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REPORT

REVIEW OF STORMWATER MANAGEMENT PRACTICES

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Review of stormwater management practices
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Preface

This report presents a short review on the problem definition concerning the stormwater pollution and quantity, as well as actual physico-chemical and sustainable urbane drainage methods available for the management of stormwater.

Klima 2050 - Risk reduction through climate adaptation of buildings and infrastructure is a Centre for Research-based Innovation (SFI) financed by the Research Council of Norway and the consortium partners. The SFI status enables long-term research in close collaboration with private and public sector, as well as other research partners aiming to strengthen Norway's innovation ability and competitiveness within climate adaptation. The composition of the consortium is vital in order to being able to reduce the societal risks associated with climate change.

The Centre will strengthen companies' innovation capacity through a focus on long-term research. It is also a clear objective to facilitate close cooperation between R&D-performing companies and prominent research groups. Emphasis will be placed on development of moisture-resilient buildings, stormwater management, blue-green solutions, measures for prevention of water-triggered landslides, socio-economic incentives and decision-making processes. Both extreme weather and gradual changes in the climate will be addressed.

The host institution for SFI Klima 2050 is SINTEF, and the Centre is directed in cooperation with NTNU. The other research partners are BI Norwegian Business School, Norwegian Geotechnical Institute (NGI), and Norwegian Meteorological Institute (MET Norway).

The business partners represent important parts of Norwegian building industry; consultants, contractors and producers of construction materials: Skanska Norway, Multiconsult AS, Mesterhus/Unikus, Norgeshus AS, Saint-Gobain Byggevarer AS and Isola AS. The Centre also includes important public builders and property developers: Statsbygg, Statens vegvesen, Jernbanedirektoratet and Avinor AS. Key actors are also The Norwegian Water Resources and Energy Directorate (NVE) and Finance Norway.

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Trondheim, May 2017

Berit Time
Centre Director
SINTEF Byggforsk

Abstract

Actual stormwater management involves the direct removal of surface water through a series of pipes to the nearest watercourse to prevent local flooding. Due to climate change and urbanisation stormwater volumes and pollution are getting more and more important leading to significant loads of sediments, heavy metals, nutrients, oils, grease, bacteria and salt pollutants which deteriorate the receiving water bodies. Consequently, modern stormwater management should aim at both flood control and pollution control especially because of the EU Water Framework Directive (WFD) which emphases the control of diffuse pollution as a key factor in enabling good ecological status. Therefore, there is a development of more environmentally-conscious approaches to stormwater management know as 'Sustainable (urban) drainage systems' (SUDS), 'low impact development' (LID) or 'best management practices' (BMPs). This report provides a review on the problem definition concerning the stormwater pollution and quantity, as well as actual physico-chemical and sustainable urbane drainage methods available for the management of stormwater. In addition, it presents an overview of the European roads runoff treatment practises and trends.

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1 Introduction

As urbanization continues to grow, so does the problems associated with stormwater. Runoff volume in rural areas are typically 10 – 20% of the average annual rainfall. Whereas in urban areas, the runoff volume is 60 – 70% of the average annual rainfall. The increase in the volume of the stormwater due to the decrease in soil infiltration, decline in the stormwater quality as the runoff collects heavy metals, oils, grease, bacteria, sediments etc. along its way can all be attributed to urban growth. Furthermore, climate changes reported worldwide leads to more extreme weather events and storm surges and altered precipitation. Ageing urban sewer systems are not conditioned to deal with today's stormwater with high volume and high pollution content. The report 'Overvann i byer og tettsteder' (NOU, 2015) presents a good overview for the Norwegian case.

Figure 1 Towards a more sustainable urban storm drainage (NTUA)

The traditional method of stormwater management mainly focused on diverting the stormwater to the closest watercourse to avert local flooding. The modern stormwater management technique considers not only the quantity of the stormwater but it also gives equal attention to the quality and amenity of the stormwater (Figure 1). This modern technique provides methods that allow source control to handle the quality and quantity of the runoff at local level. These approaches are named differently: 'Sustainable (urban) drainage systems' (SUDS), 'low impact development' (LID) or 'best management practices' (BMPs) (Fletcher et al., 2015). Their purpose are to reduce the runoff volume, to provide natural ground water recharge, to minimise the flood risk, to minimise the erosion risk, to reduce the stormwater pollutant concentration, to enhance the biodiversity, to safeguard water and air quality, to decrease the stormwater treatment and pipe capacity costs, and to increase the amenity and aesthetic value of the developed areas.

SUDS can predominately focus on reducing stormwater pollutant level at the source by cleaning street, spill and dumping control, and awareness campaigns. Such kinds of approaches are known as non-structural SUDS. The structural SUDS, on the other hand, apply different technologies as a source control, site control, and off-site control. For instance porous pavements, swales, ponds, wetlands, infiltration trenches/basins, filter strips, and treatment techniques are all considered structural SUDS.

The purpose of this report is to present the different stormwater treatment techniques that are currently applied across Europe and USA.

2 Challenges

2.1 Stormwater Quantity

The natural hydrological cycle is altered by the urbanization in terms of both hydrology and water chemistry. The main problematic change is the modification of the natural water paths though the watershed (Novotny and Harvey 2003). Figure 2 describes the modification of the watershed due to the urbanisation. Urbanisation results in increase of the runoff volume and in a reduction of infiltration leading to 55% of the rainfall which becomes surface runoff and 15% which becomes unfiltered water while for a natural forested area 50% is unfiltered water and only 10% is surface runoff.

When comparing the hydrographs of natural surface and extensive urbanisation, the later is characterised by a higher total runoff volume, a higher peak flow and a shorter time of concentration (Figure 3). This difference is attenuated after the installation of storm sewers.

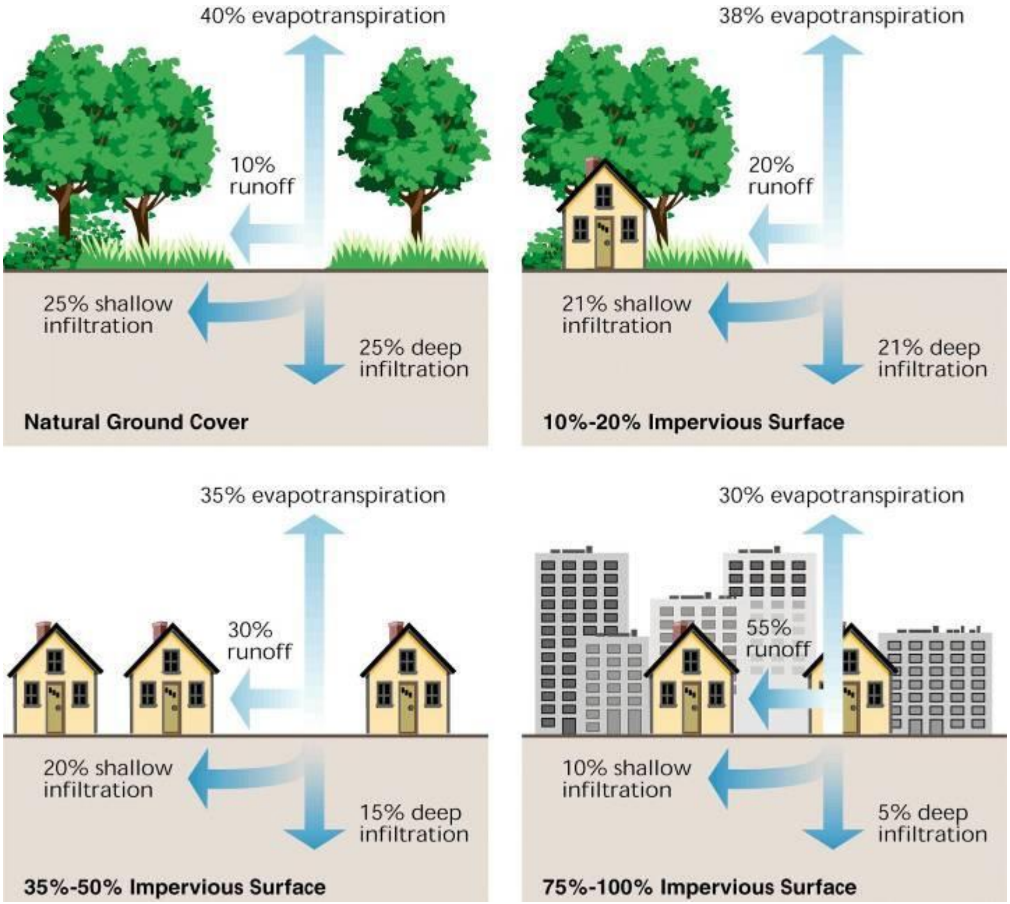


Figure 2 Change in hydrology from a natural to a fully urbanized watershed adapted from (FISRWG 1998 (revised 2001)

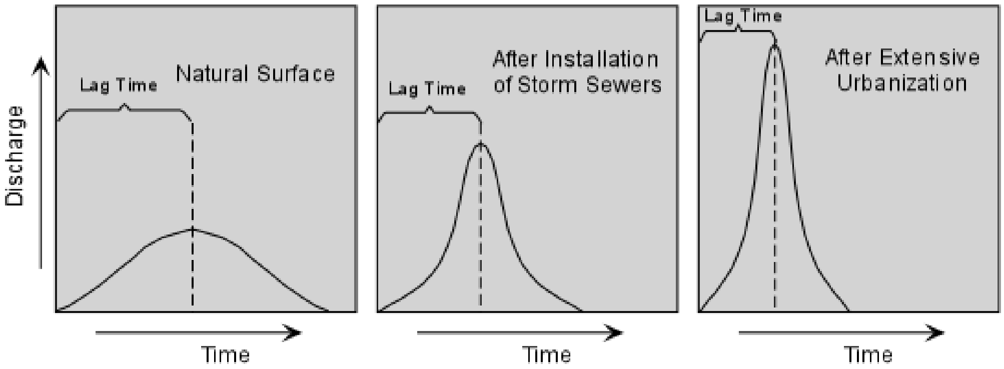


Figure 3 Effect of urbanisation on runoff hydrograph (http://www.tulane.edu/~sanelson/geol204/floodhaz.htm)

2.2 Stormwater Quality

As precipitation washes over land, it picks up and transports a variety of chemicals, pesticides, metals, petroleum products, sediment, and human and animal faecal wastes. These contaminants vary depending on the specific land uses and activities occurring in the source area (Förster, 1999). Urban surface storm water runoff can be divided in three main types:

- Partly sealed surfaces (such as overgrown soil in backyards, urban green spaces and porous paving),
- Impermeable roof surfaces and
- Impermeable road surfaces.

Furthermore, specialised land uses such as storage and trade centres in commercial and industrial areas, agricultural property, harbours and airports may contribute with additional pollutant loading such as nutrients from agricultural property or de-icer from airports (Table 1)(Viklander, 1999, Göbel et al., 2007, Lindgren, 2001)

Table 1 Suggested pollutant concentration for different type of land use (Lindgren, 2001).

Type of land use	Pb min-max (µg/l)	Zn min-max (µg/l)	Cu min-max (µg/l)	Cd min-max (µg/l)	COD min-max (µg/l)	TSS min-max (µg/l)	Tot-N min-max (µg/l)	Tot-P min-max (µg/l)
General urban areas	15-60	80-300	25-100	0.3-0.9	40-120	50-200	1-2.5	0.2-0.4
Residential district	15-40	60-200	20-70	0.2-0.5	40-75	40-160	1-2	0.1-0.4
Residential areas of block of flats	15-60	90-300	25-100	0.3-0.6	60-110	60-200	1-3	0.2-0.5
Residential and central areas	20-70	120-400	25-100	0.3-0.7	90-150	100-260	1-3	0.2-0.6
City traffic	15-70	100-350	25-110	0.3-1.0	110-230	70-250	1-2.5	0.2-0.5
Industry	10-60	120-400	25-110	0.3-0.9	60-120	70-230	1-2.5	0.2-0.6

Roof runoff typically generates low contaminant loads that mainly originate from atmospheric deposition and leaching from, or decomposition of construction materials. In contrast, runoff from roads, parking areas and vehicle service areas generate relatively high contaminant loads and contain a wider range of constituents (Table 2). For such areas, the initial phase of a runoff episode which results in a considerable increase and a subsequent rapid decline in the pollutant concentrations is called first flush.

Table 2 Highway runoff constituents and their primary sources (United States Environmental Protection Agency (US EPA), 1993)

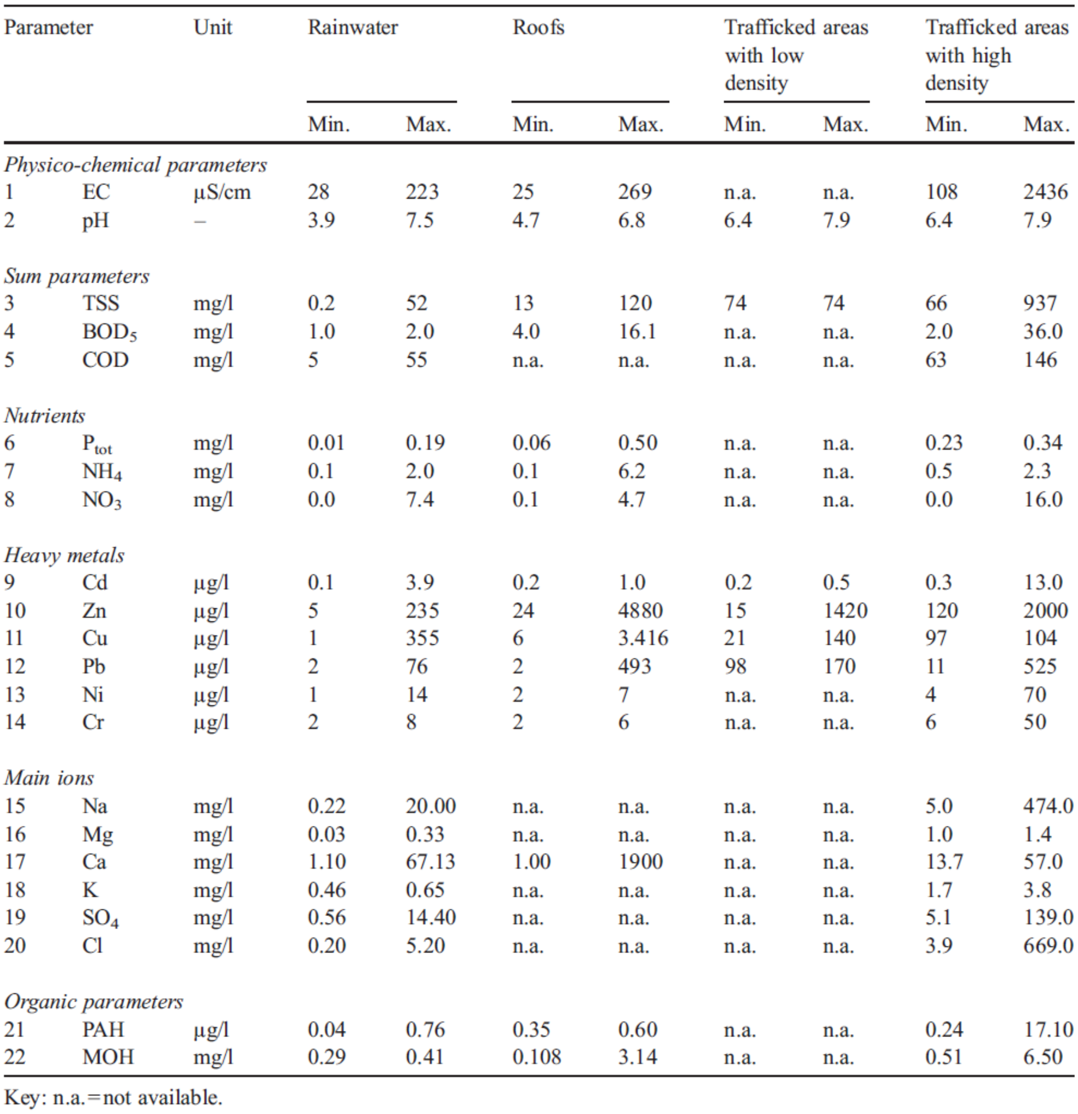
Contaminant	Contaminant Sources
Sediment and Floatables	Streets, lawns, driveways, roads, construction activities, atmospheric deposition, drainage channel erosion
Pesticides and Herbicides	Residential lawns and gardens, roadsides, utility right-of-ways, commerical and industrial landscaped areas, soil wash-off
Organic Materials	Residential lawns and gardens, commerical landscaping, animal wastes
Metals	Automobiles, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes
Oil and Grease/Hydrocarbons	Roads, driveways, parking lots, vehicle maintenance areas, gas stations, illicit dumping to storm drains
Bacterial and Viruses	Lawns, roads, leaky sanitary sewer lines, sanitary sewer cross-connections, animal waste, septic systems
Nitrogen and Phosphorus	Lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, detergents

