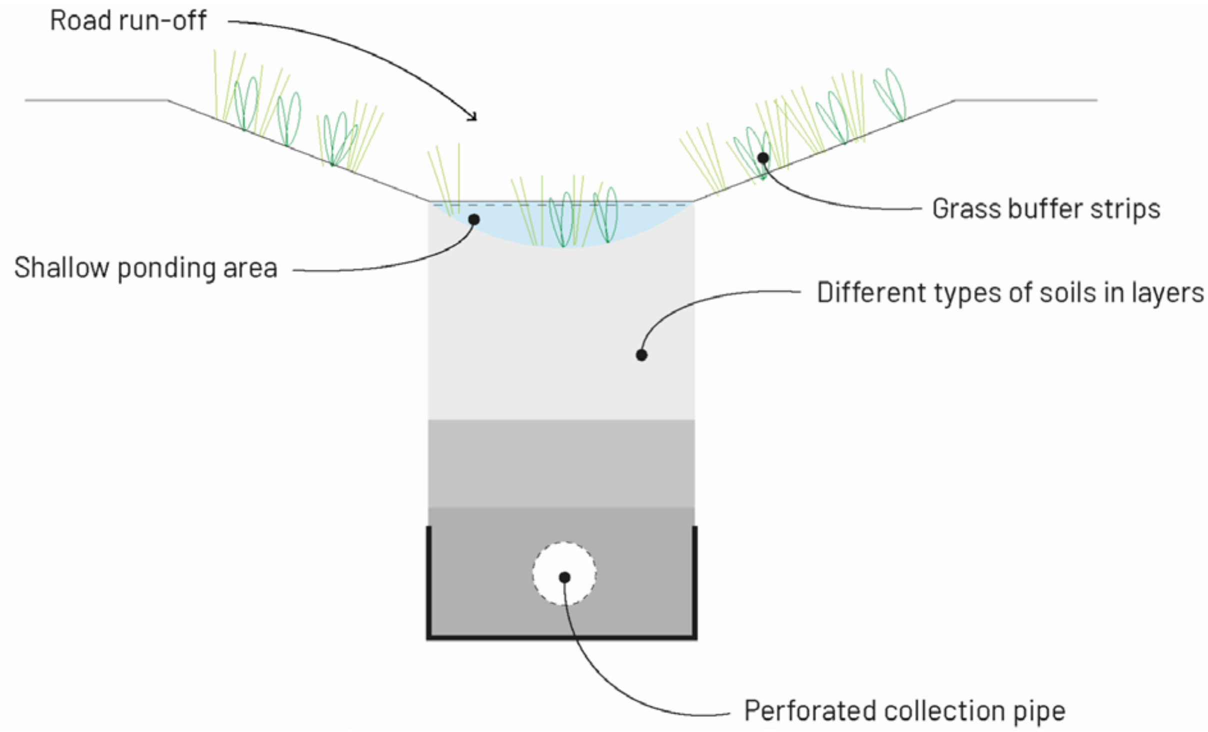

Figure 6 Bioretention basin

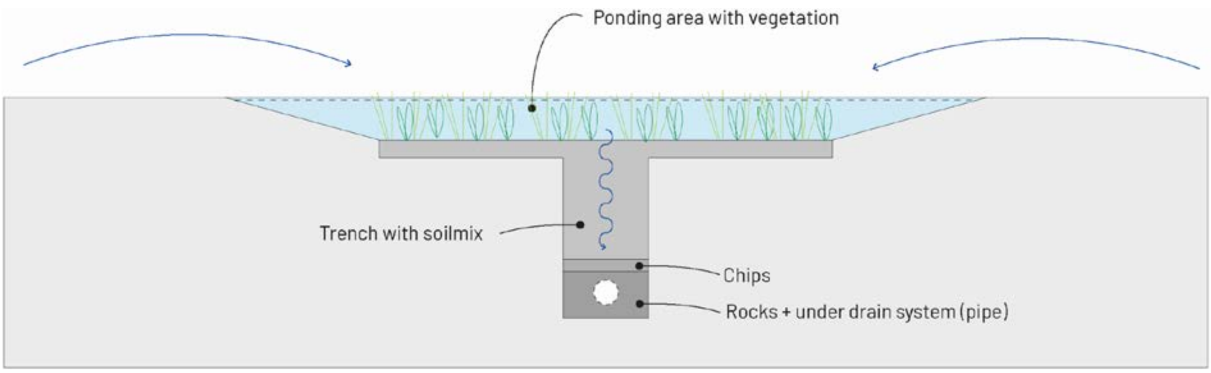

Figure 7 Swales

For cold climates it is important to be aware of the depth of frost into the soil and ensure that the drain is placed below the depth of freezing. Similar to infiltration systems, it is important to ensure that the systems are well-drained to avoid freezing during winter.

3.1.7 Filter Strips

Filter strips, also called buffer strips, are suitable to hold back runoff water from low-intensity storms and are effective at removing pollutions from these (Figure 8). Filter strips are a broad and slightly sloped vegetated area/line placed between a hard-surfaced area with polluted runoff water and an area that must be protected. Thereby the filter strip provides a buffer between the contaminant source and the adjacent area (for example between a road and a grassed field). When road runoff reaches a filter strip, its vegetation will trap organic and mineral particles. Part of the water will filtrate through the soil and hereby retain pollutants. Filter strips have both low construction cost and can easily be integrated into the surrounding context. Filter strips can have underground storage, and are often integrated in public open spaces or road verges, where the vegetation like wild grass and flower species can be added to improve the visual interest (susdrain, 2018; 3 Rivers Wet Weather, 2018)

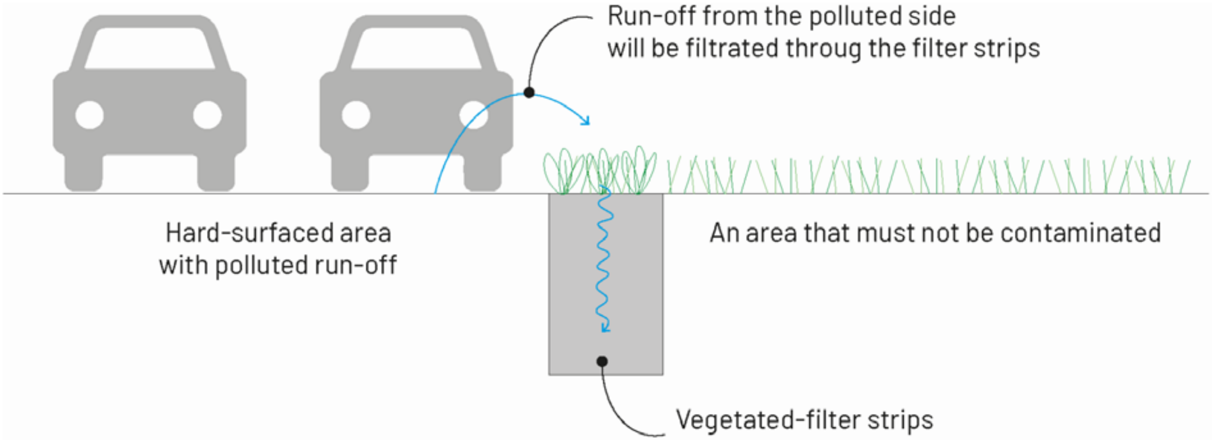

Figure 8 Filter strips with underground storage or direct infiltration to the sub-soil

3.1.8 Retention ponds (wet detention ponds, suds pond)

A retention pond, also often called a wet detention pond or a suds pond, is a large-scale structural storage system with the purpose of storing stormwater runoff for some time. During storage the pollutants of the runoff will be reduced by processes similar to those of natural lakes and wetlands. A retention pond can also allow hydraulic control and has the potential to create recreational values and biodiversity values to the surrounding area.

