Chapter 2
Treatment Techniques for Variable Flows

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Abstract A wide range of ecotechnologies has been applied to treatment of variable stormwater and wastewater flows. Stormwater ponds and basins were already introduced as common 'end-of-the-pipe' treatment solutions in the 1960s, almost parallel to the first attempts to develop structured wastewater treatment with the help of plants, inspired by natural wetlands. Constructed wetlands specifically designed for the treatment of variable flows emerged in the 1990s and were joined by a growing group of vegetated filter systems, named bioretention filters, rain-gardens or retention soil filters, all following the principle of gravity-driven wastewater filtration. This chapter provides a general overview of these treatment facilities, including swales and buffer strips. Although the latter ones are gravity-driven filtration systems, they are commonly used for the treatment of road runoff and are highly adapted to fit into their landscape structure, they are described in a separate section. Each section includes references to detailed design and operation guidelines.

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Treatment Systems

Ecotechnologies for the treatment of variable flows, especially for those driven by stormwater, combined sewer overflows (CSOs) and agricultural runoff, come in various designs and definitions. As described in Chap. 1, several concepts exist to group these techniques by their purpose or design. This chapter provides an overview of principle design components and operational challenges of the most common and widely used techniques as background information for the following chapters. Each section includes references to detailed design and operation guidelines.

Stormwater Ponds and Basins

Stormwater ponds (also called wet detention basins and sedimentation basins/ponds) and other sedimentation-based treatment facilities are common 'end-of-the-pipe' treatment solutions for the storage and treatment of large stormwater volumes.

Stormwater ponds have been implemented since the 1960s in the USA (Clar et al. 2004) and their number has increased constantly since then (Marsalek and Marsalek 1997; Starzec et al. 2005; Karlsson et al. 2010).

During the last three to four decades, design and dimensioning of ponds have been improved by research and practical experience. Their main design elements are the different hydraulic structures (inlet and outlet, overflow structures) and their volume (extended detention volume, storage volume for sediment). Furthermore, hydraulic efficiency has to be considered to ensure that flows are distributed as evenly as possible throughout the pond to ensure efficient sedimentation.

Outlets, which are frequently designed to detain fractions of runoff for multiple days after a storm, are prone to clogging, which can affect the water level in the pond and, thus, its function. Hence, regular (at least annual) inspections of the key structures of ponds are required.

Usually the whole runoff volume is captured in the facility and released over time (sometimes up to several days), a process that enables settling of suspended sediments and associated pollutants. These ponds can provide treatment mostly through sedimentation when designed, constructed and maintained to this purpose. However, field experience shows that, in practice, sediment settling is a rather complex process which is affected by a range of factors (e.g. disturbance by turbulence generated at high flow rates, waves or currents).

Accumulated sediment must be removed regularly from the pond to maintain its treatment volume and guard against remobilisation during high flow events. How often sediment needs to be excavated depends on the catchment to pond ratio, the sedimentation efficiency and the sediment load from the catchment, but an interval of five years is reasonable. Ponds must thus be accessible for personnel (regular inspection) and machinery to ensure a sufficient long-term function (excavation of accumulated sediment).

Pollutants such as metals often occur as very small particles. Xanthopoulos (1990) investigated the size distribution of particulate matter for several heavy metals and found 67–87% were bound to particles with a grain size of less than 60 μm. Boogaard et al. (2014) confirmed these results in runoff from the Netherlands, showing that approximately 50% of the investigated particle mass is bound to particles <90 μm. Accordingly, how effectively stormwater ponds remove pollutants depends heavily on their association with settleable solids. Healthy Waterways (2006) proposes targeting sediment that is 125 μm and larger in ponds and choosing alternative treatment technologies to remove finer material and/or dissolved pollutants from urban stormwater. However, in practice, many ponds also remove considerable loads of finer sediment (Al-Rubaei et al. 2016).

Often stormwater ponds are combined with a smaller upstream pretreatment basin or a forebay which provides an initial deposition area for coarse and larger soil particles. These coarser particles represent a relatively large volume of the total sediment, but carry only a minor portion of the total pollutants. Thus, forebays which are typically sized to comprise 10% of a pond's surface area facilitate maintenance of the whole system.

Theoretically, a gradient from coarse to fine sediment will form as the flows pass through the pond, since the settling velocity decreases with the sediment diameter (i.e. gravel and sand settle close to the inlet, Fig. 2.1). The theoretical sediment settling efficiency can then be easily calculated with empirical equations.

However, field experience shows that sediment settling in practice is a rather complex process affected by various factors (e.g. disturbance by turbulence generated at high flow rates, waves or currents). Al-Rubaei et al. (2016) showed in a performance survey of 30 municipal ponds in Sweden that in some ponds, the percentage of fines (<125 μm) was below 5% at both inlet and outlet while in others it was already above 90% close to the inlet. Some ponds also showed a decreasing content of fine solids from the inlet to the outlet. These variations underline how various factors influence the settling performance in practice. Due to this settling, ponds remove the pollutants attached to the sediments.