Many authors identified the same pollutants from road runoff (Makepeace et al., 1995, Barett et al., 1998). A link between pollutant concentrations and traffic density has been identified in many studies with a highest pollution loads from highways and highway bridges (Storhaug, 1996, Marsalek et al., 1999). The particle size fractions and the metal concentrations analyses have shown that heavy metals are attached to the smallest particle with sizes below 10 µm (Boller, 2004, Westerlund and Viklander, 2006). It is recognized that particulate metals are less toxic than in their dissolved forms and therefore portioning coefficient for metals is important to determine the toxicity of the metal concentrations (Muthanna, 2007). In addition to carrying metals, suspended solids carries also many other pollutants such as polycyclic aromatic hydrocarbons (PAHs) and phosphorus and are thus frequently used as an easily quantifiable indicator of stormwater pollution (Sansalone and Buchberger, 1997, Lau and Stenstrom, 2005).

In harbours sediments have also been found to carry adsorbed PAH and polychlorinated biphenyl (PCB). For example, Hem et al. (2002) showed that PAH and PCB were mainly associated with larger particles, and by varying the operational parameters for the centrifuge it was possible to separate fine sediments into different particle size fractions (Hem et al., 2002). Later on, in an other study, Hem et al. (2004) investigated the distribution of PAH, PCB and the bioaccumulation potential of these contaminants in the concentrate (treated sediment) and centrate (water phase) from centrifugation of dredged sediments from the Sandefjord harbour. Results showed that physical separation carried out to divide the sediment based on particle size would not give any major benefit since all of the fractions could be defined as being potential harmful to the environment (Hem et al., 2004).

Göbel et al. (2007) have compiled an intensive literature search on the distribution and concentration of the surface-dependent runoff water. Table 3 contains an overview of the bandwidth of the event mean concentration (EMCs) for rain, roof runoff and runoff of trafficked areas with low and high traffic densities.

Table 3 Bandwidth of EMCs of parameters and pollutants: rainwater, runoff from roofs, and runoff from trafficked areas (Göbel et al., 2007)



Parameter		Unit	Rainwater		Roofs		Trafficked areas with low density		Trafficked areas with high density	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Physico-chemical parameters										
1	EC	µS/cm	28	223	25	269	n.a.	n.a.	108	2436
2	pH	–	3.9	7.5	4.7	6.8	6.4	7.9	6.4	7.9
Sum parameters										
3	TSS	mg/l	0.2	52	13	120	74	74	66	937
4	BOD_5	mg/l	1.0	2.0	4.0	16.1	n.a.	n.a.	2.0	36.0
5	COD	mg/l	5	55	n.a.	n.a.	n.a.	n.a.	63	146
Nutrients										
6	P_{tot}	mg/l	0.01	0.19	0.06	0.50	n.a.	n.a.	0.23	0.34
7	NH_4	mg/l	0.1	2.0	0.1	6.2	n.a.	n.a.	0.5	2.3
8	NO_3	mg/l	0.0	7.4	0.1	4.7	n.a.	n.a.	0.0	16.0
Heavy metals										
9	Cd	µg/l	0.1	3.9	0.2	1.0	0.2	0.5	0.3	13.0
10	Zn	µg/l	5	235	24	4880	15	1420	120	2000
11	Cu	µg/l	1	355	6	3.416	21	140	97	104
12	Pb	µg/l	2	76	2	493	98	170	11	525
13	Ni	µg/l	1	14	2	7	n.a.	n.a.	4	70
14	Cr	µg/l	2	8	2	6	n.a.	n.a.	6	50
Main ions										
15	Na	mg/l	0.22	20.00	n.a.	n.a.	n.a.	n.a.	5.0	474.0
16	Mg	mg/l	0.03	0.33	n.a.	n.a.	n.a.	n.a.	1.0	1.4
17	Ca	mg/l	1.10	67.13	1.00	1900	n.a.	n.a.	13.7	57.0
18	K	mg/l	0.46	0.65	n.a.	n.a.	n.a.	n.a.	1.7	3.8
19	SO_4	mg/l	0.56	14.40	n.a.	n.a.	n.a.	n.a.	5.1	139.0
20	Cl	mg/l	0.20	5.20	n.a.	n.a.	n.a.	n.a.	3.9	669.0
Organic parameters										
21	PAH	µg/l	0.04	0.76	0.35	0.60	n.a.	n.a.	0.24	17.10
22	MOH	mg/l	0.29	0.41	0.108	3.14	n.a.	n.a.	0.51	6.50

Key: n.a. = not available.

2.3 Cold Climates

By adding a snow phase to the cycle in cold climates, the hydrological cycle becomes more complex affecting the pools of water where water is stored in the snowpack and the waterborne pollutant transport (Marsalek, 1991). Cold temperatures, deep frost lines, short growing seasons, and significant snowfall are additional challenges due to cold climates (Caraco and Claytor, 1997). For instance, frozen inlets and frozen pipes can cause flooding during winter rain events. As an example, in Trondheim, 7 out of 12 major floods between 1978 and 2000 were found to occur in the winter (Nilsen and Bjørgum, 2001). Large volumes of snowfall add a snow storage problem and a subsequent snowmelt problem to cold climate urban stormwater management. The residence time in the snow can be up to several months long, compared to a residence time of hours or days for rainfall runoff, which can significantly increase the pollutant loads in the snowpack.

Accumulation of pollutants, heavy metals in particular increases as the snow is stored along the roadside resulting in metal concentrations up to ten times higher than that of snow fallen on urban grass surfaces (Malmqvist, 1978). Pollution can differ from the warm season due to the use of studded winter tires on vehicles which increases asphalt abrasion, less optimal combustion in engines as a result of cold temperatures, more heating of houses which leads to increased particle deposition (Malmqvist, 1978, Viklander, 1997). The snowmelt period can be divided into three stages:

- The pavement melts stage, where de-icing chemicals and solar radiation will melt the impervious areas where snow clearing also takes place. This process generally produces low runoff volumes and occurs several times during the winter.
- The second stage involves the roadside melt of snow piles accumulating around the roads and parking lots. This stage produces moderate flow volumes, but high pollutant loads and can occur over some time. This is the snowmelt which generally carries the heaviest pollutant loads.
- And last, the third stage melts snow on pervious areas, such as parks, grass, and other pervious surfaces in the urban landscape. This last stage can often produce the highest runoff volumes depending on the soil infiltration rates (Oberts, 1994).

The change in pollutant accumulation also affects the snowmelt water quality. Novotny et al. (1999) claimed that snowmelt generally has lower suspended solids concentrations, but much higher dissolved solids concentrations (Novotny et al., 1999). This can be said to be true as the large masses of particles are left along the roadside after snowmelt (Figure 4) and will either be cleaned by heavy rainfall or by street sweeping but not in the initial melt water (Muthanna, 2007).

Figure 4 Pictures of the road side at Södra Hamnleden in Luleå, Sweden. At the Left, street during snowmelt and the right, street sediment left on road after final snowmelt (Westerlund, 2007).

However if the snow is transported to a storage/treatment area the particles will be left as a gray cover of dirt and grit after the melt period has ended. Several studies investigating the composition and pathways of snowmelt pollutants have concluded that there is an enrichment ratio of dissolved pollutants early in the snowmelt, and as much as 80% of the dissolved pollutants can be transported with the first 20% of melt water volume (Viklander and Malmqvist, 1993, Ecker et al., 1990). During several freezing and thawing cycles of the snowpack over the winter, the dissolved components are flushed from the snow pack and accumulate at the toe of the snowpack, which will melt first (Figure 4). This process is also called ”acid flushing”, ”preferential evolution” or ”freezing exclusion” (Oberts, 1990). A study from northern Sweden comparing melt water runoff and rain runoff concluded that the concentration of sediments were significantly higher in the melt period, and a stronger correlation between total suspended solids, particle sizes and metal (Cd, Cu, Ni, Pb, and ZN) concentrations (Westerlund and Viklander, 2006). It is well recognized that the use of chloride salts as road de-icing chemicals is an environmental concern for a host of reasons including damage to vegetation, weakening of concrete structures, corrosion of vehicles, contamination of shallow groundwater and impacts on freshwater ecosystems (Marsalek, 2003, Howard and Beck, 1993, Emerson and Traver, 2008). Infiltration of de-icing salt constituents has also been observed to increase the mobility of metals in roadside soils (Amrhein et al., 1992, Norrström and Bergstedt, 2001) and increase metal concentrations in underlying aquifers, (Granato et al., 1995, Norrström, 2005) although contamination of groundwater by metals is a relatively rare occurrence that appears to be limited to older, high traffic areas (Toronto and Region Conservation, 2009).

3 Legislation

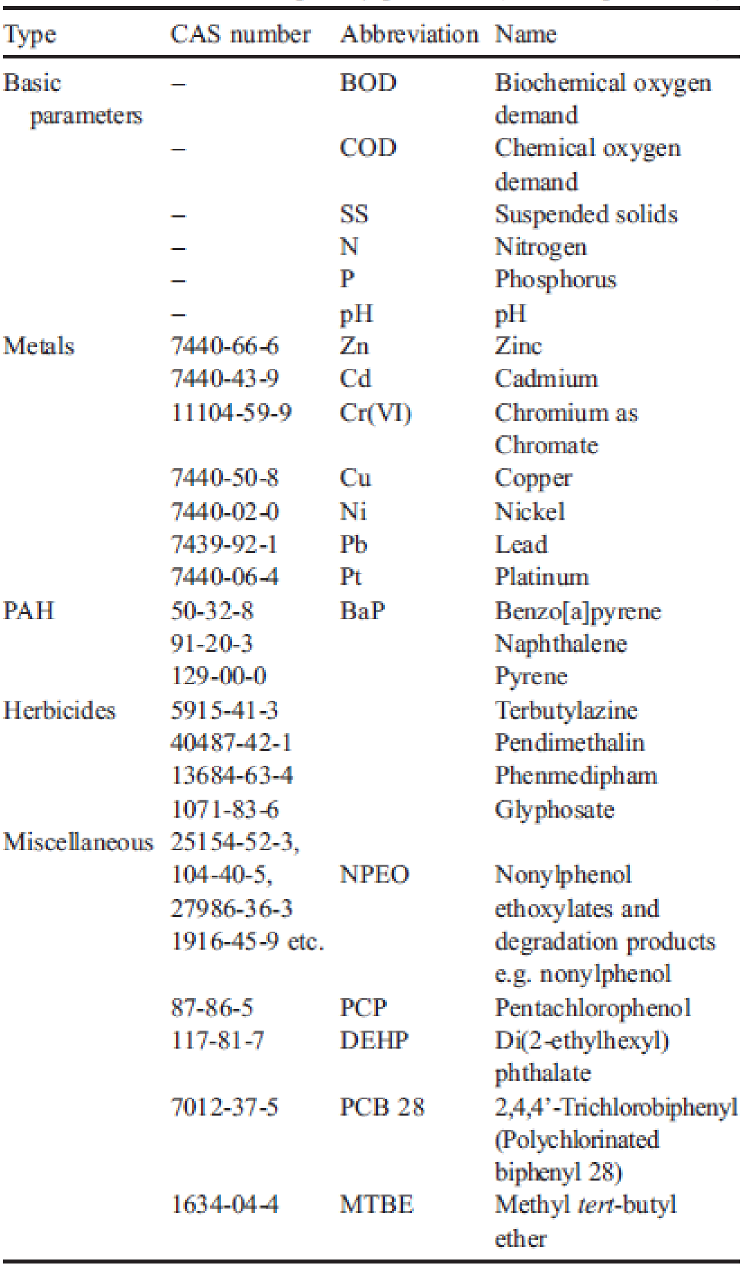
Traditionally, stormwater has been managed for flood control, and direct connections between impervious surfaces and recipient waters via separate or combined sewers have been used to facilitate quick and efficient collection, conveyance and discharge of surface runoff water (Figure 5) (Blecken, 2010). However, these systems were usually installed without considering water quality aspects (Bedan and Clausen, 2009, Walsh et al., 2005, NOU, 2015).

Figure 5 Disharge of untreated stormwater from a stormwater sewer

Indeed, release of untreated urban stormwater runoff to receiving waters may cause physical, chemical, biological and combined effects that impair their quality and thereby affect aquatic ecosystems and their beneficial use by humans. These effects differ in various climatic regions, but seem to be particularly severe during snowmelt or rain-on-snow events (Marsalek, 2003).

The EU Water Framework Directive (WFD) (EU, 2000) identifies the control of diffuse pollution as a key factor in enabling good ecological status to be achieved in aquatic systems (NOU, 2015). A list of 33 priority substances has been regulated in the Decision 2455/2001/EC and a number of specific “daughter” directives by defining emission limit values and quality objectives in water bodies, namely surface and coastal waters, for member states (Zgheib et al., 2011). Researchers have shown an increased interest in the monitoring of priority and/or emerging substances to generate information about their occurrence and effects in the environment (Burton and Pitt, 2001, Gasperi et al., 2009, Gasperi et al., 2008, Thévenot, 2008, Eriksson et al., 2007, Rule et al., 2006a, Rule et al., 2006b). However, to date there has been little agreement in the international researcher community on a list of substances to be monitored, especially for stormwater (Zgheib et al., 2011). For instance, Eriksson et al. (2007) proposed a list of substances to give valuable support for stormwater managers regarding the comparison of various stormwater management strategies. Their approach was based on a theoretically assessment of the stormwater substances presence called the CHIAT (Chemical Hazard Identification and Assessment Tool) methodology.