A retention pond appears in the landscape as a small, shallow lake and is often indistinguishable from a natural pond. Its main purpose is to retain pollutants prior to discharge into the receiving environment. It consists of a permanent wet volume, where the majority of the treatment takes place during the retention time of the water in the pond. The vet volume can be over-layered by a detention volume which allows flow attenuation (section 2.1.1 and Figure 9) so that downstream watercourses are protected against flooding and erosion. A retention pond is designed and constructed to collect road runoff (stormwater runoff) and detain it for days to weeks, allowing time for the processes detailed in Chapter 2 to remove pollutants from the water stored in the wet volume of the pond. Characteristics of retention ponds are a permanent water volume with a permanent minimum water level. It hence is often designed with an impermeable bottom layer to ensure that there always is water in the pond. The permanent water level is also called the ‘minimum water level’ or the ‘dry weather water level’. The incoming runoff is often called the ‘treatment volume’. It is important to allow for a sufficient water residence time to ensure that the pollutant removal processes have time to proceed before the water is discharged to the receiving environment (MPCA, 2005; Hvitved-Jacobsen et al., 2010, NWRM, 2014).

The main types of pollutant-removal-processes that occur in a retention pond are:

- Pollutant accumulation in the pond sediments. The main process is sedimentation of primary particles and particles formed by coagulation and flocculation (and associated pollutants).
- Adsorption of smaller particulate materials on fixed surfaces such as plants, stones, and bottom sediments.
- Sorption of soluble pollutants by the sediments.
- Uptake of soluble pollutants by the vegetation.
- Degradation of accumulated organic pollutants in the various matrixes.

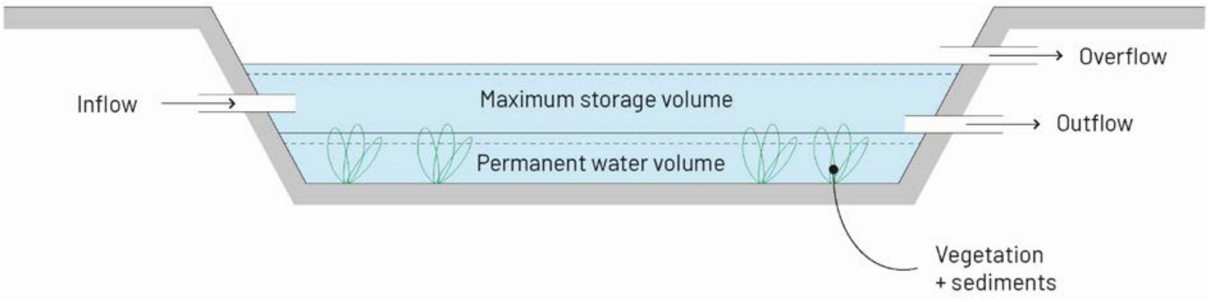

Figure 9 A wet detention pond is constructed with a solid base and the water is allowed in and out through an inflow and outflow (pipes)

A retention pond often includes a storage volume (detention volume) overlaying the permanent water volume (Figure 99). The purpose of the detention volume (indicated in Figure 9 as 'Maximum storage volume') is to reduce outflow rates to protect downstream channels or water courses against flooding and erosion. The importance of the detention volume in terms of treatment is negligible and flow attenuation is hence not needed if the sole purpose is road runoff treatment (Vollertsen et al., 2007; 2009). Ponds discharging to lakes or marine waters do hence not require a detention volume overlaying the permanent water volume.

The permanent water volume of the pond is often seen as the key parameter when designing a wet detention pond. In temperate climates, a pond volume of 200-300 m^3 per impervious hectare is often used as a rule of thumb. This volume is also called the water quality volume (where 200-300 m^3 per impervious hectare is the same as 20-30 mm of water quality volume). Another way is to design for an annual average retention time, where water retention times of 2 weeks in the permanent water volume (Figure 9) tend to give a good treatment performance (Hvitved-Jacobsen et al., 2010). For much of Europe the 2 weeks of mean retention time correspond to the 200-300 m^3 per impervious hectare. For example under Danish conditions, stormwater ponds receive roughly 5000 m^3/(impervious hectare * year), resulting in a mean residence time around the recommended 2 weeks. However, in climates where precipitation varies between seasons, or climates where snowmelt contributes significantly to the annual runoff, such rules of thumb can lead to under-estimation of the necessary pond size (Vollertsen et al., 2009).

Retention ponds should have permanent water depths in excess of 1 m as wind-induced turbulence can lead to sediment resuspension during strong winds (Bentzen et al., 2009). Another issue with shallow ponds is that they tend to become covered in marsh vegetation. While this is not an issue for the treatment performance (as this is mainly a function of the permanent water volume and hence the water residence time), it will lead to the pond appearing as a marshland and not a small lake. Water depths should not exceed 2-3 meters as ponds getting too deep are in risk of deoxygenation.

The wet volume is more important than the actual shape of the pond. The shape is often governed by the outside conditions and practical considerations. It is though important to select suitable positions for the inlet and the outlet in order to avoid shortcutting and dead-zones.

It is a good idea to install a forebay (with a size of approx. 10% of the total wet volume), before the runoff enters the actual treatment pond. The bulk of the sediments will deposit in such forebay, and hence not fill up the retention pond. This will extend the operation time of the wet detention pond. The forebay needs to be easily accessible as it must be emptied frequently. Another benefit of the forebay is that it will slow the velocity of the runoff before it enters the retention pond, and thereby reduce short-circuit currents (Vollertsen et al., 2012). Retention ponds should be equipped with an emergency spillway (overflow) to accommodate spills during extreme events.

Retention ponds must be dredged at regular intervals. The particulates in the runoff will sooner or later fill the pond, leading to poor treatment efficiency. The exact time before dredging is required is impossible to predict for individual ponds, as it depends on how much particulate matter enters the pond – a parameter that (like other water quality parameters) varies significantly between ponds. A typical sediment buildup rate in a pond designed according to the previously mentioned criteria is (for a 1 m deep pond with no forebay) on the order of 1 cm/year. Dredging will hence be required with roughly 20 to 25 years intervals.

Dredging of a permanently wet pond is costly and the wet sediments that need to be dewatered before they are finally disposed of are a major issue. To ease this maintenance step, it is recommended to include space at the wet pond where the dredged sediments can drain prior to final disposal.

If the pond is sufficient deep (at least 0.8-1 m permanent water level), the pond surface itself is unlikely to be covered in emerging macrophytes. If left to itself, its embankments will however become covered in woody or marshland vegetation. If the latter is undesired, the embankments must be maintained at regular intervals.