Often, the percentage of settled sediment is used as a parameter to describe a pond's treatment efficiency. However, Marsalek et al. (2005) argue that this measure is insufficient since it does not take into account the particle sizes of settled and

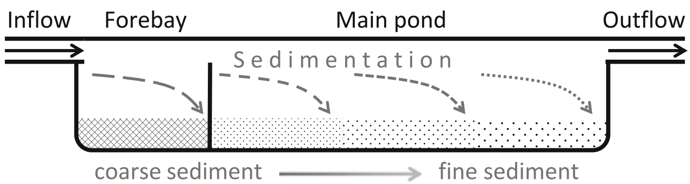

Fig. 2.1 Simplified sketch of sedimentation of different particle size fractions in a stormwater pond including a forebay (*Scheme* G.-T. Blecken)

Table 2.1 Mean inflow and outflow concentrations, with nominal removal efficiencies (%) of TSS (mg/L) in nine stormwater wet ponds*

Reference	TSS (mg/L)		Removal efficiency (%)
	In	Out	
Pettersson et al. (1999)	55.2	16.6	70
	153	25	84
Comings et al. (2000)	16.2	2.9	82
	22.8	8.9	61
Mallin et al. (2002)	10.5	4.4	58
Vollertsen et al. (2009)	276	43	84
Istenič et al. (2012)	48	15	69
	53	5	91
	37	2	95

*Table partially based on the work of Al-Rubaei (2016) and Søberg (2014)

discharged sediment; even with a substantial removal of 70%, a pond may be poor at removing fines (Greb and Bannerman 1997). This is important for the overall treatment capacity since the fine particles commonly exhibit relatively high pollution loads (Sansalone and Buchberger 1997; Liebens 2002) and, along with dissolved forms, tend to be the most bioavailable and toxic to aquatic life (Luoma 1983).

There are a large number of studies evaluating removal efficiencies in stormwater ponds. Since the removal rates vary considerably, Table 2.1 gives an overview of total suspended solids (TSS) removal in a range of studies. A larger International Stormwater Best Management Practices (BMP) Database has been compiled with performance data summarised for a wide range of different stormwater treatment devices and contaminants by Leisenring et al. (2014).

In general, ponds only remove dissolved pollutants to a limited extent since sedimentation is the main treatment process. Dissolved pollutants can be removed by biological processes associated with emergent vegetation planted in shallow parts of ponds (Van Buren et al. 1997). Under favourable conditions (e.g. large vegetated shallow areas), relatively high removal rates can be achieved. Nonetheless, ponds are not a sufficient treatment solution if removing dissolved substances is a high priority even though some ponds can achieve relatively high removal rates.

During typical temperate climate winters (Fig. 2.2), high variability in flows, characterised by extended periods with no runoff followed by snowmelt events with large stormwater volumes over a short period, may result in reduced removal efficiencies (German et al. 2003). Due to density differences compared to pond water, salt-laden and/or cooler inflows from roads may pass through the pond as an underflow or sinking jet (Marsalek et al. 2005). This can generate flow shortcuts, with higher flow velocities disturbing and resuspending already accumulated sediment. Conversely, in warm regions, hot inflow water may pass in the top water layer only.

Fig. 2.2 Stormwater pond in winter (*Photo* G.-T. Blecken)

Roseen et al. (2009) evaluated the seasonal variation of removal efficiencies in stormwater treatment facilities in New Hampshire, USA. While nitrate removal in ponds was less efficient during winter, no significant differences of TSS, phosphorus and zinc removal were detected. Neither did German et al. (2003) observe direct temperature effects on the removal of TSS, phosphorus and nitrogen. Kadlec and Reddy (2001) conclude that the physical treatment processes (mainly sediment settling) are not directly affected by cold ambient temperatures. Since sedimentation is the main treatment process in ponds, their overall treatment performance during winters is likely to be primarily influenced by flow dynamics rather than low temperatures. Conversely, under warm conditions with minimal flushing, phytoplankton and filamentous algal may proliferate in wet retention ponds causing increases in particulate loads to receiving waters once flow resumes (Gold et al. 2017).

Constructed Wetlands

Constructed wetlands (CWs) are being used for the treatment of wastewater and stormwater worldwide, but are also increasingly becoming a recognised system for treating agricultural wastewater and drainage water. CWs have the potential to deal with fluctuations in usage and loading because they harness robust natural treatment processes and have extended residence times.

Based upon flow routing, there are two basic types of CWs: surface- and subsurface-flow wetlands. Four variants are dominantly used for the treatment of variable flows:

– surface-flow wetlands,
– floating treatment wetlands, a variation of the surface-flow wetlands,
– subsurface-flow wetlands with horizontal flow and
– subsurface-flow wetlands with vertical flow, which are summarised with the bioretention filters in this book due to their similar design and function.

Surface-Flow Constructed Wetlands

In surface-flow constructed wetlands (SFCWs), especially in Australasia referred to as constructed stormwater wetlands (CSWs), the deeper pools facilitate sedimentation, while the diverse water-vegetation-soil matrix in the shallower, extensively vegetated zones of SFCWs provide complex multiple pollutant treatment mechanisms. These include sedimentation, flow detention, filtration, adsorption, precipitation, microbial decomposition and plant uptake. Vegetation within a pond/wetland system reduces flow velocities and allows suspended solids to settle out of the water column. In addition, nutrients and metals can be taken up by vegetation (Fig. 2.3).

In contrast to large detention/sedimentation facilities like wet ponds, which are dominated by large open water areas, SFCWs include various zones with different water depths, thus improving flow retention and providing more diversified high quality treatment mechanisms, particularly with respect to more effective removal of dissolved pollutants and nutrients. Moreover, CSWs are commonly equipped with a forebay to minimise the sediment load and facilitate maintenance. In general, it is preferable to choose native plant species, since the introduction of foreign species via CWs led to spreading of neophytes with severe consequences for native species in some cases (Albert et al. 2013) (Fig. 2.4).