Table 4 List of selected stormwater priority pollutants (indicator parameters)(Eriksson et al., 2007)



Type	CAS number	Abbreviation	Name
Basic parameters	–	BOD	Biochemical oxygen demand
	–	COD	Chemical oxygen demand
	–	SS	Suspended solids
	–	N	Nitrogen
	–	P	Phosphorus
	–	pH	pH
Metals	7440-66-6	Zn	Zinc
	7440-43-9	Cd	Cadmium
	11104-59-9	Cr(VI)	Chromium as Chromate
	7440-50-8	Cu	Copper
	7440-02-0	Ni	Nickel
	7439-92-1	Pb	Lead
	7440-06-4	Pt	Platinum
PAH	50-32-8	BaP	Benzo[a]pyrene
	91-20-3		Naphthalene
	129-00-0		Pyrene
Herbicides	5915-41-3		Terbutylazine
	40487-42-1		Pendimethalin
	13684-63-4		Phenmedipham
	1071-83-6		Glyphosate
Miscellaneous	25154-52-3, 104-40-5, 27986-36-3 1916-45-9 etc.	NPEO	Nonylphenol ethoxylates and degradation products e.g. nonylphenol
	87-86-5	PCP	Pentachlorophenol
	117-81-7	DEHP	Di(2-ethylhexyl) phthalate
	7012-37-5	PCB 28	2,4,4'-Trichlorobiphenyl (Polychlorinated biphenyl 28)
	1634-04-4	MTBE	Methyl *tert*-butyl ether

4 Physico-chemical stormwater treatment

4.1 Sedimentation Treatment

Sedimentation treatment which is usually applied in underground settling tanks is a basic treatment that exploits the gravity force to separate water from solid particles. Figure 6 shows an example of the layout of such system.

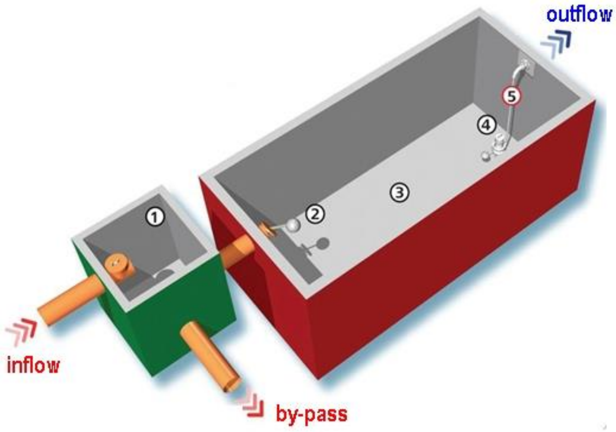


Figure 6 Scheme of a sedimentation tank, for uptake and storage of stormwater. The capacity of tank is used for sedimentation and removal of solids before the discharge in the receiving water body. 1. automatic floodway tool, 2. float shutoff valve; 3. grit removal chamber, floatation/ sludge storage, first flush storage chamber, 4. lifting pump, 5. flowmeter.

A reduction of pollutant substances in large areas (such as cars parking areas) could be obtained by application of distributed sedimentation treatment: in particular, sediments can be reduced by the installation of little settling tanks along and under the storm drain system (under the inlet grates). The efficiency of this application depends on the frequency of cleaning operations.

Though the pollutant removal efficiency of this system is dependent on how often the system is cleaned, in general 90% of Total Suspended Solids (TSS), 90% of Settable Solids (SS), and 30% of COD & BOD_5 can be removed by this technique.

4.2 Filtration treatment

4.2.1 Surface sand filter

The filter bed and the sediment chamber are above ground. It is generally designed as an off-line practice, where only the water quality volume is directed to the filter. It consists of a pretreatment basin, a water storage reservoir, flow spreader, sand and underdrain piping (Figure 7).

Effective in removing many of the common pollutant runoff, sand filters have shown to have a moderate level of bacterial removal. They have not been effective at removing dissolved solids and nitrate-nitrogen. Pollution removal is 87% of TSS, 59% of TP (total phosphorus) and 32% of TN (total nitrates).

Sand filters are very adaptable and have few site constraints. They can be used in high-density urban sites with small drainage areas that are completely impervious (such as parking lots). They are intended primarily for quality control and not for quantity control. Indeed, a diversion structure, such as a flow splitter or weir, is provided to route the first flush of runoff into sand filter, while the remainder continues on to a storm-quantity-control (if any) or in the urban drainage system.

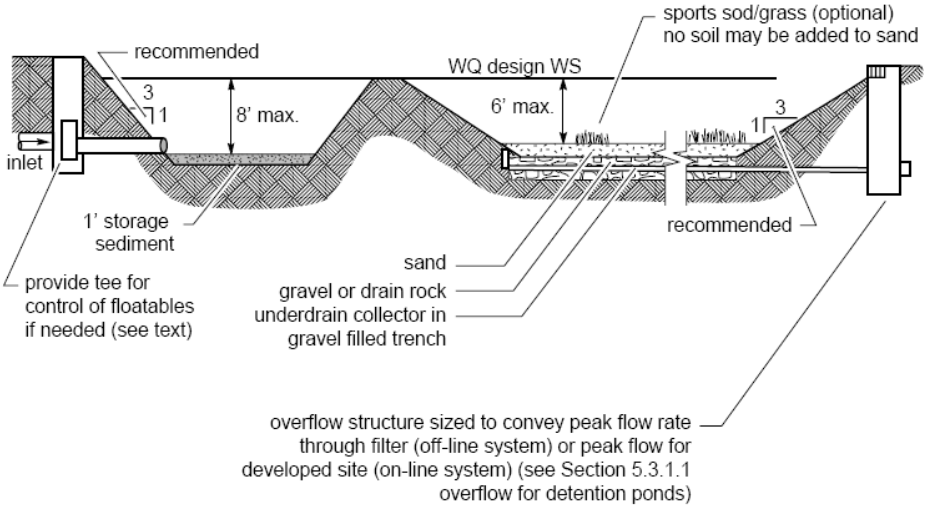


Figure 7 Surface sand filter, cross section view, recommendation for design. (Washington State Department of Ecology 1999)

4.2.2 Underground filter

This system is similar to the surface filter except that the sand filter (or other media) and underdrains are installed below grade in a vault (Figure 8). They are intended to address the spatial constraints that can be found in intensely developed urban areas, where drainage areas are highly impervious. Underground filters are most effective when designed off-line; they are intended primarily for quality control. A diversion structure is provided to route first flush of runoff into the underground filter, while the reminder continues on to a stormwater quantity control practice (if any). Underground sand filter is typically a three chamber system. The initial chamber takes care of pretreatment, utilizes a wet pool and temporarily stores runoff. The first chamber is connected to a second sand filter chamber by a submerged wall. Water flows to and is spread over the sand filter where pollutants are either trapped or strained out. These two chambers temporarily store water during storms. Perforated drains extend into a third chamber collecting filtered runoff. This solution have been demonstrated to be effective in removing many pollutant substances (TSS, Heavy Metals, Floatables as primary benefits, TP, TN, Oil and Grease, Feacal coliform, BOD as secondary design benefit).

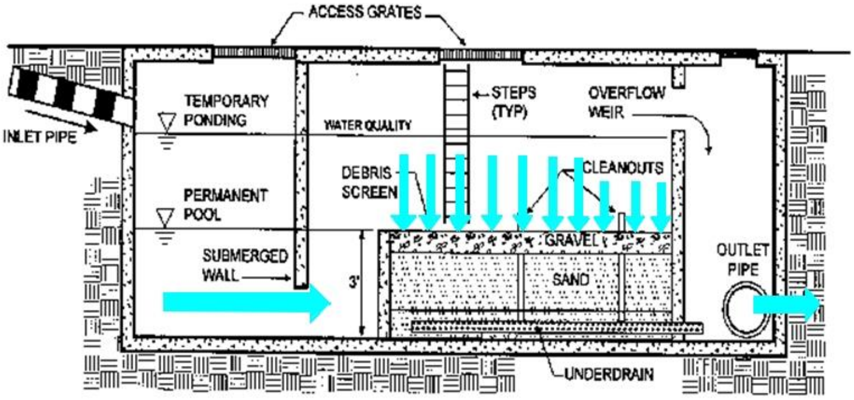


Figure 8 underground filter with conventional sedimentation tank (profile view) (http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Tool6_Stormwater_Practices/Filtering%20Practice/Sand%20and%20Organic%20Filter%20Strip.htm)

4.2.3 Perimeter sand filter

Perimeter sand filter is also known as Delaware Sand Filter, it includes a sedimentation chamber and a filter bed. It is designed as an on-line practice, with all flows entering the system through grates, with larger events bypassing treatment by entering an overflow chamber (Figure 9). An advantage is that it requires little hydraulic head, a good option in areas of low relief. It is highly accepted by the community, but the cost and maintenance can be high. This solution can remove 79% of TSS, 41% of TP, and 47% of TN, although these numbers are based on limited data. It has small footprint and it is a good solution for parking lots.

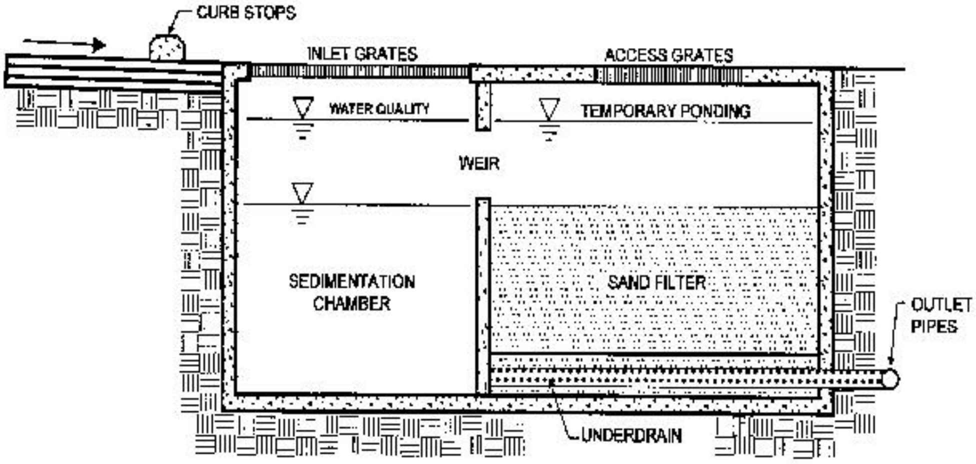


Figure 9 perimeter sand filter, profile view (http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Tool6_Stormwater_Practices/Filtering%20Practice/Sand%20and%20Organic%20Filter%20Strip.htm).

There are also pocket sand filter and bioretention areas included in measures suggested by the Centre of Watershed Protection, but they are less applicable to highly urbanised areas.

In the application of underground filter, sediment removal could be reached by the application of a vortex chamber or a conventional sedimentation tank. If flux of water is pre-treated in a vortex chamber (Figure 10), the efficiency of pollutant removal can reach the 84% for the TSS and 98% of hydrocarbons, against 70% and 80%, respectively, with sediment tank without vortex pre-chamber (Figure 10). Furthermore the system with vortex pre-chamber allows obtaining the removal of 69% of BOD_5, 59% of COD and 85% of lead.

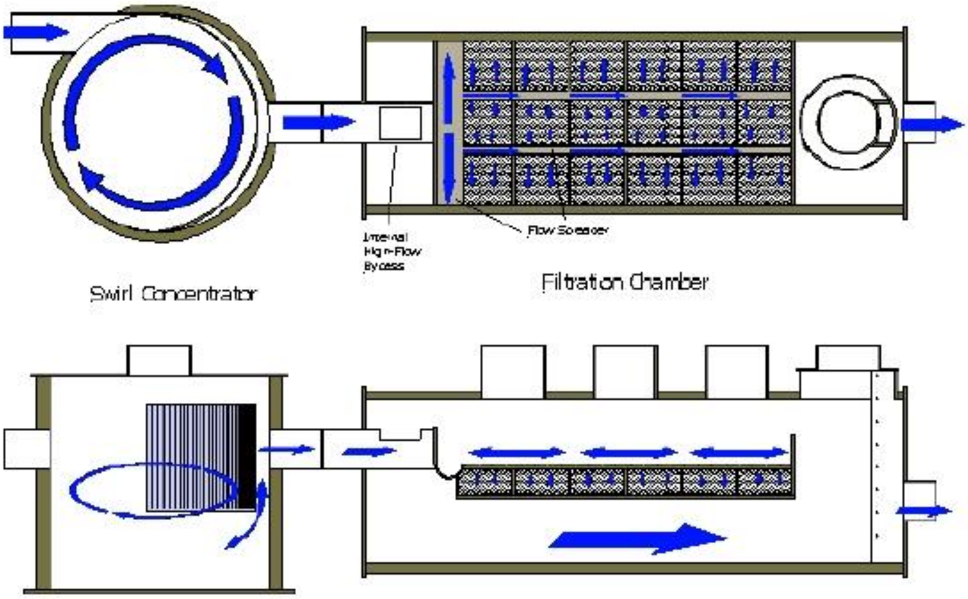


Figure 10 Plan view and profile view of a filtration treatment plant with a pre-chamber of Vortex sedimentation.

Common characteristics of filtering systems are that filtering media can be sand, soil, gravel, peat or compost but they all filter pollutants entrained in stormwater runoff. Second, filtering systems are typically applied to small drainage areas (five acres or less). Third, filtering systems are designed solely for pollutant removal. Water volumes from extreme events are bypassed around the filter to a downstream stormwater management facility. The filter media is incorporated into the filter bed. The three key properties of the bed are its surface area, depth, and profile. The required surface area for a filter is usually calculated based on the amount of impervious area treated and the media itself, and may vary due to regional rainfall patterns and local criteria (or regulations) for computing water volumes that have to be treated. A relatively shallow filter bed is generally preferred for hydraulic and cost reasons, and because most pollutants are trapped in the top few inches of the bed.

Many key pollutant removal mechanisms associated with filters are related to the filter media (Centre of Watershed Protection, 2001). For example, filtration, adsorption, and microbial action are all influenced by the media type.

The application of Compost has given results of 90% of TSS, 88-98% of heavy metals and 85% of fats and oils. New concept filtration systems consider the application of:

- Different filler of loose material put in layers;
- One or more layers of zeolite or GAC (granular activated carbon), or fibers from thermoplastic synthetic;
- Tools in which the filter layer is placed into cartridges that allow backwash of filters.

The application of multi-layer filters is easy to be applied in prefabricated plastic boxes, with pre-sedimentation and grates too (Figure 11).