3.1.9 Detention pond (extended detention basins; dry ponds)

A detention pond is also called an extended detention basin or a dry pond. Its primary purpose is to detain flows to protect a downstream watercourse against flooding and erosion. Detention ponds are often open, dry depressions of grass that can be flooded with water during storm events (NWRM, 2014). The outlet is designed to discharge the water slowly from the onset of an event. Some water might also infiltrate or leak out (exfiltrate), depending on groundwater levels, as the bottom seldom is designed impermeable. A detention pond is dry most of the time and hence does not have a permanent water level between storm events. It is typically designed to be self-cleansing and the hydraulic residence time is rather short. It will hence not have much treatment effect. On the other hand, poor self-cleansing is the case more often than not, and in practice such system does retain some sediments and does yield some treatment. Its actual efficiency is difficult to predict as it mainly is caused by unintended sediment deposition. Detention ponds should be equipped with an emergency spillway (overflow) to accommodate spills during extreme events.

Not having a permanent water pool, and having a low sediment retention, also means that a detention pond requires less maintenance in terms of emptying out sediments. It is simpler to design than a retention pond because there is no specific requirements for the shape of the pond or for the placement of the inlet and outlet, and it does not require an impermeable bottom as long as possible infiltration to the groundwater is not viewed as an issue. All in all, detentions ponds hence are easier to design and maintain, but at the cost of having limited treatment efficiency.

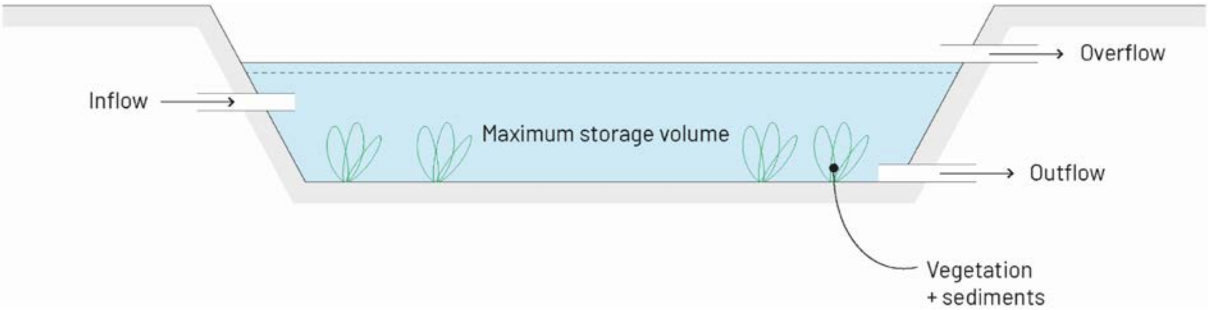

Figure 10. Detention pond

Dry ponds require less maintenance than wet ponds as they partly collect less sediments, and partly because the collected sediments drain dry on the bottom of the pond. The embankments may over time become covered in woody vegetation, while the bottom of the pond is less prone here for as plants growing here must be able to sustain prolonged dry periods as well as intermittent submersion.

3.1.10 Constructed wetland / stormwater wetlands

A constructed wetland is designed as a complex and diverse ecosystem; with marshlands that are intermittently wet, open water areas, dense vegetated spaces, spaces with a low water depth and sometimes even with small islands – this is all in order to mimic the function of a natural wetland and utilize its natural processes to treat and store stormwater runoff. The actual scale and water depth of the constructed wetland varies depending on the rainfall pattern at the location. The footprint of a constructed wetland is larger than that of a retention pond to ensure proper pollutant removal. The importance of various physical, chemical, and biological processes occurring in a wetland system vary depending on its detailed structures and how these are implemented. Like other stormwater management systems, constructed wetlands should be equipped with an emergency spillway (overflow) to accommodate spills during extreme events.

The design of a constructed wetland can to some extent be compared with the design of a wet detention pond, because the permanent water volume also is a governing factor for the treatment performance of constructed wetlands. Well-designed constructed wetlands have been shown to have as good or better treatment performance as wet detention ponds (Clary, Jones, 2017). There are three basic types of constructed stormwater wetlands: shallow wetlands, pond/wetland systems and extended detention shallow wetlands:

Shallow wetland: A shallow wetland is constructed with a mix of different shallow areas and relatively deeper marshes. The deeper marshes are located as a sediment forebay at the inlet of the constructed wetland and likewise a micropool at the outlet of the wetland.

Pond/wetland system: The pond/wetland systems both have a wet pond and a shallow marsh to achieve the best water quality. The stormwater runoff goes into the wet pond where the sediments are allowed to settle to the bottom of the pond, likewise the water velocity is reduced before entering the shallow marsh area (wetland). This solution has the lesser footprint. It is the one that requires less land than the two other solutions.

Extended detention shallow wetland: The extended detention shallow wetland is a combination of a permanent water pool and an additional storage area. The additional storage area is designed to store the water for a period of approx. 24 hours before it is drained away. Instead of building a wide marsh area, the temporary storage area can be seen as a substitute for the shallow marsh storage, which means that the total footprint can be smaller.