Suspended solids serve as pollutant transport vectors from the input source to the downstream receiving environment. Phosphorus and metals adhere to solids surfaces as they travel along the route. Removal of suspended solids from the water columns in pond and wetland systems is primarily achieved by sedimentation and filtration. Stormwater ponds are primarily designed to provide sufficient removal of TSS with absorbed pollutants from stormwater by sedimentation (VanLoon et al. 2000).

Fig. 2.3 Surface-flow constructed wetland during rain (left), in summer (middle) and in winter (right) (*Photos* G.-T. Blecken)

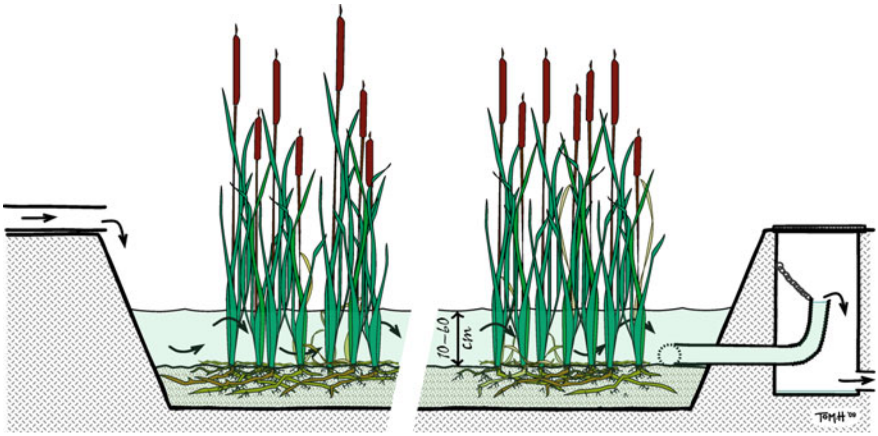

Fig. 2.4 Simplified sketch of a surface-flow constructed wetland (figure courtesy of Tom Headley)

Table 2.2 Mean inflow and outflow concentrations with nominal removal efficiencies (%) of TSS in surface-flow constructed wetlands*

	TSS (mg/L)		
	In	Out	Removal (%)
Carleton et al. (2001)	–	–	−300–99.6
Bulc and Slak (2003)	42	11	69
Birch et al. (2004)	48–154	33–172	−97–56
Terzakis et al. (2008)	203	22	89
Yi et al. (2010)	282.8	33.4	84.7
Lenhart and Hunt (2011)	23.6	32.7	−39
Merriman and Hunt (2014)	9.89	8.37	15

*Table partly based on the work of (2016) and Søberg (2014)

However, this removal process can be disturbed by solids scouring in ponds and chemical releases from the deposited sediments (Marsalek and Marsalek 1997).

In practice, high variations of CSWs' treatment efficiencies have been observed. Commonly, CSWs are combined with a preceding forebay or pond to reduce sediment loads entering the wetland itself.

Table 2.2 gives an overview of total suspended solids (TSS) concentrations in the inflow and outflow of different SFCWs.

Floating Treatment Wetlands

Floating treatment wetlands (FTWs), also known as Constructed Floating Wetlands and a wide range of alternative names, consist of buoyant artificial rafts or islands

Fig. 2.5 Floating Treatment Wetlands in a residential stormwater treatment pond in Illinois (USA) (*Photo* C. C. Tanner)

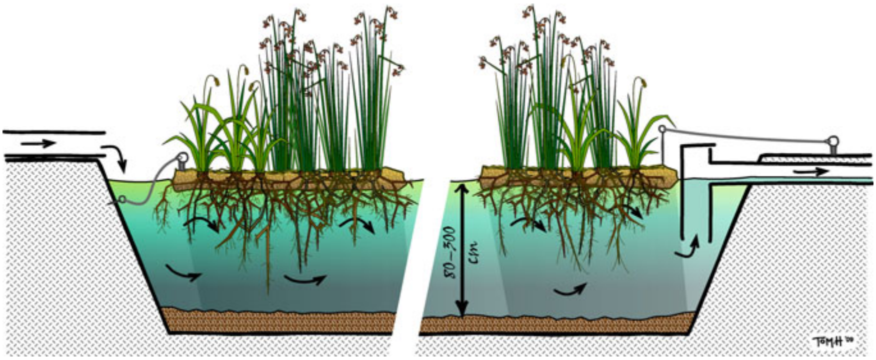

Fig. 2.6 Generalised sketch of a Floating Treatment Wetland (figure courtesy of Tom Headley)

vegetated with emergent macrophytes. They are ideal for systems that experience large variations in flow because their buoyancy allows them to rise and fall with fluctuating water levels, therefore avoiding submergence stress on the emergent plants (Headley and Tanner 2012). They also have the advantage that they can be retrofitted into existing pond systems to augment conventional pond treatment processes (Fig. 2.5).

The floating island matrix (Fig. 2.6) is often made of post-consumer plastics with the aid of synthetic foam sections in combination with organic material such as coconut fibre. The islands are anchored to avoid drifting.

The design of FTWs has been adapted from naturally occurring floating vegetated islands, which can be found in freshwater lakes and ponds, and are comprised of a matrix of floating organic material and plant associations growing at the water surface. Buoyancy is provided by gaseous emissions from organic decomposition (mainly CH_4 and N_2) trapped beneath the organic mat and the air spaces (aerenchyma) within the roots, rhizomes and stolons of vegetation (Hogg and Wein 1988; Mitsch and Gosselink 1993). In contrast, most artificial FTWs rely primarily on buoyant structures to keep them afloat, likely aided by plant tissue buoyancy as vegetative biomass increases.