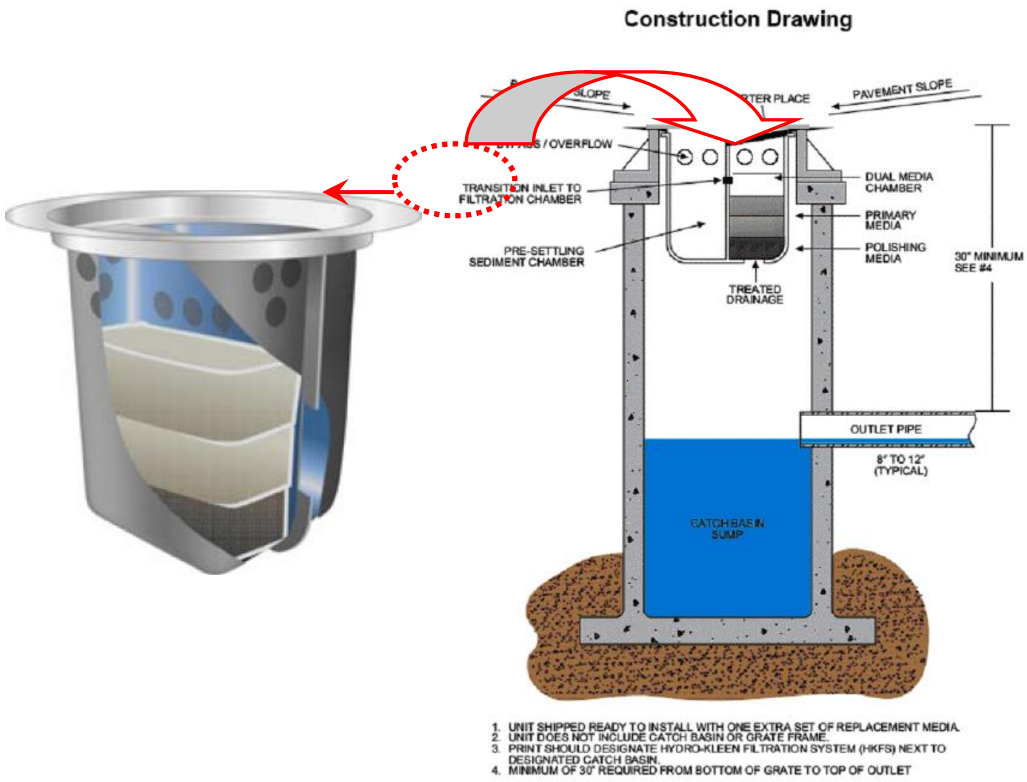


Figure 11 Profile of a filtration system with a prefabricated module.

The application of a zeolite layer allows a good metals removal: one or more layers of zeolite can give different efficiency (Table 5).

Table 5 Removal efficiency (percentage) applying one, two or three layers of zeolite.

LAYER	Zn %	Pb %	Cu %	Cd %
1	39	72	44	30
2	53	83	58	51
3	69	98	76	75

The insertion of a GAC filter to a sand filter layer only allows removing oils, fats and organic compounds, because of the adsorption properties of activated carbons.

High removal efficiency can be obtained with the application of thermoplastic fibers, placed in plastic or stainless steel boxes, that allows further than the filtration action, also a coalescence effect of hydrocarbons, PBC (Polychlorinated biphenyls), Cu, Zn, Pb, Cr VI and other heavy metals. This system does not require the application of sedimentation pretreatment that means minor volumes and costs.

Removal efficiencies are 90% of TSS, 98% of Cu, 89% of Pb, and 99% of Zn and hydrocarbons.

All filter need washing operational and maintenance. To solve this, many backwash systems have been introduced at the end of filtration. These systems are made by one or more modules in cylindrical cartridges; each cartridge is made up by a cylinder of metal surface that contains the filter media, and by a layer of filter material (sand, perlite, GAC, compost or other adsorbing materials), at the end there is a internal valve that enable the connection with the water discharge allowing the backwash of cartridge.

A best management practice (BMP), designed to meet stringent regulatory requirements, is the Stormwater Management StormFilter^{TM} . It removes the most challenging target pollutants – including fine solids, soluble heavy metals, oil, and total nutrients – using a variety of sustainable media. Its patented, surface-cleaning system prevents surface blinding, which extends the cartridge life cycle, see: www.contech-cpi.com/Products/StormwaterManagement/Filtration/StormwaterManagementStormFilter.aspx

A StormFilter^{TM} consists of concrete vault that house siphon-driven cartridges containing alternative filtration media (fabric inserts, perlite, zeolite, and patented CSF leaf media). A typical StormFilter^{TM} contains an inlet bay which serves as a grit chamber and provides a flow transition into the cartridge bay. This transition is via a flow spreader that traps floatables, oils and surface scum prior to their entering the cartridge bay. After the surface scum is separated by the flow spreader, the water passes over an energy dissipater and begins filling the cartridge bay. Once the water reaches a designed level, water is pulled through the filtration media where pollutants are abated. The treated stormwater passes through a slotted centre tube where it is then routed via pipe manifold, cast into the floor of the concrete vault. After leaving the pipe manifold, the treated water can be sent directly to a waterway.

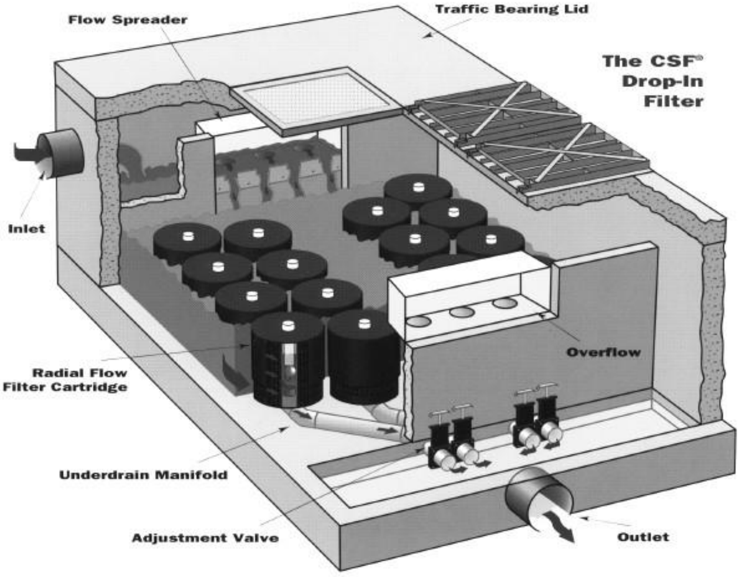


Figure 12 General scheme of StormFilter^{TM} plant.

The system (Figure 12) could be applied in-line or off-line, in a concentrated (many cartridges concentrated in a unique chamber, along the drainage network) or distributed way (many single cartridges under grates along streets, etc.).

This system allows removing 94% of TSS, 78% of COD, 70% of TN, 58% of TP, 80% of TPH (total petroleum hydrocarbon), 81% of Cu and Pb, and 78% of Zn.

4.2.4 Floatation systems

Treatments based on floatation are usually applied to remove pollutant from industrial plants drainage areas. Most of pollutants deposited on these impervious areas are oils, fats and hydrocarbons. Oil separators aim at removing all pollutant with a specific weigh lower than water unit weight.

There are three types of oil separator units which are presented in the following subsections.

4.2.4.1 Gravity oil separator

A gravity oil separator also called API oil-water separator (Figure 13) is a device designed to separate gross amounts of oil and suspended solids from the wastewater effluents of oil refineries, petrochemical plants, chemical plants, natural gas processing plants and other industrial sources. The name is derived from the fact that such separators are designed according to standards published by the American Petroleum Institute. The API separator is a gravity separation device designed by using Stokes Law to define the rise velocity of oil droplets based on their density and size. The design of the separator is based on the specific gravity difference between the oil and the wastewater because that difference is much smaller than the specific gravity difference between the suspended solids and water. Based on that design criterion, most of the suspended solids will settle to the bottom of the separator as a sediment layer, the oil will rise to top of the separator, and the wastewater will be the middle layer between the oil on top and the solids on the bottom. Typically, the oil layer is skimmed off and subsequently re-processed or disposed of, and the bottom sediment layer is removed by a chain and flight scraper (or similar device) and a sludge pump. The water layer is sent to further treatment (usually dissolved air flotation DAF for removal of residual oils and biological treatment for dissolved chemical compounds).

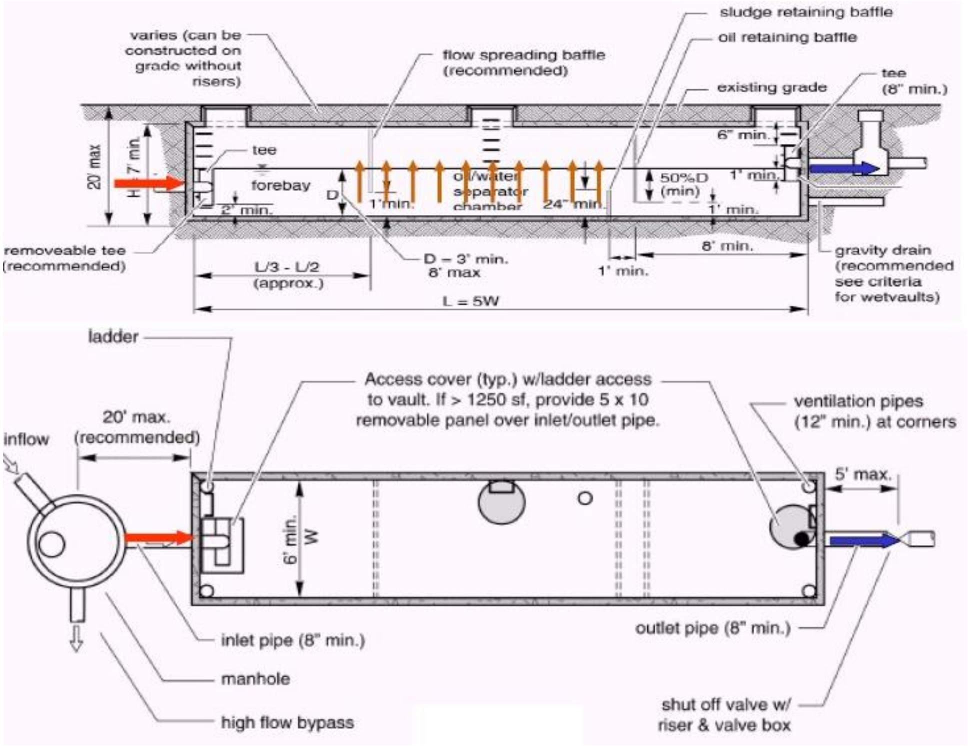


Figure 13 Gravity oil separator for first flush treatment in industrial areas, source API 421.

Because of the variability of rainfall characteristics, automatic devices are often applied. These modules require large areas not always available, therefore prefabricated structures are preferred.

As an example, the BaySaver® Separator (Figure 14) is a physical separator, relying on gravity settling, flotation, and other related mechanisms, to remove sediments, floating debris, and free oils from stormwater. The system comprises three main components: the BaySaver Separator Unit, the Primary Manhole (PM), and the Storage Manhole (SM). Both manholes are of standard concrete construction and function as sediment-accumulation sites. During a storm event, the Separator Unit acts as a flow control to route the influent flow through the most effective flow path for treatment. For example, under low-flow conditions, the entire influent flow is treated in the PM and SM. Under moderate flows and up to the maximum treatment rate, water is treated through both the PM and SM, with a portion of these flows diverted through T-pipes.

The T-Pipes are structures that enhance the performance of the system during high-intensity storm events that are below the MTR of the separator. This flow path allows for full treatment of floatable pollutants, while still treating sediments under moderate flow conditions. During maximum flow conditions or maximum hydraulic rate, most of the influent flow passes over the bypass plate and will not be treated.

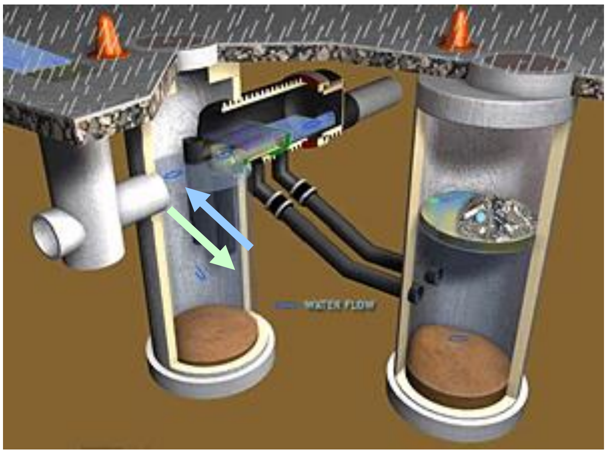


Figure 14 BaySaver® Separator

This system requires inspection every trimester (4 times at year) and an annual maintenance operation, unless a large amount of collected sediments and oils is noted.

4.2.4.2 Coalescence oil separator

If the floatation treatment exploits a coalescence effect, it is possible to reduce the volume occupied by the chamber of about 40%: this effect is given by oleophilus mobile devices in plastic material inside the oil separation chamber. These elements are characterised by a wide specific surface (corrugated plates, etc.) and allow obtaining hydrocarbons concentrations lower than 5 mg/L. An example of coalescence separator has been developed by Ecol (http://www.ecol-group.com/technology.php) as shown in the following picture (Figure 15).

Figure 15 Coalescence oil separator (http://www.ecol-group.com/technology.php).

4.2.4.3 Adsorbing pillow oil separator

These pillows (Figure 16) preferentially absorb oils and greases, helping to accelerate the breakdown of absorbed hydrocarbons by bacterial action. The pillows are designed for the continuous absorption of oily waste but may also be used to assist in spill clean up operations absorbing excess oils and grease from accidental spillages. Combining a blend of hydrocarbon degrading bacteria and oleophilic fibre, pillows application degrades the blooms of hydrocarbon-based materials commonly found in interceptors and similar oily water catchment systems (http://www.accepta.com/biological-treatment/oil-absorbent-pillows.asp).

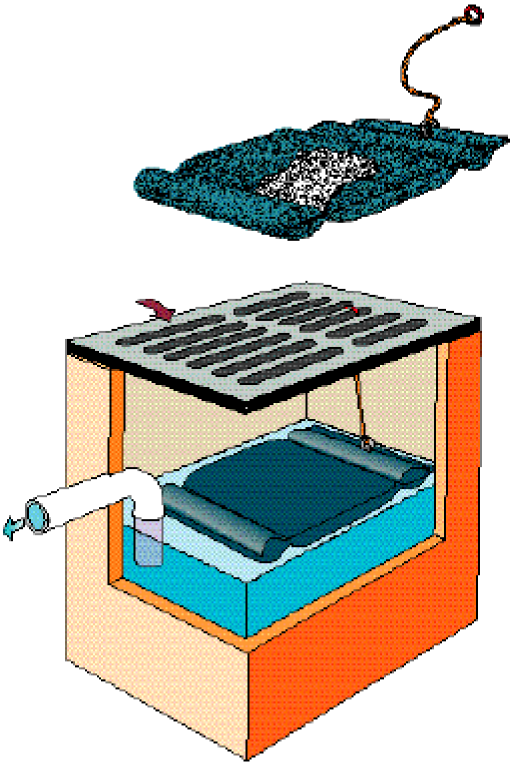


Figure 16 Oil separation by adsorbing pillow (http://www.accepta.com/biological-treatment/oil-absorbent-pillows.asp).

