Design methods for stormwater treatment – Site specific parameters

Dr. T. Larm[1]* and Dr. M. Hallberg[2]

[1] SWECO, P.O. Box 34044,100 26 Stockholm, Sweden
[2]ITT Water & Wastewater, 147 87 Sundbyberg, Sweden

**Corresponding author, e-mail thomas.larm@sweco.se*

ABSTRACT

The used design methods for stormwater treatment facilities (STF:s) are often based on compiled field data of relative reduction of a pollutant. However, relative reduction is bias in regard to the influent runoff quality. In addition, the bulk of removal occurs between storm events in the STF:s water volume. In this study field data from eight Scandinavian STF:s was elaborated on. The STF:s had a ratio between permanent volume and runoff volume (V_p/V_r) between 0.14 and 7.0. This study suggests that the use of V_p/V_r or the ratio between permanent area and reduced watershed area (A_p/A_{red}) is less applicable as a design tool for STF:s with inflow TSS concentrations approaching the irreducible concentrations. The range of irreducible outflow concentrations was suggested to be 5-32 mg/l (TSS), 44-144 µg/l (P) and 6-34 µg/l (Cu). Assessment of TSS reduction suggested that the major removal occurs within 6-12 hours under quiescent conditions. Based on data from the field studies we suggest the design methods to be complemented with e.g. inflow and outflow concentrations, detention volume and share of vegetation. The model StormTac is being updated with these factors for further elaboration on case studies.

KEYWORDS

design; stormwater; suspended solids; copper; phosphorus; treatment

INTRODUCTION

Experiences from Swedish projects have shown a need for improved and updated tools for designing Stormwater Treatment Facilities (STF:s) in regard to site specific conditions, limit pollutant concentrations to the receiving waters, flood control, cost restrictions, aesthetic and recreational purposes. The dominating treatment system for stormwater in Sweden is wet ponds.

Design criteria are often based on the relative reduction of pollutants. Important parameters that affect the reduction efficiency are the volume and area of the STF, inflow pollutant concentration, the detention volume, the hydraulic load (inflow/pond volume), surface load (inflow/pond area), location and construction of inlet and outlet, the percentage of stormwater runoff volume or number of runoff events captured and the sedimentation time for particles (Guo and Urbonas 1996; Hallberg, 2007; Pettersson, 1999; Vikström *et al*, 2004). In addition, seasonal variations in pond performance also have to be considered (e.g. Semadeni-Davies, 2006). These site specific variations will influence the accuracy when the empirical data are utilised in general design models. The International Stormwater BMP Database (ASCE and USEPA, 2008) does not use percent removal to assess STF (BMP) performance due to, e.g. that percent removal is primarily a function of influent quality so the use of percent removal may be more reflective of how “dirty” the influent water is rather than how well the facility is actually performing, and that many STFs that are functioning well appear to reach an irreducible concentration. The minimum outflow concentrations or "irreducible concentrations" refers to a STF's inability to reduce pollutant concentrations below a certain level. Consequently, if the mean inflow concentrations are close to the irreducible concentrations, no further reduction is likely. Irreducible concentrations often represent the internal production of nutrients and turbidity within a pond or wetland, due to biological production by microbes, wetland plants and algae (Center of watershed protection, 2007; Schueler and Holland, 2000). In ponds, the major part of the pollutant reduction will be from the removal of the particulate material since the pollutants have an affinity to the particulate material (e.g. Hallberg et al. 2007; Urbonas and Stahre, 1993).

The aim of this paper is to evaluate pollutant removal in STF:s in regard to (I) the permanent volume and surface area of the STF, (II) inflow concentrations (III) outflow concentrations and (IV) effects of detention times in regard to total suspended solids (TSS) removal during and between storm events. The effects of vegetation are discussed. The paper uses Scandinavian case studies, for which enough reliable data were available. Apart from TSS, phosphorus (P) and copper (Cu) were also studied. There is a focus in Sweden on phosphorus for its known eutrophic effects and copper is selected for representing one of a number of metals in regard to their toxic impacts on receiving waters.