Recognising the habitat value of floating islands, particularly for birds, the UK Royal Society for the Protection of Birds constructed artificial islands for the conservation of threatened species in as early as the 1960s (Hoeger 1988; Burgess and Hirons 1992). Following these early successes, FTWs have since been used for a variety of purposes including treatment of stormwaters, mine and landfill leachates, CSOs, domestic, industrial and agricultural wastewaters, and eutrophic ponds, reservoirs, lakes, drains, streams and rivers (Chen et al. 2016; Headley and Tanner 2012; Pavlineri et al. 2017).

The plant roots and attached biofilms that extend into the water beneath the floating mats are considered to be crucial to the functioning of FTWs (Headley and Tanner 2012). This root mass reduces flow velocities beneath the FTWs, promoting settlement and physical filtering of suspended solids (Fig. 2.6). Biofilms attached to the suspended root mass promote adhesion of fine particulates, adsorption and nutrient transformations (Borne 2014; Borne et al. 2013a, b, 2014; Tanner and Headley 2011; Winston et al. 2013). Plant detritus can act as metal biosorbent (Southichak et al. 2006), and, along with roots and biofilms, contribute organic exudates, extracellular polymeric substances and humic compounds that promote floc formation that may enhance settling of fine particulates (Borne et al. 2015; Kosolapov et al. 2004; Tanner and Headley 2011).

FTWs may also indirectly affect contaminant removal processes by modifying the physicochemical environment in ponds. FTWs shade the water surface, moderating temperatures (Strosnider et al. 2017) and reducing growth of phytoplankton and submerged macrophytes (Jones et al. 2017). Ponds with a significant cover of FTWs generally show deoxygenation beneath the beds and within the root mass, due to the respiratory demand of the large root and microbial biomass and restriction of atmospheric exchange (Tanner and Headley 2011; Strosnider et al. 2017). Such anaerobic conditions can promote microbial processes such as denitrification (Borne et al. 2013b) and sequestration of metals in underlying sediments (e.g. as metal sulphides) (Borne et al. 2013a, 2014).

The plants growing on FTWs, of course, also take up a range of nutrients, metals and organic compounds directly from the water column via their roots. However, the importance of such plant assimilation compared to other removal processes varies depending on relative nutrient loading rates, pond coverage, plants species, stage of growth, season, etc. (Chen et al. 2016; Headley and Tanner 2012; Pavlineri et al. 2017). Where plant uptake is a quantitatively important removal mechanism, harvesting of emergent biomass is a potential way to permanently remove nutrients from the system and sustain ongoing uptake (Keizer-Vlek et al. 2014; Wang et al. 2014).

Although FTWs are mainly applied for treating stormwater from separate sewer systems, there are also a few examples of FTWs used for CSO treatment. The first system described was a system in Belgium (Van de Moortel et al. 2011). As is common for CSO treatment, a preliminary sedimentation basin lined with hardened bitumen reduces the energy of the incoming water and minimises the resuspension of settled sediments. When entering the second treatment stage, a floating baffle retains large floating debris. The second stage consists of a long basin that is almost completely covered with FTWs and is designed to enhance plug flow.

Another system in the USA combines a FTW, serving as the preliminary stage, with a vertical-flow wetland as the secondary and a SFCW as the final stage (Tao et al. 2014).

Plant species for FTWs have to be chosen according to the environment where the treatment systems are applied, e.g. stormwater ponds or lagoons for CSO treatment. In general, the species should be able to provide the aforementioned root system which removes fine suspended solids and dissolved substances from the inflowing water. For the removal of nutrients, a strong plant uptake without extensive growth on the mat surface is favourable.

The knowledge base on FTW performance treating a wide range of different stormwaters and wastewaters is increasing rapidly (see reviews by Chen et al. 2016; Headley and Tanner 2012; Pavlineri et al. 2017). However, most quantitative studies were conducted on relatively small and immature experimental systems, and so long-term experience is missing. This is especially important for understanding and optimising the scale-dependent indirect effects of FTWs and managing possible unintended consequences on the biogeochemistry and ecology of water bodies. For instance, high covers of FTWs under certain circumstances could result in excessive deoxygenation of the water column, stimulating processes such as phosphorus and methylmercury release from sediments or impacting on resident or downstream aquatic fish and invertebrates (Fig. 2.7).

Headley and Tanner (2012) proposed a conceptual design for incorporating FTWs into a stormwater treatment train. However, at this stage, there are still no established guidelines for optimal coverage, distribution or configuration of FTWs in ponds, and reliable estimates of their performance remain a significant engineering need. A simple first-order model to predict treatment performance for the water body plus the additional treatment provided by different coverages of FTW has recently been developed (Wang and Sample 2013). An expert panel convened by the Chesapeake Stormwater Network on the eastern seaboard of USA has recently assessed the evidence base for FTW stormwater treatment performance and, for regulatory purposes, determined expected enhancements of sediment and nutrient removal rates for FTW retrofits in the region (Schueler et al. 2016). Preliminary guidance on implementation and maintenance of FTWs for urban stormwater treatment has also been developed based on experience in USA and New Zealand by Borne et al. (2015).