5 Sustainable urban drainage systems (SUDS)

Approaches to stormwater management known as ‘Sustainable (urban) drainage systems’ (SUDS), ‘low impact development’ (LID), or ‘best management practices’ (BMPs), (Faram et al., 2005, Fletcher et al., 2015) represent a diverse range of control procedures, which integrate stormwater quality and quantity control as well as enabling social and amenity perspectives to be incorporated into stormwater management approaches.

The following are techniques used in SUDS to control quantity and quality of runoff at or nearby the source.

5.1 Green roofs

Green roofs consist of a deep layer of soil that is planted with grass and other vegetation (Figure 17). The green roof components may be installed separately or it can be modular. For the modular installation system the drainage layers, filter cloth, growing media and plants are set as movable interlocking grids. Green roof will absorb the stormwater and temporarily stores it. The absorbed water will be used by the vegetation, will be transpirated and most importantly will reduce the quantity of runoff getting into the stormwater system and also enhances the quality of the stormwater. This technique is highly appreciated for its ability to decrease stress on the sewer systems at peak flow in urban areas. Green roofs can also moderate temperature of the given building. 70 - 90 % of precipitation and 25 – 40 % of water in winter is retained by green roof. Green roof can retain 10 - 15 cm of water if it has 4 - 20 cm layer of growing medium. According to Augustenborg Botanical Roof Garden (Malmö, Sweden) research paper, green roof retains 50 % of the rainwater on yearly basis, allowing only for the 50 % of the rainwater to run off of the roof. Capacity of green roof is dependent on the season; hence, there is a great deal of runoff variation due to season changes (Stahre, 2008).

Figure 17 German company before and after green roof installation photo

5.2 Swales

Grassed channel, dry swale, biofilter are all included in the term “swale” for it represents an open channel system of series of vegetated practices to treat stormwater (Figure 18). As the stormwater flows through channels and infiltrates into the vegetation and underlying soils, it is being treated as well. Though there are differences in the design of grassed swale, grassed channel, dry and wet swale, they all are the upgraded form of traditional drainage ditch. In order to avoid erosion, the slope of the grassed channels should be less than 4%. The cross section of open channels is often trapezoid or parabolic and have flat sides that must be between 60 – 240 cm wide. This will allow for the runoff to have a slower velocity providing more time for the runoff to flow through vegetation and infiltrate into the soil. The flow velocity of stormwater in large areas is more than what this system can handle so grassed channels are often designed for small drainage areas that are less than five acres. Most soils, excluding soils that are highly impermeable, can be used for this system. There should be minimum of two 60 cm gap between the bottom of dry swale and groundwater level to avoid groundwater contamination. It must be noted that the gap between the swale type and ground water table is dependent on the applied channel. But for wet swale, the design can allow an intersection between the wet swale and groundwater table since wet pool amplifies the treatment. Pretreatment techniques such as small forebay and pea gravel diaphragm should be applied upstream of the swale system to avoid sediment strap and clogging. The design of swales must consider a 10-year storm to handle larger storms. 2 year storm is what is considered for most swales to avoid erosion due to runoff.

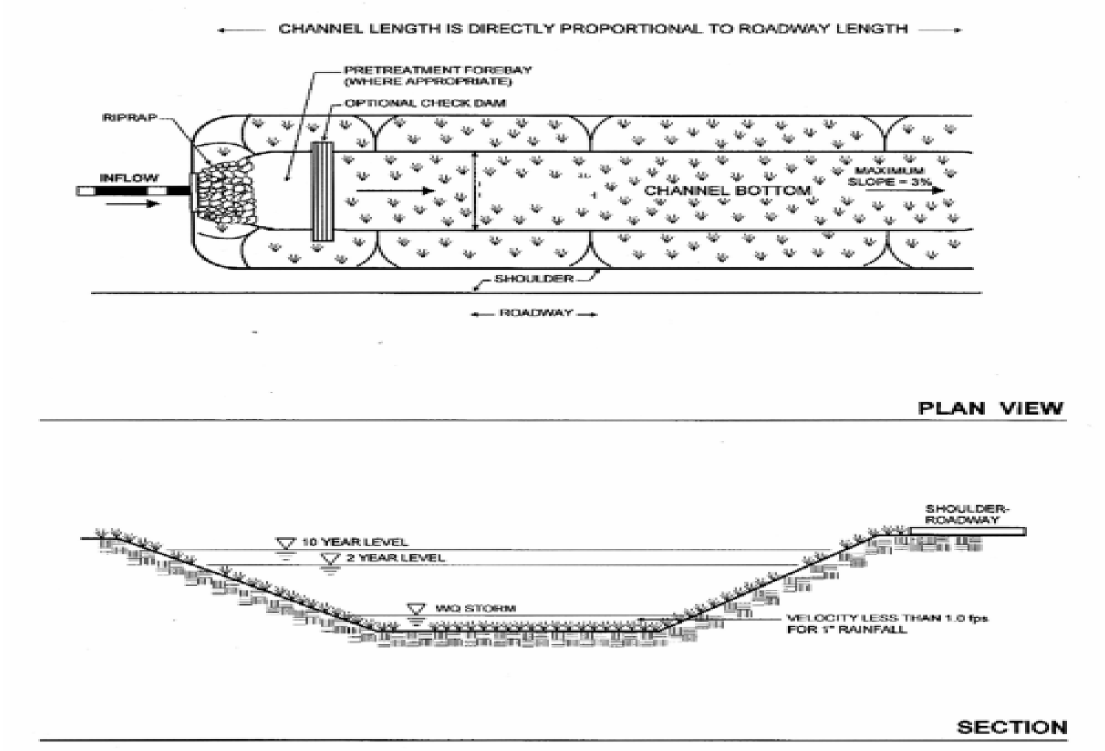


Figure 18 Plan view and section of a typical grassed channel (Source: www.stormwatercenter.net).

The swale technique cannot be applied to large drainage areas. Unless the design and construction has the proper slope, the system also fails to remove pollutants successfully. Wet swales can also provide a good environment for mosquito breeding. Wet swales are also not used to recharge groundwater for the bottom of the swale is filled with organic debries blocking infiltration of treated water into the groundwater.

The small slope needed for swales makes the system a good choice for treating runoff from highway or residential areas. Due to how ultra-urban areas are not suitable for open channel treatments, swales are not appropriate for urban areas. Hotspot runoffs should also not be conveyed to grassed channels, except in dry swale design. Both grassed channels and dry swales can be used to recharge groundwater if and only if the system has high standard of infiltration. Removal rates exceeding 80% of total suspended solids are quoted for swales having flow velocities less than 0.15 m/s and with high soil infiltration rates (Scholes et al., 2008a)

In cold climates, swales are common practices because of the potential to store snow and to control the melted snow. However the drawback of these systems is the decrease of snowmelt conveyance during the ice blockage at swales inlet and outlets (Middlesex University, 2003, Westerlund, 2007). Bäckström (2003) reported a removal for TSS and concentration of Cu, Pb, and Zn in range of 78-99% for snow covered swales and this removal was dependent of the incoming pollutant concentrations (Bäckström, 2003).

5.3 Soakaway

Soakaways (Figure 19) are often small areas (<4 m^2 in plan area) which receive stormwater from a large impermeable catchment. They serve only one household and are constructed in the private grounds surrounding the property. Often constructed no more than 2 m deep and with the storm drain discharging to the pit around 1m below ground surface, the resulting volume of water storage in the pit is only some 1 m^3 (assuming 30% void space in the stone or rubble fill)(Scholes et al., 2008b).

Soakaways, which are type of infiltration technique, are considered a great SUDS method because it allows for rainwater treatment to be handled at the source. The size of the area and the percolation rate of the permeable surface are the two factors that control soakaway's storm management technique. Of course, the level of the water table is also an important aspect to investigate before installing soakaway for there should be an underground space for the water that infiltrates through the permeable surface. Removal of solids by physical filtration and the growing of microorganisms in the soil that cause biochemical reactions are the different ways soakaway treats runoff. Soakaways have high impact on removal of total suspended solids, heavy metals, phosphorous & nitrogen removal, runoff volume reduction, and hydraulic control. Soakaways are also often used to recharge underground water. They can be suited to many ultra urban areas. They should not receive pollution hot spot runoff. Can also be used to manage overflows from rain barrels or other rainwater harvesting systems.

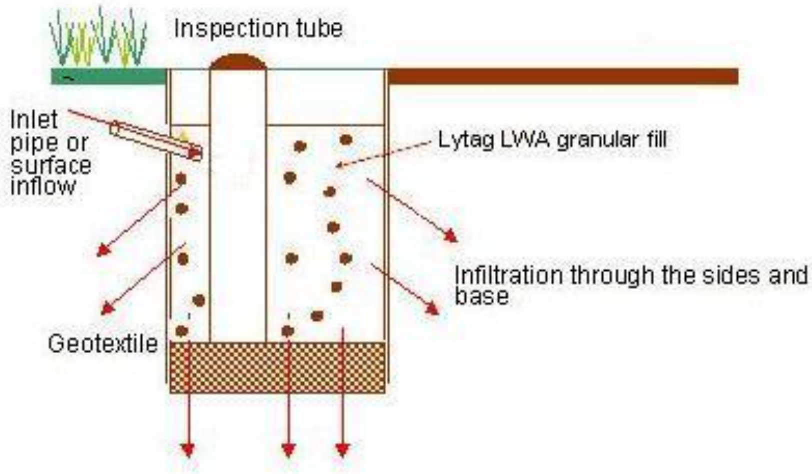


Figure 19 Cross-Section through a traditional soakaway (source: www.lytag.co.uk/applications/suds.php)

5.4 Filter/buffer strips

Unlike swales, buffer strips (Figure 20) are set on flat areas with very low slopes. Buffer filters are used as pretreatment method. Buffer strips that may be located along streets and highways use lateral runoff from land adjusts to streams, drains and basins to block suspended solids and associated pollutants. Provided that the flow is kept shallow and slow, coarse particulates can be removed by applying the buffer strips method. The slope should be 0 - 2 % to allow for the system function fully. The quantity of runoff coming to the buffer strips, type of vegetation, the size of the filter strip, the soil infiltration rate, flow path, and flow length determine the pollutant removal efficiency of this system. If the filter strips are using grass like turf grass only, its pollutant removal capacity and slowing runoff is very low. The cost for this treatment type is dependent on the amount and type of vegetation planted and the buffer strips performance capacity. Since buffer strips consume a large amount of space they are often not applied in urban areas. Buffer strips also provide snow storage and treatment in cold climate areas. A well maintained, highly vegetated filter strips have 80% efficiency of removing suspended solids. This technique can have a 98 % sediments and pollutants removal efficiency if the filter strip has porous media that allows for water to infiltrate easily (US Environmental Protection Agency, 1999).

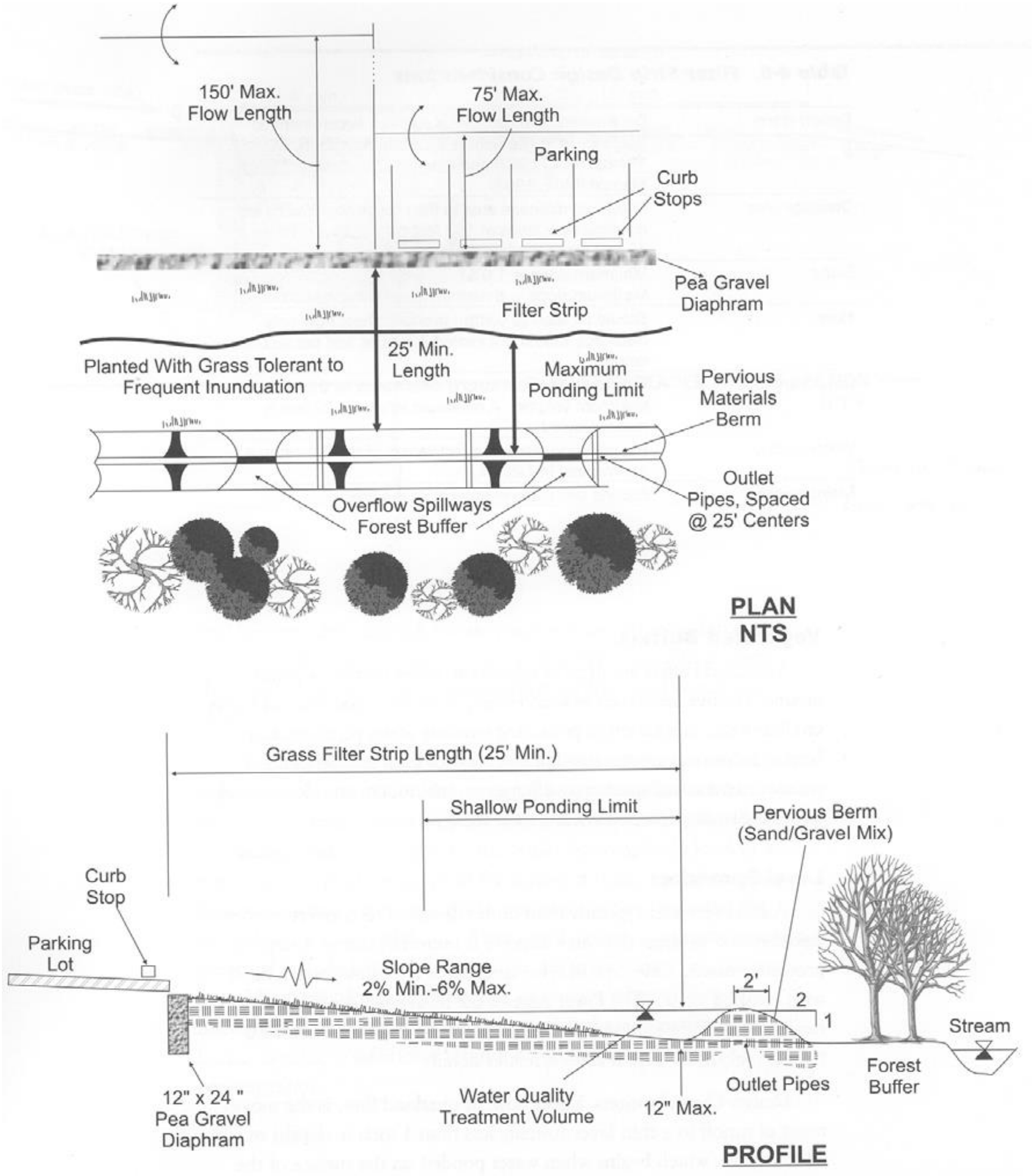


Figure 20 Filter strips (source: U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT, 2003).