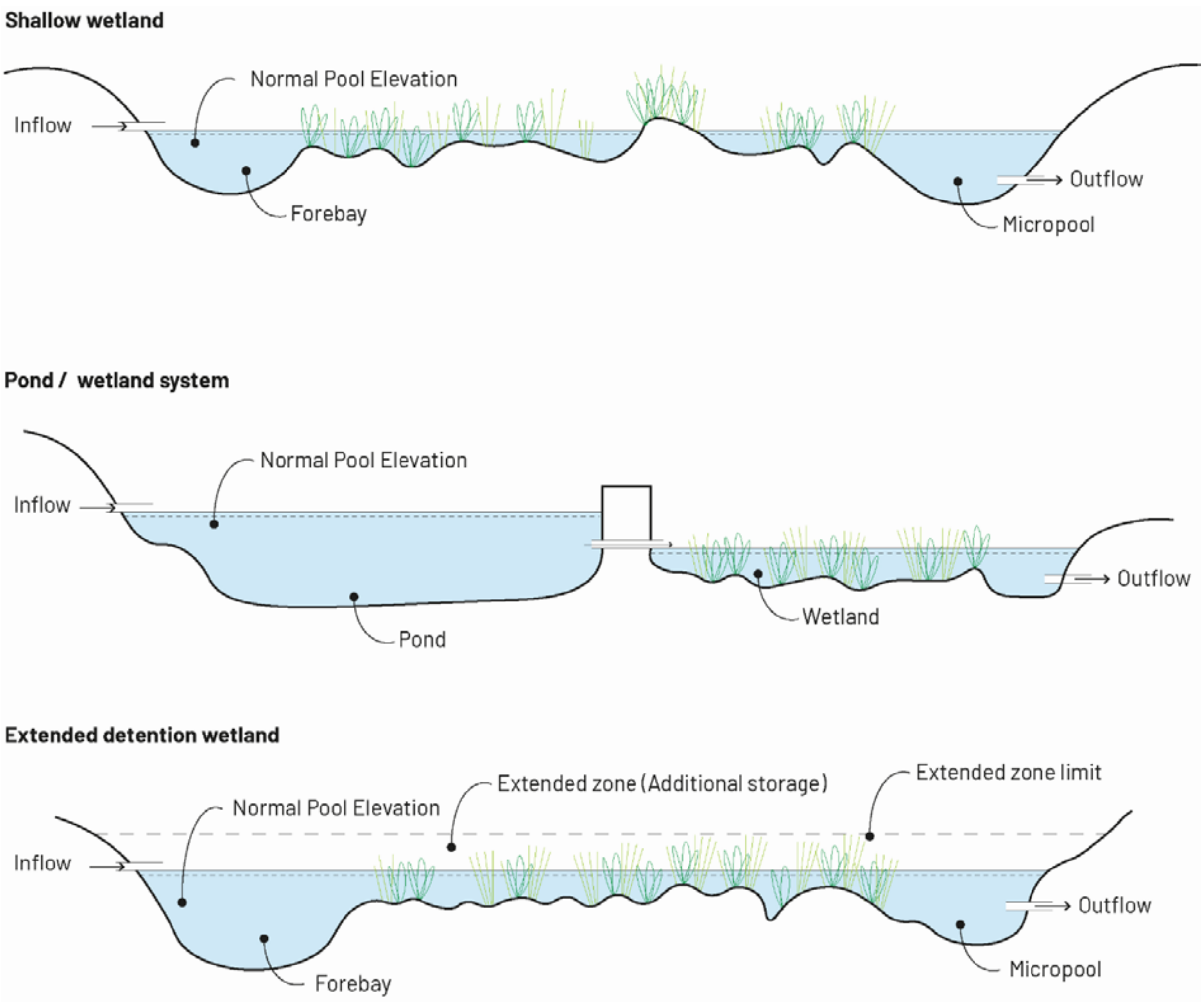

Figure 11. Three types of wetlands

Extended wetlands have similar maintenance requirements as retention ponds (section 3.1.8).

3.1.11 Infiltration basins

Stormwater infiltration is the process where runoff is captured and temporarily stored before it infiltrates into the underlying soil and then to the groundwater. Stormwater can be infiltrated in close vicinity of the site where the runoff has been created, for example in swales or infiltration trenches, or it can be piped to larger facilities like infiltration basins. It can either be infiltrated with a temporary storage volume above ground, for example an infiltration basin, or with a storage volume below ground, for example a soakaway. As the road runoff infiltrates into the underlying soil, physical filtration retains pollutants. Dissolved pollutants can be sorbed to the soil matrix. The alternating wetting of the soil surfaces ensures oxygenated conditions which enhance biological and chemical breakdown of organic pollutants.

When applying infiltration systems for road runoff, the natural permeability of the soil, is important. Infiltration in soils with hydraulic conductivities < 10^{-6} m/s should generally be discouraged (DWA-A, 2005). A successful infiltration also requires a suitable distance to the groundwater level, bedrock or other impermeable layers. Infiltration basins are vegetated depressions in the ground designed to detain road runoff from typically 2 to 20 hectares of impervious surface and allowing it to percolate gradually through permeable soils and into the ground. The soil top layer of the basin can be specially designed with a layer of gravel or sand. As the road runoff percolates through the soil, physical, chemical, and biological processes take place and effectively remove sediments, particulate pollutants and some dissolved pollutants in its upper layers before the water continues to the groundwater.

Infiltration basins are typically constructed with a depth between 0.5 and 3.0 m. The groundwater level should at all times be at least 1–1½ m below the bottom of an infiltration basin to ensure proper functioning. Hilding (1996) judged a too short distance to the groundwater to be the main cause of infiltration basin malfunctioning. Furthermore, an infiltration pond should not be located too close to drinking water wells, to avoid the possibility of contamination.

The infiltration capacity of an infiltration basin will depend on the soil conditions and the particle loads conveyed by the road runoff. The particles from the runoff will accumulate on the top of the infiltration surfaces, and also migrate somewhat into it, where they create a colmation layer. For soils of good hydraulic conductivity, it is the conductivity of this colmation layer that determines the infiltration rate and not the conductivity of the soil itself. For example does MPCA (2008) state that the following infiltration rates are suitable long-term infiltration rates: 40 mm/h for gravel, sandy gravel, gravel with small amounts of silt; 20 mm/h for sand with some gravel and no silt; 15 mm/h for silted sand; 8 mm/h for coarser silts; 5 mm/h for finer silts. Debo og Reese (2003) state that 50 mm/h can be expected for sand; 12 mm/h for sand with some silt; 6 mm/h for sand with much silt: 3 mm/h for sand with much silt and some clay.

Some guidelines suggest that a sand layer of 10-20 cm is laid out on the bottom of the infiltration basin to ease maintenance and reduce clogging rates (DWA-A, 2005; NJDEP, 2017; VSNR, 2017). The sand will catch the majority of the particulates and it will often be sufficient to reestablish this sand layer to regain the original hydraulic capacity of the facility. Some guidelines suggest to plant the infiltration surface with plants with deep roots as these will loosen up the soil (FHA, 1996; VSNR, 2017). However, one must be aware that plants covering the bottom of an infiltration basin will have to be robust as they will be subject to prolonged dry periods followed by submersion.

It is beneficial to equip an infiltration basin with a forebay to extend the service life of the infiltration surface itself. Such forebay should be designed to allow easy removal of accumulated sediments. A rip rap channel or another energy dissipating structure should be included at the inlet to avoid erosion. Infiltration basins should be equipped with an emergency spillway (overflow) to accommodate spills during extreme events. Vegetation can be included in the design on the bottom and on the sides of the basin. The roots of the plants improve the water infiltration capacity, reduces the amount of ponding, and enhances aerobic conditions in the top soil which will enhance degradation of organic pollutants.

In regions with significant frost and snow coverage, infiltration basins might receive snowmelt runoff into a frozen infiltration soil. To avoid malfunction of the facility, the soil must be well-drained between events, i.e. the distance to the temporary groundwater level created during infiltration must be at least 1-1½ m and the permeability of that soil must be good.

Infiltration basins require regular maintenance. Particulate material in the road runoff will sooner or later lead to silting of the basin and clogging of the infiltration surface. The hydraulic conductivity of the surface can though be re-established by removing the silted material and the soil top layer holding the colmation layer.