Fig. 2.7 Extracted section of a Floating Treatment Wetland treating road runoff showing root mass extending beneath floating mat (Karine Borne, Auckland, New Zealand) (*Photo* C. C. Tanner)

Subsurface-Flow Constructed Wetlands

Subsurface-flow constructed wetlands (SSFCWs) can be designed as horizontal or vertical-flow systems (Kadlec and Wallace 2008). A porous sand or gravel media is generally used to provide adequate hydraulic conductivity. Emergent wetland plants grow hydroponically in the media providing for at least partial interaction with the plant root zone (Brix 1997; Tanner 2001). Inflow is either introduced passively at one end of a saturated bed, promoting horizontal flow through the media, or dosed intermittently to the top of the media promoting percolation down through unsaturated media. SSF systems have the advantage that contaminated water is generally retained below the surface and so avoid potential for human contact or proliferation of mosquitos or other insect pests. The media also provides a physical filtering role, enhanced solids retention and a stable substrate for biofilm development.

SSFCWs are able to retain a large number of pollutants and to partially degrade them. The relevant treatment mechanisms have been investigated for saturated soils

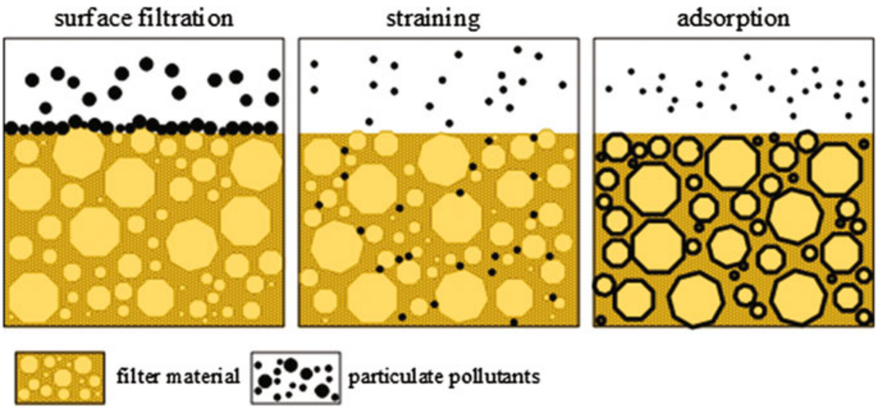

Fig. 2.8 Principles of surface filtration (left), straining (middle) and adsorption (right) in vertical-flow systems (adapted from Seidemann 1997)

and unsaturated sand as well as on laboratory and large-scale systems. The major mechanism for particle retention is filtration, which can be divided into straining and surface filtration. Surface filtration retains all particles that cannot pass the surface, which applies to particles with a size >5 µm when the filter sand is chosen with the characteristics of the one used in Germany (grain size 0/2 mm). Figure 2.8 illustrates the principles of filtration, straining and adsorption in a vertical-flow system.

Straining occurs when a particle in suspension flows through a pore opening that is too small for it to pass through so microorganisms become entrapped and accumulate on the surface of substrate media.

Suspended particles are adsorbed when their diameter is much smaller than the diameter of the filter material. Corapcioglu and Haridas (1984) found diffuse trajectories of the particles due to Brownian motion and gravitation forces on a particle as drivers for this phenomenon. There is a difference between the sorption capacity of organic and inorganic substances present in soil (abiotic sorption) and the one of microbial structures such as biofilm: the so-called biotic adsorption increases as a biofilm grows in the filter. The sum of exchangeable cations defines the overall sorption capacity of the soil or sand in question.

Low temperatures generally decrease soil biological activity, which may impair biological treatment processes (e.g. biofilm growth, plant uptake). They also result in reduced organic matter decomposition, possibly leading to lower dissolved organic matter (DOM) concentrations in the outflow. Other than the overall treatment performance of ponds, the treatment performance of bioretention filters relies on temperature-dependent biogeochemical processes to a larger extent and, thus, varies with seasons.

Only few studies specifically addressed the problem of clogging in CWs for stormwater treatment, although the phenomenon is well described for systems with relatively constant inflow, e.g. systems for domestic wastewater treatment

(Knowles et al. 2011). The main factors leading to clogging—accumulation especially of fine solids, biofilm development, vegetation and chemical decomposition —can be reduced by intermittent operation and sufficient dry periods (Knowles et al. 2011), which is the general nature of stormwater treatment. Insufficient sizing and an overload with fine solids, constant infiltration inflow and the choice of inadequate filter material remain major risk factors for clogging of the systems (Laber 2000; Grotehusmann et al. 2017). However, this is often reversible either by eliminating the cause of the clogging, e.g. by replanting, introducing pretreatment or redirecting infiltration inflow (Laber 2000; Grotehusmann et al. 2017).

Both systems are used to treat fluctuating wastewater and combined sewer flows (Griffin 2003), and more rarely urban, industrial and rural stormwaters (e.g. Laber 2000; Shutes et al. 1997).

The **vertical-flow constructed wetland (VFCW)** is most commonly used in the treatment of variable flows. However, for the treatment of stormwater and wastewater flows—the latter limited to the treatment of CSOs in this book—the system will be described in the Section 'Bioretention Filters'.

Alternatively, in the so-called French vertical-flow systems, raw wastewater is applied directly to the wetland creating a sludge layer on the surface through which inflows are initially filtered (Molle et al. 2005). Such systems are operated in sequence with extended rest periods to maintain the porosity of the media and require periodic removal of the surface deposits after 10–15 years. They have been shown to be able to maintain functioning with stormflows of up to 10-fold normal hydraulic loadings (Molle et al. 2006). Another system based on vertical-flow wetlands is described by Hasselbach (2013): two VFCWs operating in parallel treat the dry weather flow after having been pretreated in a pond. In case of a rainfall event, a third VFCW is fed as well, so that a total flow of two times the dry weather flow and additional infiltration inflow can be treated.