5.5 Infiltration trenches

This system (Figure 21) allows runoff to infiltrate and be stored in between stones and /or transport to underground pipe. Before the runoff enters and gets stored in the trenches, pretreatment techniques like sediment basin is applied on the stormwater runoff. Soil filtration is the main primary technique for removing pollutants. Application of infiltration trenches is often limited due to the high probability of polluting underground water by untreated runoff. Consequently, infiltration trenches are installed to areas that are less than five acres and on flat grounds. The infiltration rate should consider the probability of avoiding clogging because of low permeable soils and the potential of contaminating underground water due to lack of proper treatment by highly permeable soil. The soil is recommended to have maximum 20% of clay and no greater than 40% silt/clay content (Centre of Watershed Protection, 2001). This will provide 1.3 -0.7 cm per hour of infiltration rate. Though the designs of infiltration trenches differ from site to site, all trenches should be able to infiltrate runoff within twenty four hours and trenches should have a pretreatment mechanism for the runoff. The pretreatment mechanism increases the pollutant removing capacity of the trenches and also decrease clogging of trenches making the maintenance procedure much easier. In order to prevent adjacent soils clogging the infiltration trenches, geotextile fabric should be lined by the sides of the trenches. They are designed with emergency overflow structures for major storms that will allow runoff be directed to the public stormwater system.

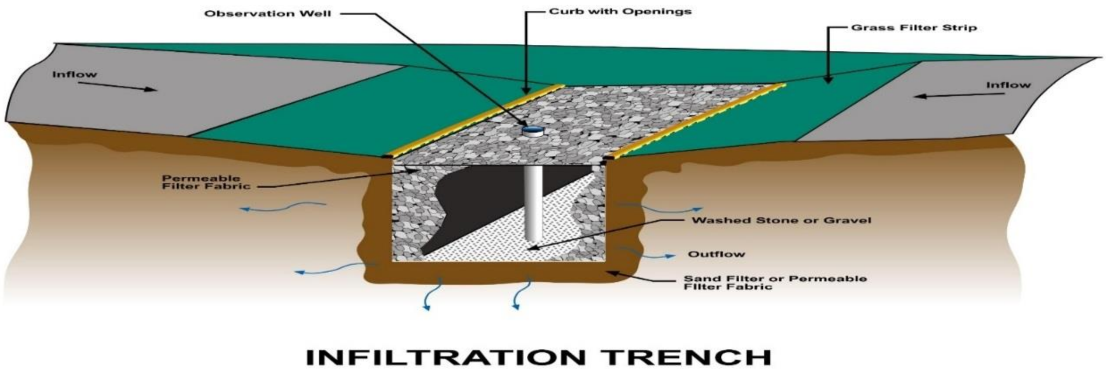


Figure 21 Infiltration trench design source (https://keneulie.wordpress.com/2010/02/06/infiltration-trench/)

Infiltration trenches have one of the highest probability of failure in the stormwater management techniques unless there is a combination of pretreatment included in the design. Maintenance for infiltration trenches is estimated to cost 5% to 20% of the total construction cost. This method is hardly applied in urban areas because soils in urban areas have low infiltration rate. This system is also not applicable for areas that have the landscape formed from dissolution of soluble rocks like limestone, dolomite, and gypsum. In general, infiltration trenches are not practical for underground drainage systems with sinkholes and groundwater pollution.

Channel protection, capacity to recharge groundwater, and if properly maintained, the system's ability to treat runoff, are the advantages of infiltration trenches. Since they can use up to only 2-3% of drainage site, infiltration trenches can be placed in thin linear areas.

Infiltration trenches can be very effective for reducing runoff volumes and for filtering sediments.

Table 6 presents typical removal achieved by infiltration trenches.

Table 6 Typical removal achieved by infiltration trenches.

Site type Load Reductions	(American Society of Civil Engineers (ASCE), 2000)	(Guo et al., 2006)
TSS	70 – 90 %	
Zn	-	91 % (Dissolved form) 98 % (Bounded form)
Pb	-	51 % (Dissolved form) 85 % (Bounded form)
Cd	-	49 % (Dissolved form) 85 % (Bounded form)
Cu	-	91 % (Dissolved form) 97 % (Bounded form)

Site type / Load Reductions	(American Society of Civil Engineers (ASCE), 2000)	(Guo et al., 2006)
Heavy metals	70 – 90 %	
Nitrogen	40 – 70 %	
Phosphorus	50 – 70 %	

5.6 Infiltration basin

This system (Figure 22) is similar to infiltration trenches only water is stored in visible pond and is applied to larger areas for infiltration basin. Infiltration basin’s purpose is to infiltrate stormwater into the soil. During design of this technology the infiltration rate of soil, methods how to avoid groundwater contamination, and easy maintenance techniques should be considered. The system should be applied to areas with less than ten acres. Similar to infiltration trenches the soil must have maximum of 20% clay and 40% of silt/clay with infiltration rate of 1.3 -0.7 cm per hour. The basin can be drained early winter season and snowmelt can be treated during spring season by using underdrains and level control valves of the infiltration basin. Risk of underground water contamination can be minimized by providing separation between the bottom of the infiltration basin and the ground water level. The recommended separation is between 5 to 12 cm. Infiltration basin, similar to infiltration trenches also require a multiple pretreatment system in order to avoid clogging and minimize maintenance cost. Grass swales, sediment basins, filters are some of the pretreatment the design can include. The pretreatment method for runoff before it gets to infiltration basin system includes the consideration of upland soils stability with thick layer of vegetation to avoid clogging of the basin with sediment. Because of the many pretreatment needed, this technique is applied only in small areas and are “off-line” practice.

Groundwater contamination and soil’s saturation are limitations associated with this practice. As a result, maintenance of this system is both costly and also requires an extensive pretreatment measure. This technique is not reasonable to apply in urban areas, cold climate regions, and stormwater hotspots.

Infiltration basins ability to recharge groundwater and in the process, its ability to remove pollutants are the main advantageous of this system. Since the system takes only 2% -3% of the draining system, it is relatively cheap. The maintenance cost for infiltration basin is estimated to be 5% -10% of the construction cost. Provided that the infiltration basins have a good pretreatment systems installed and the basin is well maintained, it is estimatesd that 75% of TSS, 60-70% of TP, 55-60% of TN, 85-90% of metals, and 90% of bacteria can be removed by using infiltration basins.

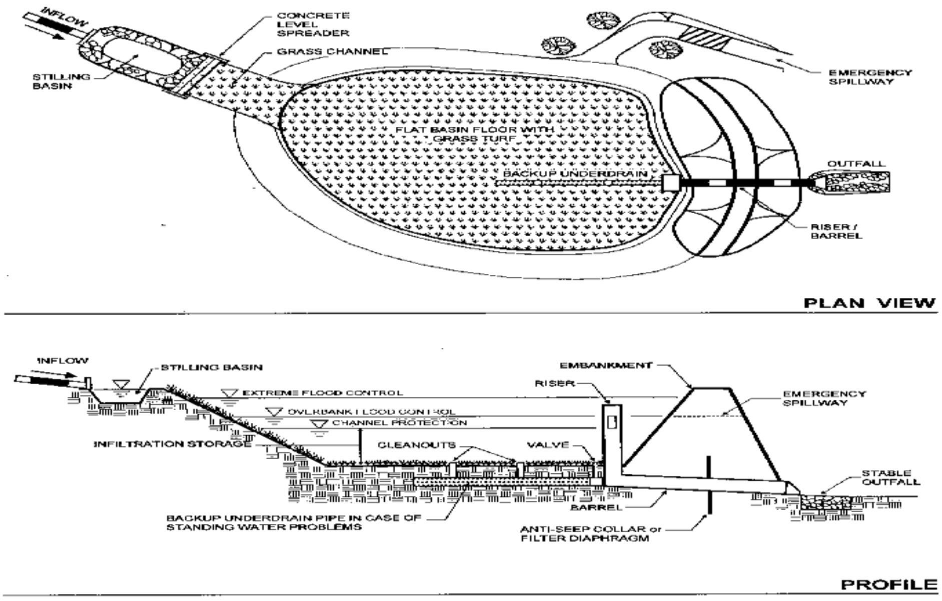


Figure 22 Components and configuration of an infiltration basin (STORMWATER CENTER, 2011)

5.7 Retention (wet) ponds

Wet ponds (Figure 23) as the name indicates are ponds that are wet during wet seasons if not the entire year. Settling and alga uptake are the main methods of treating runoff by this system. Wet ponds also known as balancing ponds or storage basins, serve the purpose of removing pollutants by biological process which can be enhanced by marginal planting (Scholes et al., 2008b).

Wet ponds have permanent pool of water with depth of 1.3 -3 meters and 25-50% of area is covered by vegetation. 25 acres of drainage area is needed in humid areas to maintain permanent pool. Whereas arid and semi-arid regions require bigger drainage area. Consequently, wet ponds need to wide though they only take 2-3% of the contributing drainage area. Water is transported from the inlet to the outlet of the pond by gravity; therefore, there must be a substantial drop while keeping the local slope in the pond shallow.

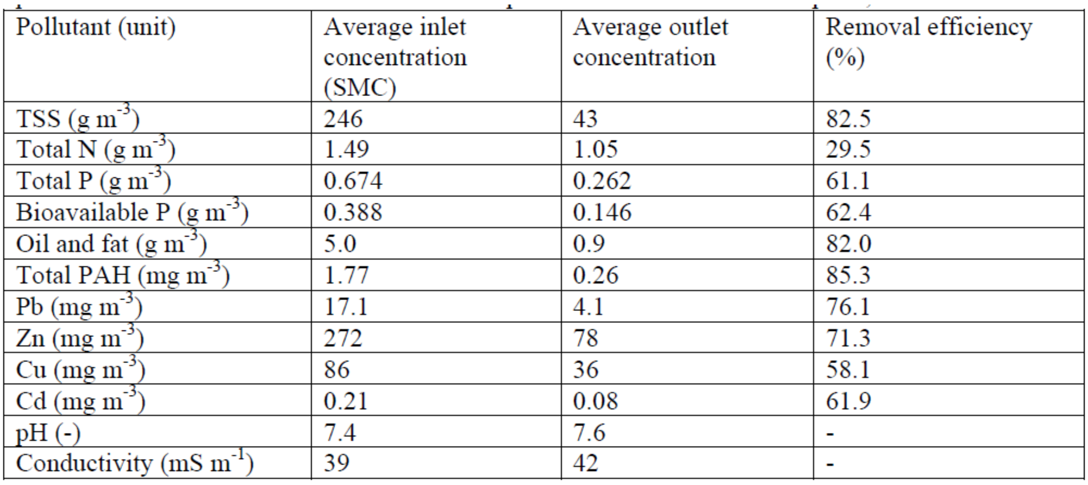
The design of the pond is proportional to the volume of runoff it is expected to treat. The longer the runoff stays in the pond, the longer time the sediments have to settle. This can be achieved by designing permanent pool with large volume. The minimum length to width design ratio for wet ponds must be 1.5 - 1 m. Elongating the pond also allows for the runoff to go through longer path, giving time for settlements to settle. Flow velocity can also be decreased by installing multiple ponds in series allowing for a better treatment of the runoff. Major problems associated with wet ponds includes warming at the outlet area of the pond, erosion due to the outflow, and flood. Providing some shade to the outlet of the pond area will solve the warming problem. If the system has stabilized outfall, erosion due to outflow from the pond will not occur. For the purpose of maintenance, easy access to the forebay and main pool should be provided. Besides adding the aesthetic value to a given area and provide a good environment for habitants, landscaping of wet ponds can also increase the pollutant removal capacity of this method.

Since the bottom of the pond is generally filled with settled materials like organic derbies, it is impossible to recharge the groundwater by the wet pond technique. Though wet ponds take relatively small area, the size of the pond often cannot fit into highly populated urban areas. Ponds are not installed in arid and semi-arid regions for ponds in such regions require constant addition of chemicals to the permanent pool. Wet ponds also have the ability to warm streams, therefore they are not allowed to be installed in cold water streams.

Figure 23 Wetpond in Maryland, Talbot County (Source: http://www.roads.maryland.gov)

A wet detention pond located in Oslo, Norway that receives highway runoff from a 2.2 ha impervious area is selected as example (Vollertsen et al., 2006). This example is selected because the design is well defined and particularly because continuous monitoring at the inlet and the outlet of the pond has been performed during a 1-year period. Totally, 87% of the incoming stormwater during this year has thereby been monitored. Main results from the monitoring program are shown in Table 7 (Aalborg University, 2007).

Table 7 The yearly average pollutant removal efficiency and flow weighted yearly average pollutant concentrations in the inlet to the wet pond and the outlet from the pond.



Pollutant (unit)	Average inlet concentration (SMC)	Average outlet concentration	Removal efficiency (%)
TSS (g m^{-3})	246	43	82.5
Total N (g m^{-3})	1.49	1.05	29.5
Total P (g m^{-3})	0.674	0.262	61.1
Bioavailable P (g m^{-3})	0.388	0.146	62.4
Oil and fat (g m^{-3})	5.0	0.9	82.0
Total PAH (mg m^{-3})	1.77	0.26	85.3
Pb (mg m^{-3})	17.1	4.1	76.1
Zn (mg m^{-3})	272	78	71.3
Cu (mg m^{-3})	86	36	58.1
Cd (mg m^{-3})	0.21	0.08	61.9
pH (-)	7.4	7.6	-
Conductivity (mS m^{-1})	39	42	-

5.8 Wetlands

Constructed wetlands (Figure 24) are artificial, designed complex vegetative water bodies that can provide treatment (and re-cycling) of both wastewater effluent and stormwater runoff. Surface flow systems (also known as free water systems) are wetlands in which water primarily flows above the ground surface and through the litter layer (Ellis et al., 2003). They simulate natural marshes, employing shallow channels and basins planted with emergent, submergent and/or floating vegetation through which water flows at shallow depths and low velocities (Scholes et al., 2008b).

Properly designed wetlands can remove significant amounts of nitrogen and phosphorus, suspended solids, and other pollutants from urban environments. The relative amounts of pollutant and suspended solid removal is similar to other BMPs, however, with removal rates ranging from 40 to 80 percent. Though this technique is recommended for rural areas, the large area needed for the filter is disadvantageous for urban areas.

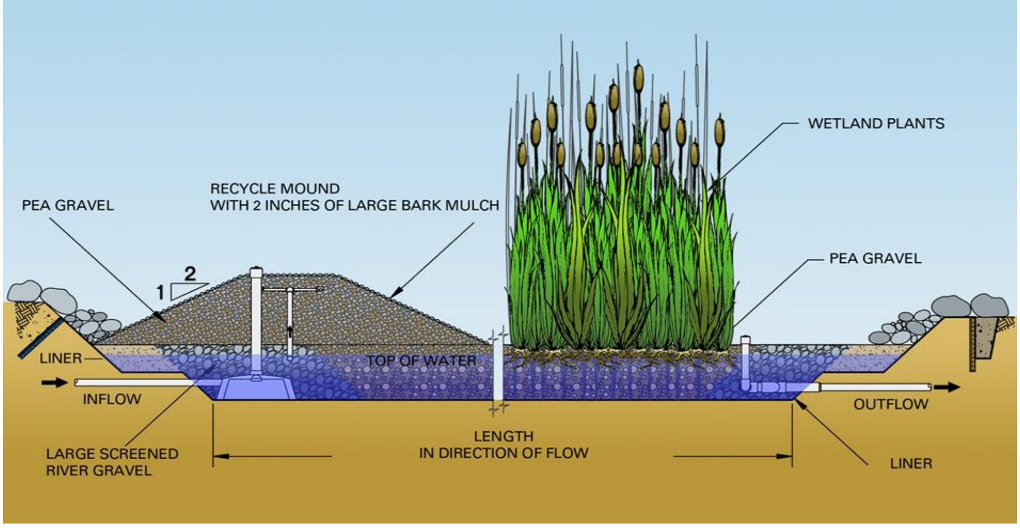


Figure 24 Subsurface Constructed Wetlands, (source: http://www.natsys-inc.com/resources/about-constructed-wetlands/)

5.9 Bioretention

It is a shallow excavated surface depression containing mulch and a prepared soil mix and planted with specially selected native vegetation that captures and treats runoff (Figure 25). During storms, runoffs collect in the depression and gradually filter through the mulch and prepared soil mix and root zone. Also referred to as rain garden, bioswale or biofilter (Toronto and Region Conservation, 2009).