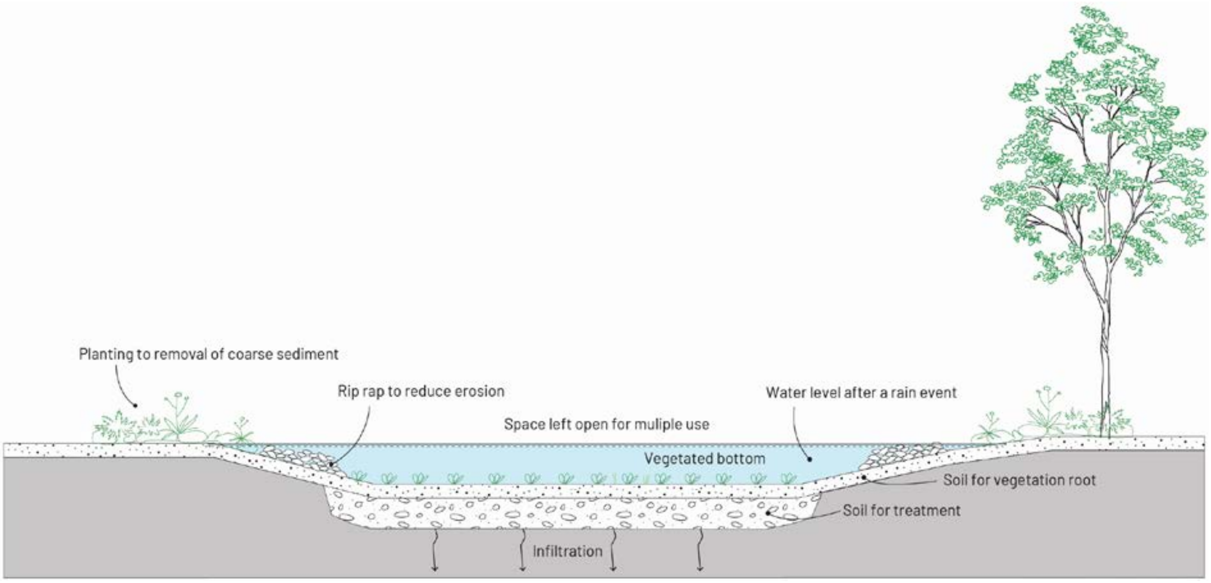

Figure 12 Infiltration basin

3.1.12 Enhanced filtration and infiltration systems

Where receiving waters are very sensitive and treatment by filtration through fine-grained media is deemed not to suffice, these systems can be enhanced by adding a sorption step, for example by conveying the runoff through a sorption bed. There are many ways to go around the detailed design of such system and many suitable sorption materials. In all cases it is important to reduce the load of particulate material on the sorption filter. Hence some trapping of coarse particles is advisable, similar to the use of a forebay at infiltration basins (section 3.1.11). The most costly part of the sorption filter is typically the sorption bed itself and it should hence be further protected. For example by over-layering the sorption bed by a sand bed with the purpose of physically filtering out particulate matter so that the sorption material does not clog and mainly has to handle dissolved substances. The principle of one such design is laid out in Figure 13, where the runoff water first passes through a retention pond (section 3.1.8) and then is conveyed to a filter unit consisting of a sandwich construction of sand enriched with peat followed by a sorption bed. Two such systems are constructed in full-scale at a Danish highway and Figure 14 shows an aerial photo of one of these (Vollertsen et al., 2018a). The one on the aerial photo holds a 30 cm top layer of sand mixed with 5% w/w peat, 50 cm hard limestone, 30 cm olivine granulate – sand mixture, 20 cm limestone and finally a drainage layer with drain pipes. The second filter (not shown) consists of a 30 cm top layer of sand mixed with 5% w/w peat, 100 cm hard limestone, and finally a drainage layer with drain pipes.

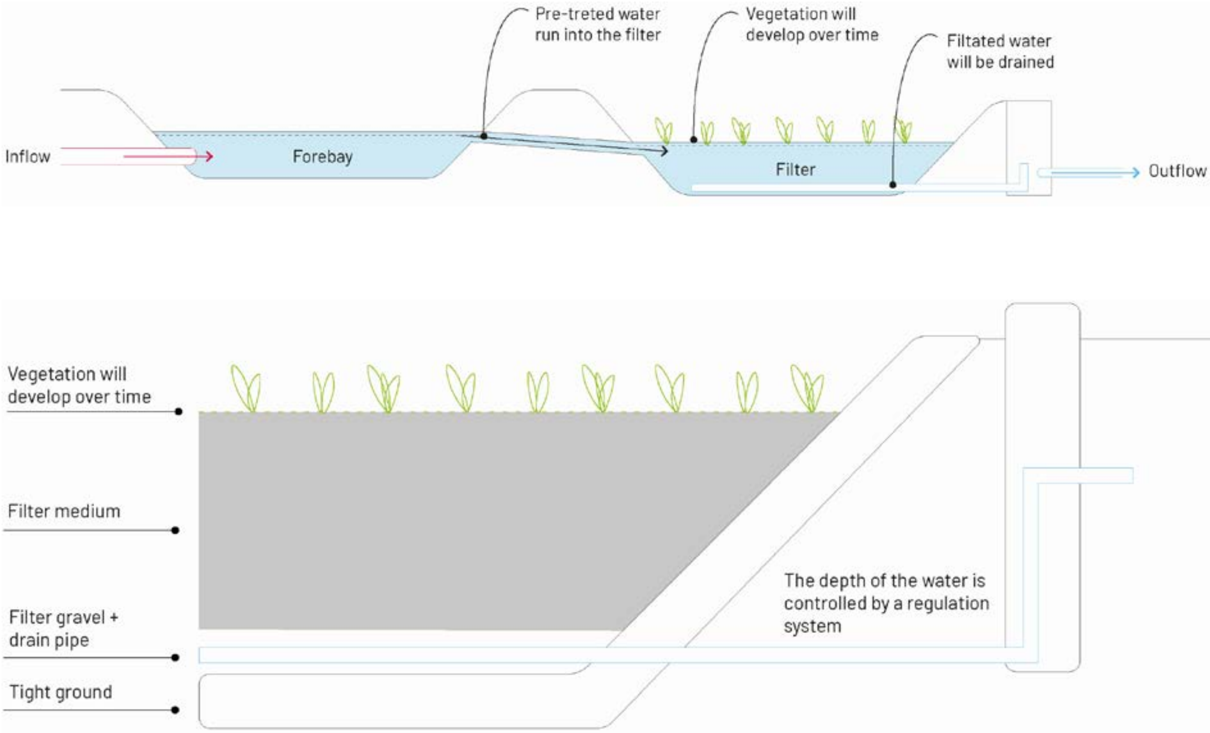

Figure 13 Principle of a sorption filter built in full-scale in Denmark

Figure 14. Aerial photo of a sorption filter built in full-scale in Denmark. The basin to the left is a retention pond for pre-treatment. The basin to the left is the sorption filter

As mentioned, many materials can be used to sorb dissolved substances in stormwater. The choice of materials range from naturally occurring and affordable materials such as shell-sand to sorbents specifically crafted to treat polluted runoff (e.g. Wium-Andersen et al., 2012; Ernst et al., 2016; Dongah et al., 2018).

3.1.13 Oil-water separators

Oil-water separators are intended to remove hydrocarbons from stormwater runoff as it moves through the device. There are many types and brands of such devices on the market. Oil-water separators require that the water is allowed sufficient time in the separator for the oil to float. These separators are well suited for treating water with high oil-content, but not well suited for road runoff applications as stormwater has highly variable flow with high discharge rates, turbulent flow regime, low oil concentration and high suspended solids concentration (e.g. IDEQ, 2005; City of Tacoma, 2012).