Lucas et al. (2015) report of 67 CWs for stormwater treatment in the UK, most of which are designed as **horizontal-flow constructed wetlands** (HFCWs), used

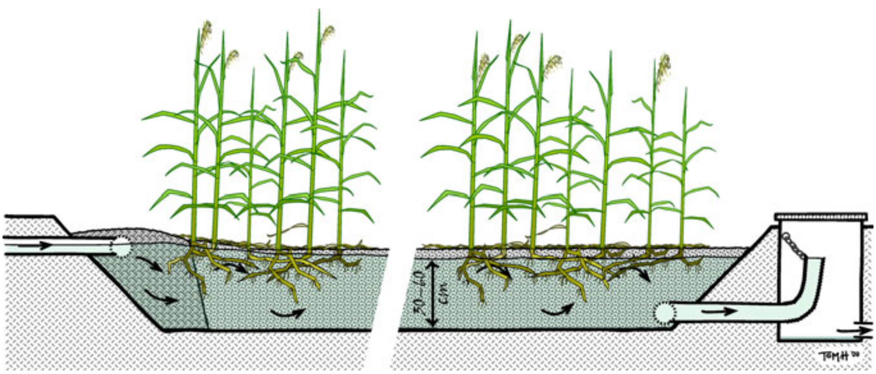

Fig. 2.9 Generalised sketch of a horizontal subsurface-flow wetland (figure courtesy of Tom Headley)

also for combined sewer systems, separate sewer systems and road runoff. The authors hereby present the largest study on HFCWs for stormwater treatment, including comparisons of design guidelines and a ratio of the required CW area to the catchment of 1–5%. A generalised sketch of the principle is shown in Fig. 2.9.

Some of the systems were already addressed by Ellis et al. (2003) and Rousseau et al. (2005). The removal efficiencies presented by Ellis et al. (2003) were comparably low with regards to vertical-flow systems (see Section 'Bioretention Filters'): the performance of six sites was presented, of which three reached removal efficiencies of −4–75% for TSS, whereas the other three reached 95–99%. Rousseau et al. (2005), who presented the results of a survey on seven HFCWs, suggested that accumulated sludge can be washed out of the system and lead to low or even negative removal rates. Pollutant traps such as settling tanks or ponds could reduce this risk. However, Ávila et al. (2013) described something similar when using a horizontal-flow constructed wetland as part of a treatment train (hybrid wetland): the authors investigated a system treating combined sewage both during dry and wet weather flow, which consists of a pretreatment via screens, sand and grease trap and an Imhoff Tank, followed by a VFCW, a HFCW and a SFCW. During wet weather conditions, the TSS concentrations in the HFCW increased compared to the influent, which the authors led back to a washout of material retained in the gravel bed.

The filter media in the CWs is not only the main treatment media, but also decides the hydraulic retention time. Its porosity determines the water storage capacity; however, it can also be the cause of scouring of filter media (Ellis et al. 2003). In general, vertical-flow systems are preferred over horizontal-flow systems due to their shorter hydraulic retention time, which is crucial especially for the treatment of highly fluctuating stormwater flows.

Bioretention Filters

A wide range of filter technologies is available for stormwater treatment including among others: unvegetated sand filters, vegetated biofilters and compact filters facilitating reactive filter materials for targeted treatment of dissolved pollutants.

The planted gravity flow system—based on slow sand filtration with retention volume on top of the filter level—has proved to be relatively stable in terms of treatment performance, operation and sustainability. It is analogous to the vertical subsurface wetlands used for wastewater treatment (see above), but is only operated during rain periods. In dry weather, the bed drains and is aerated through the drainage pipes. The conditions in the filter sand during operation, change from unsaturated to saturated and back to unsaturated after draining (Dittmer 2006).

Vegetated vertical-flow bioretention filters (also known as rain gardens, biofilters or retention soil filters) typically consist of a vegetated swale or basin, underlain by a filter medium. The water infiltrates and percolates through the filter and during its passage it is filtered by the filter media, plants and microbes via a combination of mechanical and biochemical processes. The treated water is either infiltrated into the surrounding soil or collected in a drainage pipe at the bottom of the filter and then discharged to a recipient or the existing sewer system.

Depending on region, historical background—or as Fonder and Headley (2013) humorously put it, ‘the author’s desire to give the impression that their design is new or innovative’—the system is called vertical-flow constructed wetland for the treatment of stormwater, CSOs or highway runoff, biofilter, bioretention filter or cells, rain gardens or vegetated sand filter (further names to be continued). In Germany, the term ‘Retention Soil Filter’ (RSF) is used and accepted for the system. Though this term is used for constructions that treat CSOs, stormwater from separate sewer systems and for highway runoff, international literature commonly uses the term only for application in combined sewer systems.

When such systems were first implemented in Germany in the late 1980s, cohesive material such as soil was used as filter material for CSO treatment. Around the same time, Prince George’s County (1993), Maryland, USA, started developing stormwater biofilters as stormwater treatment systems. Since bioretention filter is the most common name for the system, it will be used in the following (Fig. 2.10).