Bioretention areas are landscaping features adapted to treat stormwater runoff on the development site. They are commonly located in parking lot islands or within small pockets in residential land uses. Surface runoff is directed into shallow, landscaped depressions. These depressions are designed to incorporate many of the pollutant removal mechanisms that operate in forested ecosystems (Ashley et al., 2011). The filtered runoff can either infiltrate into the native soil or be collected in a perforated underdrain and returned to the storm sewer system. They remove pollutants from runoff through filtration in the soil and uptake by plant roots and can help to reduce runoff volume through evapo-transpiration and full or partial infiltration. They can also provide wildlife habitat and enhance local aesthetics (Toronto and Region Conservation, 2009).

Bioretention systems are generally applied to small sites, but can be applied to a wide range of development. It is feasible in many climate and geologic situations, with some minor design modifications. In cold climates, bioretention areas can be used as snow storage areas (Toronto and Region Conservation, 2009). Bioretention facilities are ideally suited to many ultra urban areas, such as parking lots. While they consume a fairly large amount of space (approximately 5% of the area that drains to them), they can fit into existing parking lot islands or other landscaped areas. They can be used to treat stormwater hotspots as long as an impermeable liner is used at the bottom of the filter bed, and they are well suited for stormwater retrofit, by modifying existing landscaped areas, or if a parking lot is being resurfaced. In highly urban watersheds, they are one of the few retrofit options that can be employed. However, it is very expensive to retrofit an entire watershed using bioretention areas since they treat small sites (Ashley et al., 2011).

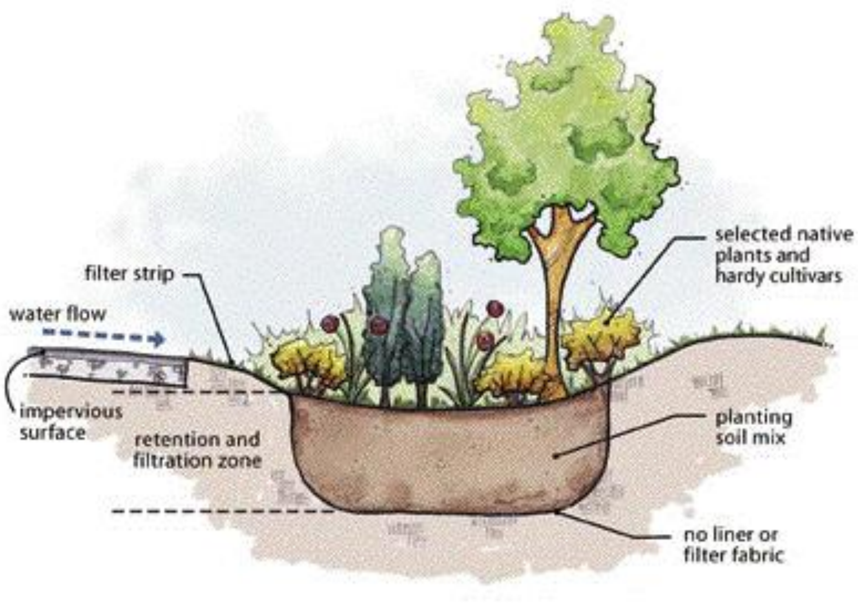


Figure 25 Typical design of a bioretention area with underdrain (PGC, 1993)

Bioretention systems are reported to be effective at reducing runoff volumes for example Davis (2008) found typical peak flow reductions of 44 to 64 % and flows peaks were delayed by a factor of 2 or more, were observed after two years of monitoring (Davis, 2008). Li et al. suggest approximately 20-50 % of runoff entering the bioretention cells was either infiltrated into the native soil or lost through evapo-transpiration (Li et al., 2009).

Bioretention systems have the potential of being the most effective BMPs for pollutant removal (Toronto and Region Conservation, 2009). Table 8 presents typical removal for some pollutants achieved by bioretention cells. When it comes to nutrient retention studies have produced more variable results (Toronto and Region Conservation, 2009). Nitrate nitrogen retention in bioretention systems has consistently been observed to be low, likely due to low adsorption of negatively charge nitrate ions to soil particles. Materials which favour anaerobic conditions improves the denitrification by bacteria (Toronto and Region Conservation, 2009).

Table 8 Typical removal achieved by bioretention systems (Toronto and Region Conservation, 2009)

Studies / load reductions	University of Maryland (Davis et al., 2003)	University of Maryland (Davis et al., 2003)	New Hampshire (Roseen et al., 2006)	Parking lot runoff at University of Maryland (Davis, 2007)	Snow melt runoff in Norway (Muthanna et al., 2007)
TSS	-	-	-	47 %	-
Zn	>95 %	64%	99%	62 %	74 %
Pb	>95 %	70 %	98 %	83 %	99 %
Cu	>95 %	43 %	-	57 %	89 %
Phosphorus	-	-	-	76 %	-

5.10 Permeable pavements

As the name indicates, permeable pavements are pavements that are permeable asphalt, permeable concrete, permeable interlocking concrete pavers, concrete grid pavers, and plastic grid pavers where opening are filled with pea gravel, sand or top soil and grass (Figure 26). Once the runoff infiltrates through the porous pavements it is directed to underground pipes or the underlying subsoil. Though permeable pavements do look like regular pavements, they are made without “fine” materials leaving void spaces in the pavement. This void space in grass pavers are made to allow grass to grow. The permeability rate of the soil must be 1.3 and 7.5 cm/hour for permeable pavements. There must be a minimum of 60 – 150 cm gap between the permeable pavement and groundwater table and be at least 30 m far from drinking water wells. The pavement’s surfaces prevents unintended materials from infiltrating through the pavement along with the runoff. So essentially the pavement surface is used as pretreatment method before the runoff gets to stone reservoir underneath. The stone reservoir that is basically small stone layer, below the pavement surface treats the runoff as it infiltrates through the stone. The infiltrated runoff then penetrates into the ground. In order to keep the bottom of the stone reservoir flat and direct the infiltrated runoff to its proper destination, sand layer and geosynthetic liner must be placed under the stone reservoir. During heavy storms the runoff must be directed to the storm drain system. To prevent clogging of pavements the landscape of the pours pavement area must be stabilized and the guidance on how to keep permeable pavement in good condition must be provided.

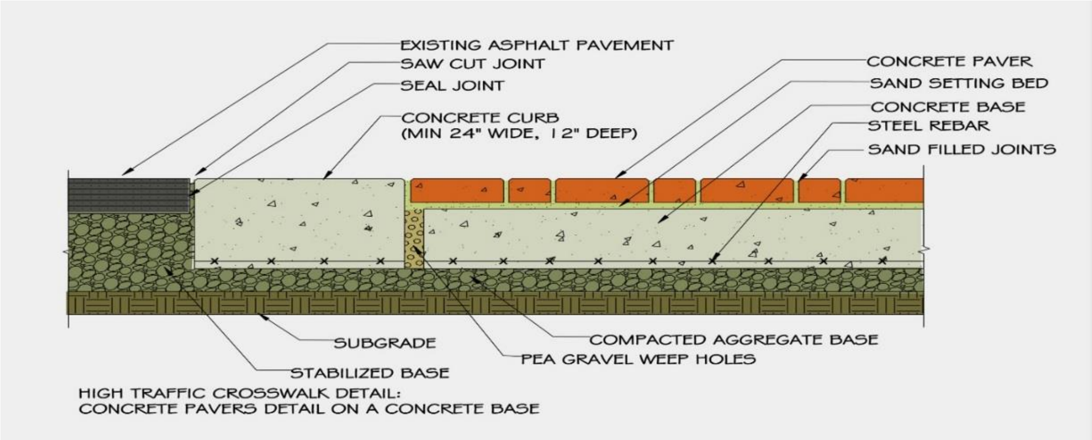


Figure 26 Permeable pavements design source (source: http://www.abbey-associates.com/splash-splash/blue_standards/porous_paving.html)

Permeable asphalt has been reported to infiltrate an average of 97 % in a study in France (Legret and Colandini, 1999). Anderson et al. (1999), examined rainfall, runoff and evaporation from permeable pavers with different bedding materials (25 to 50 mm deep) on a full scale model parking lot and found an average of 55% and 30% of rainfall was retained (Andersen et al., 1999).

In Luleå, Sweden, (Bäckström, 1999) examined runoff from two different residential road sections, one permeable and one impermeable, and found that snowmelt runoff volume could be reduced by 50 to 60% by using permeable pavement.

Bäckström (2000) also monitored winter temperatures of a porous asphalt and conventional asphalt in a residential area of Luleå, Sweden. The two pavements were found to freeze in much the same way. However porous pavement is more resistant to freezing and has a lower risk of frost heave damage relative to conventional impervious pavements (Bäckström, 2000). During the winter, water will continue to infiltrate as temperatures permit, but at a slower rate. It has been reported a 50% reduction in surface infiltration rates as temperatures declined from 20°C to 0°C.

Clogging has been a serious issue in some of the early permeable pavement installations (Lindsey et al., 1992). Many of the early permeable pavement installations were constructed with sand as a bedding layer. More recent installations use washed stone in the pavement openings and bedding layer because it resists breaking down into smaller particles with age, and the pore spaces are large enough to transmit fine particulate matter into the base course layers, thereby reducing the potential for surface sealing (Toronto and Region Conservation, 2009).

Permeable pavements improve runoff water quality by filtering and trapping contaminants within pavement pores and the underlying stone reservoir or base course. Table 9 shows typical removal for a permeable pavement.

Table 9 Typical removal achieved by a permeable surface

Site type load reductions	Roadway in France (Legret and Colandini, 1999)	Highway in France (Pagotto et al., 2000)
TSS	59 %	87 %
Zn	73 %	
Pb	84 %	74 %
Cd	77 %	
Cu	-	20 %
Hydrocarbon	-	90 %

5.11 Evaluation of SUDS

Table 10 presents a comparative study of available SUDS methods. For each technique, a description, some advantages and disadvantages are included.

Table 10 Advantages and disadvantages of source control systems (CIRIA, 2007, City of Lincoln Nebraska and the Lower Platte South Natural Resources District, 2006)

Source control system	*Description*	*Advantage*	*Disadvantage*
Green roofs	*Deep layer of soil that is planted with grass and other vegetation*	• *Slow stormwater runoff, larger detention capacity* • *Aesthetically pleasing* • *Good insulation properties* • *Reduction in impervious area for the property* • *Use in high density developments*	• *Maintenance of roof vegetation* • *Un-expensive design and construction* • *Irrigation and drainage systems necessary* • *Limited plants* • *Potential fire hazard*
Swales	*Vegetated broad shallow channels for transporting stormwater*	• *Less expensive than conventional conveyance practices* • *Encourages infiltration* • *Reduce runoff rates and volumes*	• *Can only treat a limited area* • *Risks of blockage in connecting pipe work*
Soakaways	*Underground chamber or rock-filled volume: stormwater soaks into the ground via the base and sides; unplanted but host to algal growth*	• *Require small land area* • *Easily constructed and operated* • *Groundwater recharge*	• *Not for poor drainage soils* • *Not for polluted runoff* • *Possible reduction of performances during wet periods*
Filter strips	*Grassed or vegetated strip of ground that stormwater flows across*	• *Effective at controlling flood and reducing erosion* • *Effective as pre-treatment* • *Effective at controlling pollution* • *Low cost and easy to build* • *Fits easily in the landscape*	• *Require large land* • *Not appropriate for hotspots and where there is risk of groundwater contamination* • *Not appropriate for hilly terrain* • *Need maintenance for the vegetation cover and to remove trash*
Infiltration trenches	*A long thin soakaway; unplanted but host to algal growth*	• *Can significantly reduce runoff rates and volumes* • *Effectively removes or reduces many pollutants, including suspended solids, bacteria and trace metals*	• *High clogging potential without effective pre-treatment*
Infiltration basin	*Detains stormwater above ground which then soaks away into the ground through a vegetated or rock base*	• *Reduction of peak flow rate, erosion and scouring* • *Can be very effective at pollutant removal and contribute to reduction of local flooding* • *Contribute to groundwater recharge* • *Maintain base flow of nearby streams* • *Simple and cost effective*	• *High potential for failure rates* • *Potential for fouling if high TSS in the runoff* • *Not appropriate for drainage area > 10 acres*
Retention ponds	*Contain some water at all times and retains incoming stormwater;*	• *Effective at removing pollution* • *Favour wildlife*	• *No runoff volume reduction* • *Limit the available land*

Source control system	Description	Advantage	Disadvantage
	frequently with vegetated margins	- *Good aesthetic and favour community recreation* - *May increase value of property*	- *May require maintenance to remove sediments* - *May require approval from safety authorities* - *Potential for development of invasive species*
Wetlands	*Vegetated system with extended retention time*	- *Effective at removing pollution* - *Favour wildlife* - *Good aesthetic and high ecological potential* - *Good community acceptability* - *May increase value of property*	- *Need to be lined to be applied where there is a risk of ground water contamination* - *Not appropriate for steep sites* - *May release nutrients* - *No runoff volume reduction* - *Limit the available land* - *May require maintenance to remove sediments* - *May require approval from safety authorities* - *Potential for development of invasive species*
Bioretention	*Shallow excavated surface depression containing mulch and a prepared soil mix and planted with specially selected native vegetation that captures and treats runoff.*	- *Provides aesthetic enhancement* - *Minimally consumes land* - *Reduce runoff rates and volumes*	- *Clogging if poor maintenance of surrounding landscape* - *Requires proper plant selection and maintenance* - *Treat relatively small drainage area*
Permeable pavements	*Continuous surface with high void content, porous blocks or solid blocks with adjoining infiltration spaces; an associated reservoir structure provides storage; no geotextile liner present; host to algal growth*	- *Significantly reduces runoff rates and volumes* - *Reduces impervious surface area* - *May provide pollutant filtering*	- *Not with high sediment loads*

6 European Roads Runoff Treatment

Based on the Conference of European Directors of Roads (CEDR) report.