Oil in typical stormwater runoff is present at concentrations below 5 mg/L, and often below 2 mg/L (e.g. Denton et al., 2006; Fuerhacker et al., 2011). Oil separators, on the other hand, typically can achieve treatment down to approx. 10 mg/L, maybe 5 mg/L. In other words, there is too little oil in most road runoff to be treatable by this technology. Furthermore, the high hydraulic load that occurs during heavy rain will tend to wash out already accumulated oil. While oil separators hence are not suited for continuous treatment of stormwater runoff, they can, if such cannot be achieved in a more appropriate way, be applied as protection against oil runoff during accidental spills.

3.1.14 Manufactured stormwater runoff treatment technologies

A number of technical solutions are on the market for stormwater runoff treatment where space is confined. For example different versions of vortex separators, filters, sedimentation devices, sorption devices and flocculation devices. Many of these do yield treatment, but often their documentation is left to the company producing or selling these devices, and little independent documentation is available. Nevertheless, for a number of applications such devices can be an alternative to more traditional stormwater management technologies.

3.2 Treatment performances

3.2.1 General considerations

Most data on treatment systems for stormwater runoff cover a combination of urban, road and highway drainage areas. However, urban and highway runoff does not differ in terms of hydrology and flow characteristics. The overall chemical composition of the runoff is also quite similar with respect to most of the pollutants of interest for road runoff. Consequently, the implemented technologies are similar and often even identical when it comes to treating urban versus highway runoff. Experience on urban runoff treatment systems can hence generally be extended to also cover highway systems.

The pollutants that have received the most attention for runoff treatment systems are suspended solids, metals and nutrients (Clary and Jones, 2017). In a number of cases, PAH (polycyclic aromatic hydrocarbons) has also been studied due to a high toxicity of some of the PAHs. However, stating the treatment efficiency of a certain category of treatment facilities, e.g. retention ponds, is not straight forward even for substances which have been studied in great detail. These systems differ on a wide range of parameters such as their specific treatment volume (the ratio of impervious catchment area to permanently wet treatment volume), detention volume and time, size, geometry, geographic location, and they differ in terms of the land use in the connected catchment and hence in terms of the pollutant loadings. The sampling approaches applied to obtain the data also differ, as do sometimes also the analytical methods applied for analyzing the samples. All in all, asking for example the question "how well does a retention pond treat?" is equivalent to ask "how expensive is a car?". An example of this issue is shown in Figure 15 where the relation between specific treatment volume and treatment efficiency (left hand figure), and treatment volume and outlet concentrations (right hand figure) is shown for a number of retention ponds.

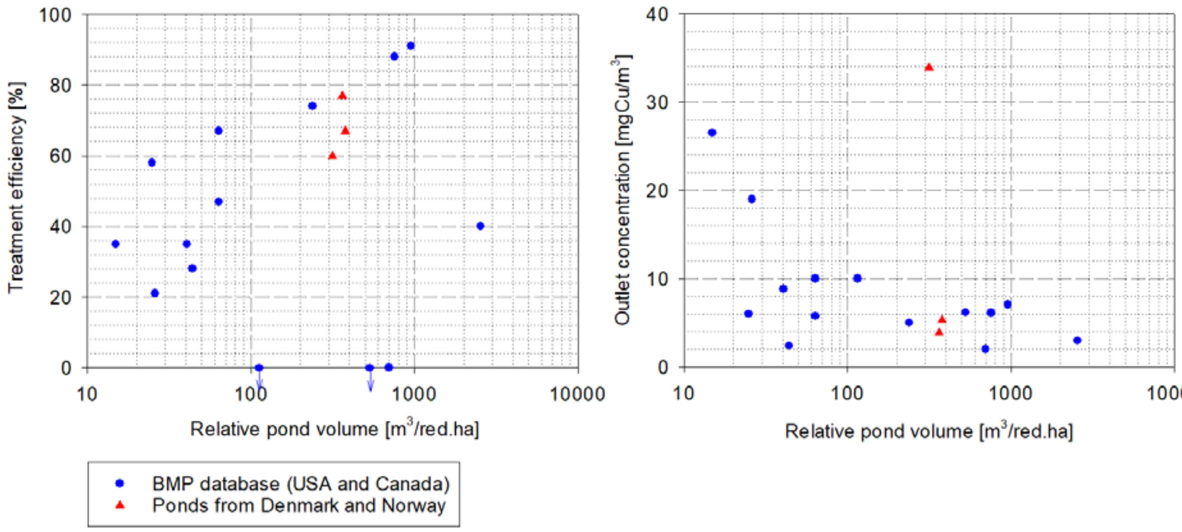

Figure 15. Treatment efficiency and outlet concentrations of stormwater ponds serving a mix of urban and highway runoff. The BMP database cover selected retention ponds up till 2012. Figure after Vollertsen et al. (2012)

Another issue which must be considered when addressing the efficiency of a treatment solution is that such efficiency is often stated as "percent of the pollutant load removed by the facility". This approach is inherently problematic for facilities that do not receive similar loads. Generally speaking, it is easier to treat heavily polluted water by a certain percentage, compared to reducing the pollutant loads associated with less contaminated waters. Doing a thought-experiment illustrates this issue: Assume that a retention pond shall treat unpolluted water. In such case the treatment efficiency of the pond is zero (because $\Delta C = C_{in} - C_{out} = 0$). Assume then that the water to be treated is heavily polluted with e.g. suspended solids, a substance that retention ponds are good at removing. Now the same pond can have efficiencies in the high 80ies or 90ies percentages. This was illustrated by Vollertsen et al. (2012), showing the relationship between measured inlet concentrations of pollutants to retention ponds versus the achieved treatment efficiency (Figure 16).

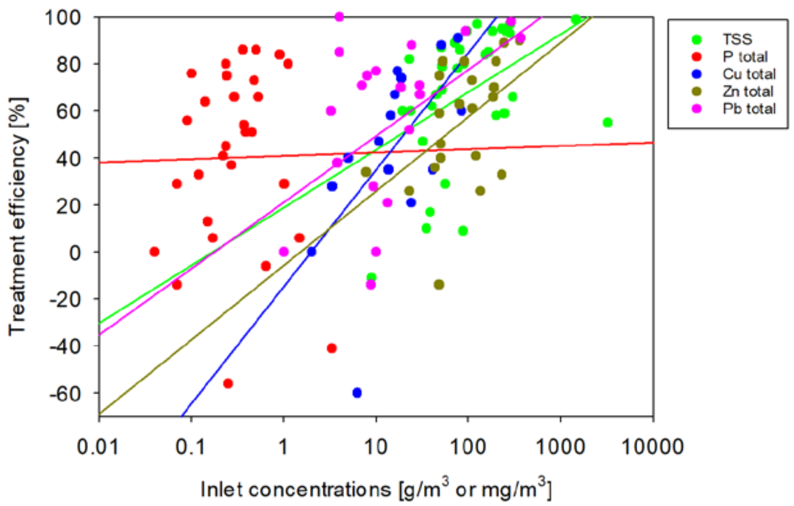

Figure 16. Correlation between pollutant inlet concentrations to stormwater retention ponds versus the obtained treatment efficiencies for TSS, phosporous (P), copper (Cu), zinc (Zn), lead (Pb). Figure after Vollertsen et al. (2012)