The overall design for all constructions is the same: a preliminary pretreatment stage protects the filter surface from clogging and erosion. In separate sewer systems and for highway runoff, it can be a simple grit chamber, while in combined sewer systems, retention tanks are often used. The bioretention filter itself typically consists of a vegetated swale or basin underlain by a filter medium. A ponding zone

Fig. 2.10 Bioretention filter (2200 m^2) for the treatment of pre-settled CSOs in Germany (*Photo* K. Tondera)

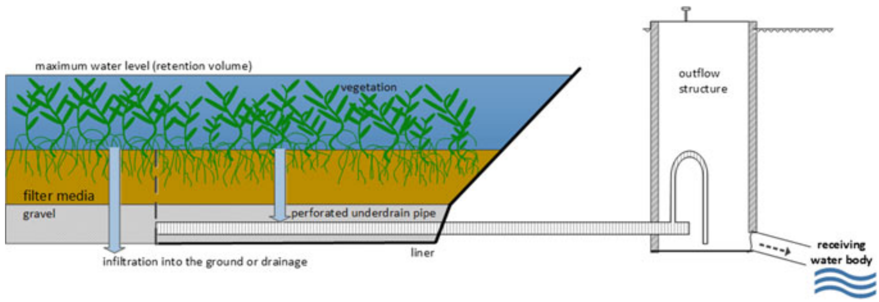

Fig. 2.11 Sketch of a general bioretention filter/vertical-flow CW for stormwater treatment design. The treated water can be either infiltrated (lower left section) or discharged into surface water (right) (*Scheme* K. Tondera)

(height: from approx. 0.2 m for stormwater in separate sewer system and highway runoff to 2.0 m for CSOs) allows temporary storage of water since the stormwater inflow commonly exceeds the infiltration capacity. The filter material consists of either natural soil or engineered media ('technical sand'), typically in a 0.5–1.0 m layer and has a surface area of approximately 0.5–6% of the impervious catchment area.

The treated water is commonly collected in a drainage pipe and discharged to the surface water body, sewer system or infiltrated directly into the surrounding soil, especially in case of highway runoff treatment (Fig. 2.11).

Bioretention filters are not designed to infiltrate high flows in general; these are commonly bypassed directly using an overflow pit or via a retention bed overflow. Thus, bioretention filters are not fully applicable for stormwater retention in the event of intense rain events and have to be combined with retention facilities when flood protection is targeted. Different to the systems treating highway runoff or stormwater in separate sewer systems, those for CSOs are not being loaded during each rain event, but only when a certain storage capacity of the sewer system is exceeded. In Germany, the storage capacity usually includes a certain 'design storm' ($r = 15$, $n = 1$) before the overflow feeds the filter bed. However, in first pilot systems built in Italy, 5 mm of the first flush are caught in storage tanks and in case of ongoing rains, the tanks are bypassed and the filter systems fed (Meyer et al. 2014). In Sweden, commonly a retention volume corresponding to 10 mm precipitation is required.

Plants are important for the system to achieve a sufficient performance since they not only contribute to erosion control by stabilising the filter material and lowering water flow velocities, but also support infiltration capacity, provide conditions for microbiological treatment processes (e.g. in the rhizosphere) and aesthetic values.

When designing bioretention filters in public space, engineers have to pay particular attention to landscape design without compromising their primary purpose of handling urban stormwater runoff. Systems for CSO treatment are planted rather monoculturally: in Europe, common reed (*Phragmites australis*) has become state of the art for the filter bed and grass for planting the bank since this helophyte has proved to be most resilient to water stress during dry phases and shock loading during feeding events. In other regions of the world, local species should be chosen in order to prevent neophytes from spreading. The helophytes need to be able to deal with the extreme conditions of long lasting droughts, temporal impounding after shock loading and low nutrient availability. At the same time, they should not produce much biomass, which would clog the filter over time.

The choice of filter material is crucial to the hydraulic conductivity of the system. Fassman-Beck et al. (2014) describe effects of filter media on the hydraulic conductivity of systems' bioretention filter cells such as New Zealand's rain gardens. The media were mixed with organic material (compost). One of the results showed that the use of a proportion of incompressible sand has a positive effect on unwanted compaction of the filter material. Long-term large-scale applications in Germany also showed that inorganic materials are more resilient to clogging, which led to a shift from using cohesive material to technical sand (0/2 mm) with a steep sieving curve (Dittmer et al. 2016; DWA-A 178 2017). An organic layer which builds up during several years of operation serves as a secondary filter layer. Over time, secondary layers form on top of the filter material from the surface filtration process and mostly contain suspended solids which accumulate on the filter surface and organic material. These secondary filter layers themselves contribute to the overall sorption capacity of the filter. However, accumulation of fines can lead to clogging of the filter surface. Hence, hydraulic conductivity and the retention of substances with no renewable adsorption capacity are in competition. In cold climates and separate sewer systems, an excessively fine-grained filter material with low hydraulic conductivity can also lead to clogging in winter: the pre-freezing soil water content at the time of freezing might lead to the soil becoming an impervious layer with none or close to zero infiltration (e.g. no pollutant removal) referred to as concrete frost. Using a coarser filter material with a higher hydraulic conductivity, thereby minimising the soil water content, might lead to granular or porous frost instead. The latter will maintain and might even exceed the infiltration capacity of the unfrozen soil, thus maintaining proper filter function regarding water quantity.

A coarser grained filter material might jeopardise pollutant removal due to an excessively short retention time in the biofilter. However, the use of a filter material with coarser grain size (e.g. higher sand and lower silt and clay content) than the normally recommended sandy loam soils has been successfully tested in several studies (Blecken et al. 2011; Muthanna et al. 2007a; Søberg 2014). These results were similar to what has been found in other biofilter studies where winter conditions were not taken into account.