6.1 Ireland

Ireland is in the process of updating their runoff treatment systems to fit the SUDS method. In order to do so more sustainable drainage systems have been introduced (Figure 27). For an effective runoff treatment, the runoff passes through series of drainage techniques before it reaches the stormwater drain. The typical SUDS utilized in Ireland involves source and site control treatment mechanisms like filter drain, infiltration trench, permeable pavement. Whereas the site control is used on infiltration basin, wetland, retention pond, and swale treatment system. Filter strip, kerb and gully are methods applied at the pre-treatment stage in Ireland.

Figure 27 Example of SUDS in Ireland. Combined wetland, sedimentation, and attenuation facilities (photo: Transport Infrastructure Ireland)

6.2 Austria

Austria has applied a runoff technique that combines sedimentation and filtration to treat road runoff (Figure 28). Equal size basin with filter is used along with drainage layer. On the other hand, basin or pond that may or may not have permanent water is used for the sedimentation stage of the treatment. The sedimentation stage requires a big space and that is considered as one of the downsides of this method. Since this technique is relatively new, the lifetime of the treatment technique is yet to be proven. As any other filtration of runoff system, this technique is also highly susceptible to filter clogging. Which ultimately reduces both the quality and lifetime of the treatment technique.

Figure 28 Standard system combining sedimentation and infiltration (photo: ASFINAG)

6.3 Switzerland

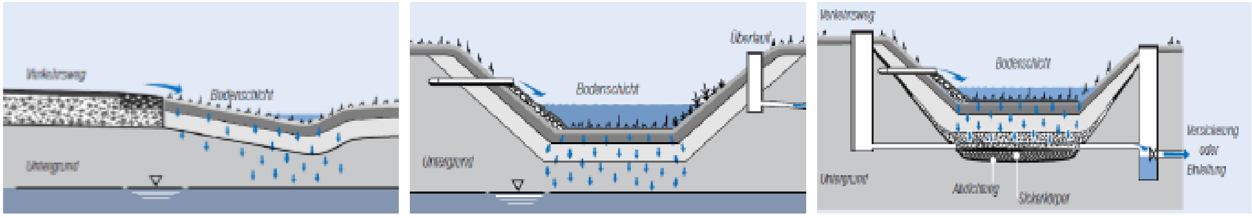


Figure 29 "Infiltration over the road verge (embankment). The middle picture is infiltration by means of ditches and hollows to groundwater. And the last picture is infiltration and filtration before discharge to surface water or groundwater" (copied from CEDR2016)

The three measures presented in Figure 29, namely: (1) infiltration over the road verge (embankment), (2) infiltration by means of ditches and hollows to groundwater and (3) infiltration and filtration before discharge to surface water or groundwater, are the only methods approved by the Switzerland environmental authorities as the sedimentation treatment on its own is not considered as a sufficient technique to treat runoff. Switzerland has also introduced new technology to treat runoff from roads. In this new technology water collected from 18 km of roads is carried to the treatment plant by 3 pumping units with small storing tanks. At this stage of runoff treatment debris is removed. The runoff is then conveyed to filters so that it can be treated by active carbon (anthracite). It is argued that investing on big treatment plants as such, that have the capacity of treating 88% of all rain events is more effective than a number of small treatment mechanisms installed at different places.

6.4 Italy

Italy's stormwater treatment approaches mainly focuses on treating first flush. This treatment mechanism involves capturing rainwater flow and pollutants within few minutes of rain event. The tank that stores the captured water is made of concrete and have the capacity of storing approximately 40 m^3 (Figure 30). The tank that is often placed underground is designed to retain particles and oil. Since the volume of the water treated by this technique is small, frequent maintenance is required. The effectiveness and efficiency of the treatment hasn't been evaluated yet.

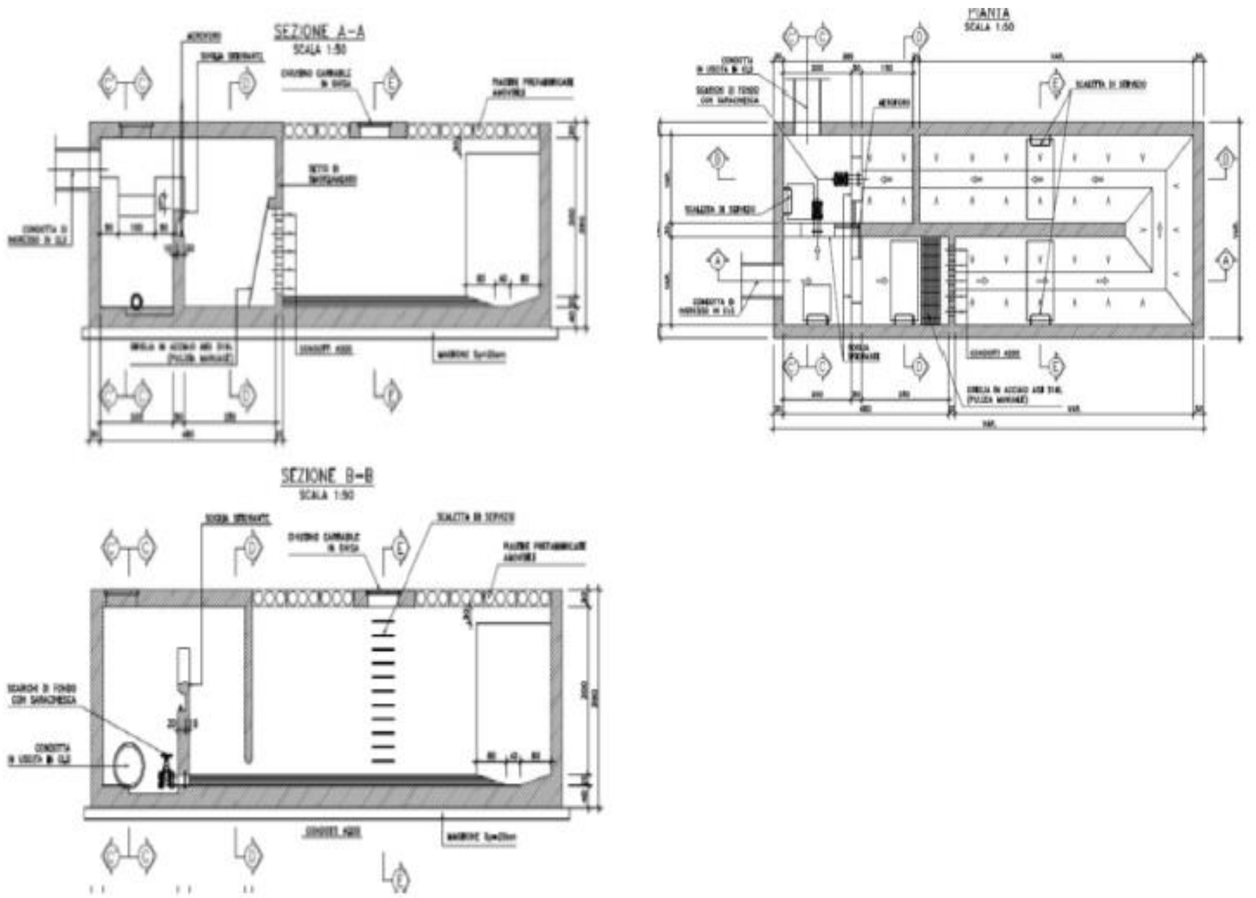


Figure 30 Technical drawing showing the section (left) and plan (right) of a concrete treatment tank used in Italy (copied from CEDR2016)

6.5 Sweden

Infiltration and the most commonly applied system of sedimentation pond are the two main road runoff treatment mechanisms in Sweden. In cases where large areas are not available, as it is required for the installation of ponds, sedimentation tanks with flocculation chemicals is applied. Silt curtains to trap and retain particles is utilized in rare cases.

6.6 Norway

Sedimentation pond in Norway is also a major runoff treatment technique. The sedimentation ponds consist of pre-sedimentation pond and main pond with permanent water (Figure 31). In order to avoid breakage or clogging of inlets and outlets during winter season, both the inlet and outlets are submerged. Filtration is not added to the sedimentation pond system as a second treatment step. It must be mentioned that the Norwegian Road Administration is currently investing in the research for filter materials to be utilized in ditches as either a pretreatment step or for full treatment mechanism. Wetlands, infiltrated ponds, and ditches are also treatment mechanisms applied in some cases. A description of norwegian methods is described in: (Åstebøl and Roseth, 2014).

Figure 31 Example of a Norwegian sedimentation pond with a smaller pre-sedimentation pond (forebay, which can be seen in front of the band of vegetation crossing the pond) and a main pond (photo: Sondre Meland)

6.7 Denmark

In Denmark controlling peak flows was considered as the major problem of runoff than pollution control for a long time. Since uncontrolled runoff is not allowed to enter the water streams, due to most lands are used for agriculture purpose, stormwater or road runoffs are not discharged into water streams. Consequently Denmark has lots of ponds with large sizes to store water (approximately one pond per km of road). Denmark is now focusing on runoff pollution control aspect. Similar to the other Scandinavian countries, Denmark too is considering sedimentation pond along with filtration as a runoff treatment mechanism.

6.8 Germany

Maintenance of the already existing treatment methods is considered as a main priority in Germany. The treatment of runoff from roads is considered a requirement when the Annual Daily Traffic (ADT) exceeds 15,000 vehicles/day. Based on the recipient, treatment of runoff from roads is still required when the ADT is in the range of 2,000 -15,000. If the ADT value is less than 2,000 treatment of the runoff is not considered as mandatory. Similar to the case in Switzerland, infiltration over the road verge (embankment) is considered as the most effective stormwater treatment mechanism. Sedimentation tank is also utilized either as a pretreatment mechanism or as a full treatment technique. Germany is using suspended particles as benchmark for pollutants within roads runoff. Since particles are the main pollutants within roads runoff, benchmark for pollutants like metals, hydrocarbons, PAHs is not given a great deal of significance in Germany.

6.9 Poland

Poland has been and still is in the process of building new roads. More than 2,000 km of roads has already been built since year 2007. Consequently the environmental impact assessment takes place at the planning, building, and operating stage. These roads must acquire a license before runoff is discharged. Oil inspectors, sedimentation tanks infiltration ponds, and wet ponds are the runoff treatment mechanisms installed for roads that require approval. Emphasis is given to discharge of particles and hydrocarbons pollutants with a benchmark of 100 mg/l and 15 mg/l respectively. If the installed treatment is tested for its efficiency 12-18 months after the road is opened and 3-5 years after that.

6.10 England

From year 2002 - 2009 the English NRA and the Environment Agency put a research and development program with 4 main objectives. Determination of pollutants from highway runoff, to study the soluble pollutants impact on the receiving waters, impact of sediments from highway runoff, and to develop a practical risk assessment tool. Using the indicated pollutants, toxicity tests like aquatic organisms were used to develop benchmarks. The risk assessment tool was developed to address the problem of polluting metals exceedance of the provided benchmarks. HAWART (Figure 32) is the assessment tool that considers biological and ecological factors along with hydraulics and traffic characteristics. This tool is an accepted method used to determine when and how runoff should be treated.

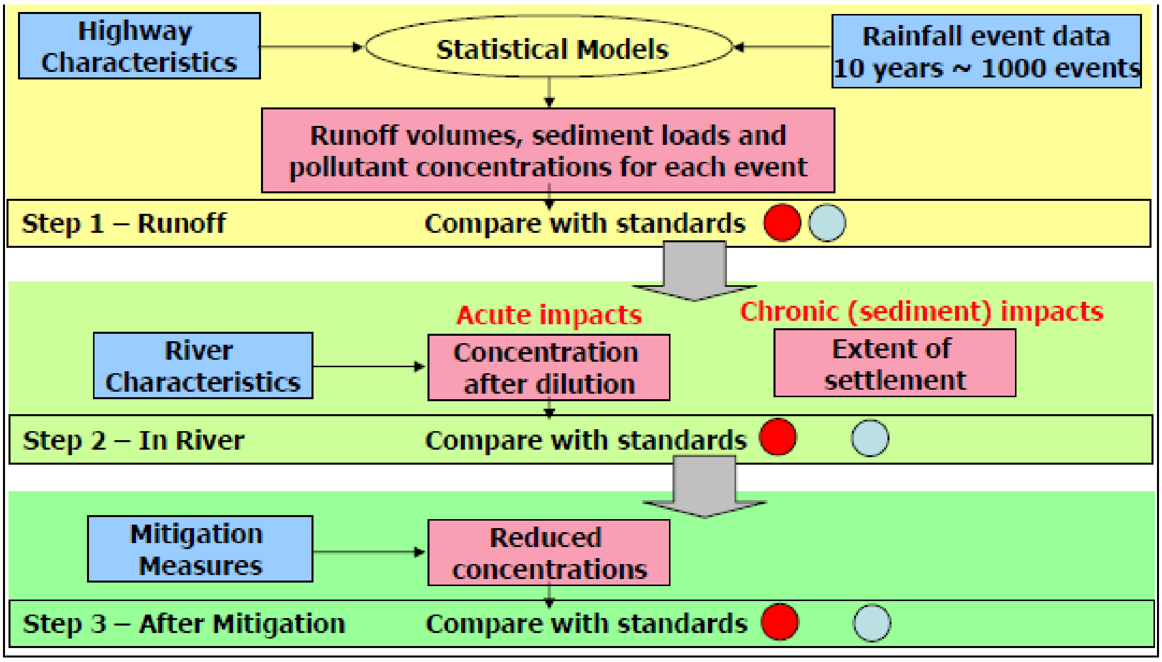


Figure 32 Flow chart of the Highways Agency Water Risk Assessment Tool (HAWRAT)

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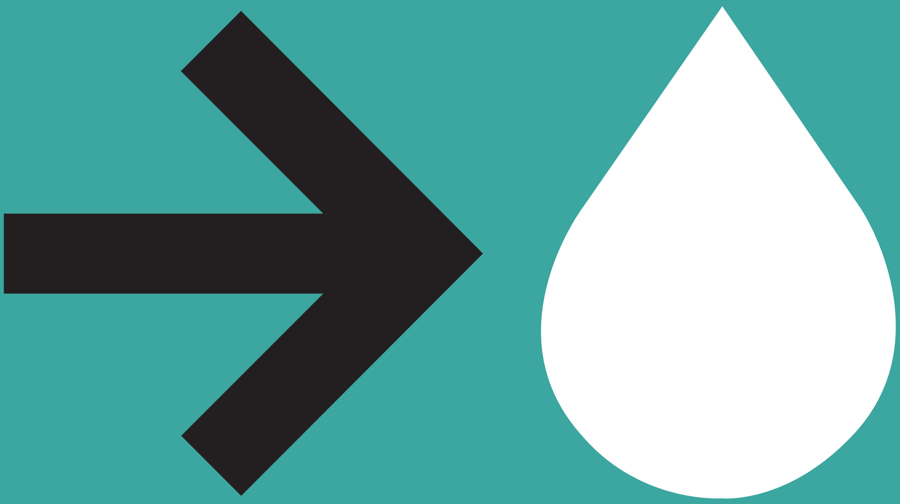

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