It is consequently difficult to state that “treatment technology X is better than treatment technology Y”. Which is “the better one” will depend on the actual sizing and design of the system, on the pollutant loading, on the hydraulic loading, and also on which pollutants are targeted. As an example, a well-designed and dimensioned whirl separator might be well suited to remove suspended solids from runoff, while it will be poorly suited to removed dissolved substances that do not sorb to particles. Such substances might require sorption combined with biological degradation, and only systems that facilitates such processes will be able to remove these substances. Nevertheless, one can formulate expectations towards what a well-designed system within a certain category is capable of, as long as one keeps all the above caveats in mind. For example can it be expected that a well-designed retention basin on average can achieve Total Suspended Solids (TSS) concentrations of 10-20 mg/L in the discharged water (Vollertsen et al., 2012; Clary and Jones, 2017), while the efficiency towards dissolved, persistent substances is low. Similarly it can be expected that well-designed filter solutions or infiltration solutions will remove particles down to the low micrometer range as well as part of the colloids, and hence tackle particulate pollutants to an even higher degree than do retention ponds. They will also be better at removing dissolved pollutants as sorption will tend to retain these.

The issue of comparing treatment solutions is also illustrated by the data gathered by the BMP database (Clary and Jones, 2017). Figure 17 shows box plots for TSS removal by a range of treatment solutions. The wide error bars must be noted, indicating the high uncertainty on the obtained data. Nevertheless, one can see that for example “Grass Swale” performs poorly compared to e.g. “Media filter”. Caution must though be exercised when applying such data, as for example detention basins are illustrated as being as efficient in retaining TSS as wetland basins and retention ponds. This makes little sense from a theoretical point of view, as a detention basin in principle is designed to be self-cleansing and hence should retain no TSS, while a retention basin in principle is designed to optimize particle retention. Nevertheless, in the following some examples of experienced pollutant retention for selected management options is given.

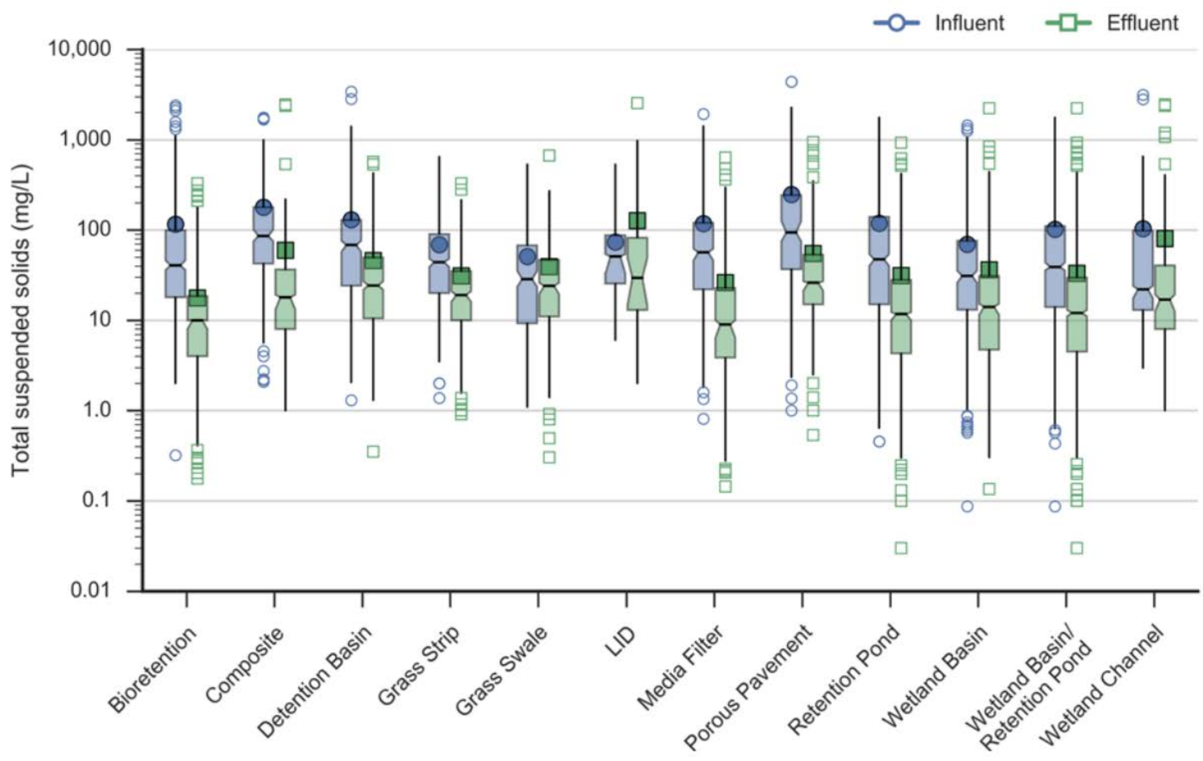

Figure 17 Box plots of influent/effluent TSS concentrations (taken from Clary and Jones, 2017)

ASTRA (2010) presents a comparison of treatment technologies which must be viewed as more consistent than the BMP database data presented in Figure 17. ASTRA (2010) reports studies performed by one agency (the Swiss ministry for roads), and the data behind the study is consistent and well documented. The BMP database, on the other hand, is an open database where water utilities can add what they have investigated, and the quality of the data hence is somewhat variable. ASTRA (2010) reports data from >20 field studies and concludes that the most efficient way to treat road runoff is through filter approaches such as filtration or infiltration through the road embankment (road shoulder), or through various types of soil/sand filters. The poorest efficiency was obtained by silt traps / sedimentation basins (Absetzbecken).

3.2.2 Retention ponds and wetlands

Stormwater retention ponds and wetlands are probably the best described technology for managing stormwater runoff. Their efficiency in retaining a wide range of particulate pollutants is well-documented, and some data also exists showing that they can reduce part of the dissolved pollutants.

Al-Rubaei et al. (2016) investigated the efficiency of a mature stormwater wetland in Sweden that had been operated for 19 years. They found that the system continued to be efficient in retaining pollutants such as cadmium, copper, lead, zinc, TSS and phosphorous do between 89 and 96%. Sébastian et al. (2014) investigated a stormwater retention pond for a number of heavy metals and pesticides. For the metals they for example found nickel, lead, copper and zinc with median removals ranging from 60% to 74%. PAHs were also efficiently reduced. The pesticides in the stormwaters were however not trapped in the pond as they mainly were dissolved. Vollertsen et al. (2009) reports data on a highway pond in

Norway and found that treatment efficiencies for metals like zinc, copper, cadmium and lead ranged between 58 and 76% while total PAHs was reduced by 85%. They also report that two large snowmelt events impacted negatively on the overall removal rates.

The list of the studies could be extended, but published studies tend to show that well-designed stormwater retention systems can be expected to remove a substantial part of especially the particle bound pollutants, but have limited effect on the dissolved fractions.