A study about seasonal climatic effects on the hydrology of stormwater biofilters (Muthanna et al. 2007b) found a strong correlation between the hydrologic performance of stormwater biofilters and temperature and antecedent dry days. Their results indicate that below zero temperatures and snowmelt can be expected to lower stormwater biofilter hydrology. However, pilot-scale stormwater biofilters have been shown to treat roadside snowmelt efficiently (Muthanna et al. 2007a).

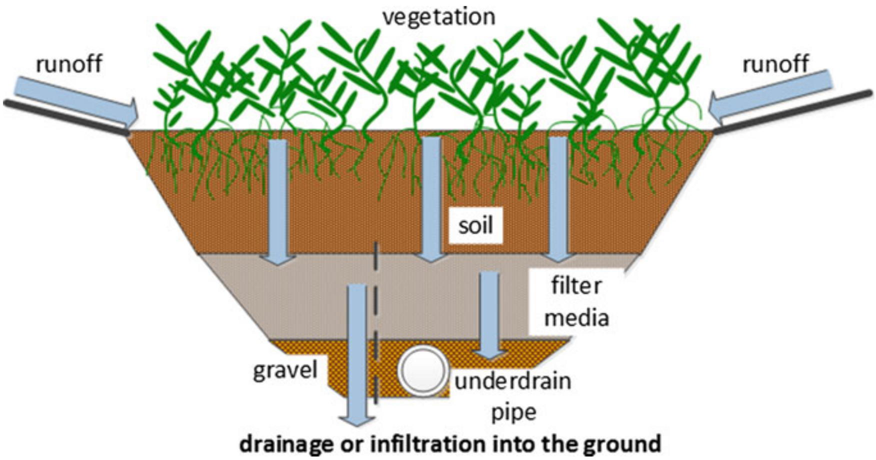

Fig. 2.12 Cross section of a roadside swale (Mangangka et al. 2016)

Swales and Buffer Strips

Swales (or buffer strips) are shallow, vegetated (generally grassed) channels with gentle side slopes (often 1V:13H or more) and longitudinal slopes (typically <1.5%) conveying runoff downstream (Kachchu et al. 2014). Swale and buffer strip use is particularly prevalent along roadways. A low-profile kerbing system is often used to allow water to discharge freely from the road surface into the swale or filter strip. Figure 2.12 shows a cross section through a schematic roadside swale. Buffer strips for runoff from agricultural fields are not treated in this book.

Swales are simple and cost-effective stormwater treatment devices for controlling runoff volumes and pollutants yielded from impervious surfaces (Deletic and Fletcher 2006). The ability of swales to reduce total runoff volumes and for flow attenuation has been reported in the literature, particularly in low to medium storm events (Deletic and Fletcher 2006; Davis et al. 2012). However, the majority of the research done on swales appears to have focused on their water quality improvement capabilities rather than their flow reduction and attenuation benefits.

Water quality treatment in a swale occurs through the process of sedimentation, filtration, infiltration and biological and chemical interactions with the soil (Winston et al. 2012). Swale performance studies by Deletic and Fletcher (2006) demonstrated average pollutant reduction efficiency of 72% for TSS, 52% for total phosphorus (TP) and 45% for total nitrogen (TN). Simulated runoff tests on nine swales by Bäckström (2002) demonstrated TSS removal rates between 79 and 98%. He also observed more particles were trapped when a swale had dense and fully developed turf.

Bäckström (2003) reported that a 110 m long grass covered swale removed sediments of particle sizes greater than 25 μm. He also found that small particles (between 9 and 15 μm in diameter) were exported from the swale. The sediment capturing performance of swales was found to reduce exponentially with the length of the swale, often reaching a constant value (Deletic 2005; Deletic and Fletcher 2006). Deletic (2005) also observed that large particles settled out within the first few metres of the swale, while smaller particles travelled further downstream. These results showed that the runoff sediment concentration is rapidly reduced after entering the swale.

Kachchu et al. (2014) investigated the effectiveness of using grass swales as pretreatment devices for permeable pavements in order to reduce clogging and extend the lifespan of these systems. While swales were effective at removing TSS from stormwater runoff, they found that they were only of limited effectiveness in the removal of nutrients. The results of their simulated runoff experiments demonstrated that between 50 and 75% of the TSS was removed within the first 10 m of the swale length. They concluded that installation of excessively long swales to reduce stormwater TSS pollution may not be the most cost-effective solution. The authors also found that swales can be used successfully to pre-treat stormwater for other stormwater treatment devices to increase the effective life of the systems.

Thus, swales can be used as an alternative to, or an extension of pipe systems, or as a pretreatment system for other treatment devices. They not only provide a stormwater retention function due to the relatively low flow velocities, but they also provide treatment opportunities through sedimentation and can promote (sometimes modest) infiltration (depending on the in situ soil characteristics). Low-intensity rainfall events can often be fully infiltrated in swales (depending on the infiltration capacity of the in situ soil) while more intense rains are generally conveyed through the swale to the downstream stormwater system or receiving waters.

The stormwater runoff from swales may be discharged through the underground stormwater pipe system when outlets are installed at the base of the swale. It is often good practice to place the outlets between 50 and 100 mm above the base of the end of the swale's lower end to encourage low-level ponding which can enhance water retention and sedimentation processes. However, prolonged ponding should be avoided. The in situ soil must therefore be suitable for infiltration.

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