3.2.3 Filtration and infiltration technologies

Generally speaking, filtration and infiltration technologies can achieve higher pollutant removal than wet ponds and wetlands. The reason is partly that also rather small particles can be filtered out of the flow. For example did Egemose (2018) investigated the accumulation of particles in a sand filter polishing the outlet from at retention pond. The study found that fine particles and also pollutants like phosphorous were trapped in the upper few centimeters of the filter. Another reason is that sorption mechanisms work towards retaining dissolved substances. For example did Walaszek et al. (2018a) address sorption of dissolved metals in a constructed wetland in France (a soil filter) and performed batch experiments. They saw that zinc, copper and lead was substantially reduced by such filter. They also addressed that the pH of the water is important as metals tend to sorb better at higher pH, and that mineral composition of the filter material also plays an important role.

Fronczyk (2017) addressed treatment of artificial road runoff in a soil filter and found removal efficiencies for most heavy metals and PAH close to 100%. Hatt et al. (2009) investigated the pollutant removal in three stormwater biofiltration systems (soil filters) and found that metals and TSS was reliably removed, for example with median removal of zinc from 84 to 99%. Data from Switzerland on the monitoring of highway runoff filtration give a similar picture, namely that these systems are highly efficient in retaining pollutants. For example did a sand filter of 0.7 m thickness reduce zinc to below 10 µg/L and copper to around 10 µg/L (ilu AG, 2016a). Walaszek et al. (2018b) investigated a system for treatment of stormwater from a small residential catchment in France which comprised a retention pond and a constructed soil filter. They found rather good removal efficiencies in the combined system, albeit incoming water tended to re-suspend particles already settled in the pond. The overall removal was generally high, ranging from 50% for naphthalene to 100% for particulate zinc. Vollertsen et al. (2018b) investigated two systems for highway runoff treatment, also comprising of a retention pond combined with a filter. The filters contained artificial soil and sorption materials (limestone and olivine granulates). The systems were able to remove the measured parameters (heavy metals and phosphorous) to levels corresponding to the background in the receiving waters. E.g. was zinc reduced to approx. 2 µg/L. Two planted soil filter in Switzerland treating highway runoff (ilu AG, 2016b) showed similarly that zinc and copper was reduced to or below 10 µg/L during a 3-year monitoring campaign. Misteli (2017) reports the efficiency of 4 other highway runoff filtration systems in Switzerland, where one consisted of a vegetated soil under which there was a layer of crushed concrete. The other systems contained a mix of different filter and sorption materials. The system with crushed concrete achieved 65% and 77% efficiency for copper and zinc, respectively. The other 3 systems achieved higher efficiencies. For copper and zinc: 71% and 84%; 90% and 93% and 86% and 93%. Steiner and Gosse (2009) reported data on pollutant retention for two highway runoff filtration systems, one with a zeolite filter material and one with an iron hydroxide filter material. Before the water reached the filters it was pre-treated through at lamella separator. The iron hydroxide filter generally brought copper and zinc below 10 µg/L and total PAH down to 0.5 µg/L. For copper the treatment efficiency corresponded to approx. 80% and for zinc to approx. 96%. The zeolite filter was also efficient, albeit a bit less so than the iron hydroxide filter.

Pazeller et al. (2017) summarized extensive experimental data from 12 highway runoff (natural) soil filters and 8 highway runoff sand filters. They concluded that the sand filters were significantly more efficient than the soil filters, and explain that this counter-intuitive result is due to soil filters developing preferential flow paths, while this does not occur in sand filters. Hence, even though the soil filters in principle should be able to retain finer particles than the sand filters, and also sorb dissolved substances to for example clay minerals, this effect was overshadowed by the issue of part of the water flowing through the filter via differential flow paths.

Runoff infiltration through porous pavements can also reduce the pollutant content. For example did Berbee et al. (1996) found that runoff from pervious asphalt contained significantly lower levels of copper, zinc, lead, PAH, mineral oils, and organic matter than did runoff from impervious asphalt. Holmes et al (2017) conduct lab tests on the sorption efficiency of porous concrete to retain heavy metals and found that with the “right” concrete mix, the sorption could be very efficient and of high capacity. Similar results were reported by for example Haselbach et al. (2014) who in lab experiments found zinc and copper was retainment at around 90%. Liu and Borst (2018) compared amongst others porous concrete and porous asphalt and found that the two pavement types had similar efficiencies in retaining metals.

3.2.4 Technical solutions for stormwater management

When simple solutions like infiltration systems or retention ponds cannot be established, and the receiving waters require treating the runoff before discharge, more technical solutions can be chosen, for example based on flocculation and/or filtration. While such systems tend to be more costly in terms of investment, operation and maintenance than retention systems, filtration systems and infiltration systems, they can be the only viable solution when space is limited or other conditions require such installations. Properly designed and maintained they can achieve good efficiencies. For example did UVEK (2014) report the efficiency of a technical filter for road runoff treatment in Switzerland, applying sedimentation basin followed by a rotating disk filter. This setup achieved retention for copper and zinc of 66% and 59%, respectively, i.e. in corresponding to the lower range of what can be expected at a retention basin. UVEK (2016) reported the efficiency of another system of similar concept which achieved 62% and 59% for copper and zinc, respectively. The achieved mean discharge concentrations were 23 and 140 µg/L, which also is in the range of concentrations commonly achievable by retention basins (Hvitved-Jacobsen et al., 2010).

3.3 Treatment of tunnel wash water

Tunnels must be frequently cleaned and the washing generates substantial amounts of highly polluted water. Meland (2012) reports that tunnel wash water contains high pollutant levels and highlights that the management of such water must be included in the design of the tunnel and the adjacent roads. Meland et al. (2010) conclude that tunnel wash water can have adverse impacts on the receiving waters and that a simple sedimentation pond is insufficient to mitigate the adverse effects of tunnel wash water. Hallberg et al (2014) state that tunnel wash water commonly has five times the TSS content of road runoff. They present results from in-situ treatment where sedimentation was combined with chemical flocculation, obtaining rather efficient treatment of the water. They obtained for example PAH < 0.1 µg/L and Zn <60 µg/L. Paruch et al. (2008a; 2008b) addressed in lab studies how organic sorbents could be used to treat tunnel wash water. They found for example 97% retainment of PAH and 98% for copper and 99% for zinc.

Vik et al. (2016) addresses the need to apply mobile treatment solutions for tunnel wash water where such are not an integrated part of the tunnel design. The mobile solutions comprise a range of high-tech technologies combined in treatment trains, and allow substantial reduction of the pollutants in the treated water.

All in all it seems clear that tunnel wash water needs special attention and that simple treatment solutions like retention ponds are insufficient to manage such waters. Instead treatment trains combining processes like sedimentation, chemical precipitation, filtration, and sorption are needed to reduce the pollutants to an unproblematic level.

4. Conclusions

In selecting solutions for road runoff treatment, it is paramount to select a solution that is simple and affordable to install and maintain and which at the same time allows protection against adverse environmental impacts of the runoff. In those cases where road runoff treatment is needed, it is in general terms preferable to infiltrate or filtrate water as close to where the runoff is generated as possible and at as low a surface loading as possible. In practice this means that it is advisable to use the road embankments or median strip for flow attenuation and treatment purposes. Treatment through porous road surfaces is also an option. Where decentralized treatment is not possible, treatment can be done in centralized facilities. For such facilities, those that operate with filtration tend to yield more efficient treatment than those based on water detention.

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