METHODS

Treatment data were collected from the five Scandinavian wet ponds; Bäckaslöv, Järnbrott, Kolardammen, Skullerudkrysset and Lilla Essingen; from the wetland Välenviken and from the underground retention basin Fredhäll. For all facilities, flow proportional sampling from the in- and outlets were performed during several months up to three years. Samples were collected for analyses one or a couple of days after each significant precipitation event.

Bäckaslöv is a wet pond followed by a wetland, each part monitored separately. The catchment of totally 320 ha has about 140 ha of impermeable area (Vikström *et al.*, 2004). Treatment data from Bäckaslöv was received from personal communication with Emma Bosson and Bosson (2004). Järnbrott is a wet pond, the catchment is 480 ha of which 160 ha is impervious. Part of the watershed is a highway with an annual average daily traffic (AADT) of 24 000 vehicles per day (Pettersson, 1999). Kolardammen consists of a wet pond, followed by a wetland area and another wet pond. The total catchment area is 850 ha of which around 340 ha are impermeable areas. The data from Kolardammen was gathered from data reported by SWECO (2003). Skullerudkrysset is a wet pond with a catchment area of 3.4 ha with 2.2 ha impervious. A highway with and AADT of 42 000 vehicles per day makes up 1.5 ha of the asphalted areas (Åstebøl, 2005). Data and information for Skullerudkrysset was received from and collaborated with Svein Ole Åstebøl, COWI, Norway. Lilla Essingen is a wet pond. The catchment area is around 1.2 ha, of which 0.95 ha is impervious. A highway with an AADT of 140 000 vehicles per day makes up 0.38 ha of the impervious areas (Aldheimer *et al.*, 2006). Välenviken is a constructed wetland. The catchment area has a total area of 193 ha including 60 ha of impermeable areas (Florberger, 2006). Fredhäll is a concrete retention basin. The Fredhäll watershed is 1.37 ha motorway with an AADT of 140 000 vehicles per day and a tunnel with a road area of 0.31 ha (Hallberg *et al.*, 2007). The treatment results from Fredhäll used for this study were gathered from Vägverket (2007).

Data for American wet ponds was retrieved from the International Stormwater BMP Database (ASCE and USEPA, 2008). Data from the STF:s was elaborated on in the model StormTac (www.stormtac.com; Larm, 2000). StormTac calculates e.g. stormwater and base flow pollutant concentrations as well as loads from continuously updated land use specific standard concentrations, effects on receiving waters and required treatment regarding water quality criteria. It also designs STF:s in regard to reduction efficiencies and chosen criteria.

To assess treatment results, the empirical relationship between the permanent volume (V_p) and the mean runoff volume (V_r), and reduction efficiency (RE) was used. The mean runoff volume can be calculated according to (1) (Larm, 2000).

$$V_r = 10\ \varphi\ A\ r_{da} \qquad (1)$$

V_r	mean runoff volume [m^3]
φ	runoff coefficient
A	catchment area [ha]
r_{da}	yearly mean precipitation depth [mm]

Furthermore, the empirical relationship between the permanent area (A_p) and the reduced catchment area (A_{red}, ha) was used, where A_{red} = watershed area x runoff coefficient (Larm, 2000). To estimate removal of total suspended solids (TSS) between runoff events the findings from the sedimentation trials at the Eugenia STF was used (Hallberg, 2007). The result from the study describes the sedimentation behaviour dependence on the initial concentration of TSS in the runoff. The minimum settling velocity (m/h) of the particle size distributions or, according to the Hazen surface load theory, the surface load (SL, m/h) could be described by the logarithmic function (2):

$$Turb_{Average} = a \cdot Ln(SL) + b \qquad (2)$$

where a and b are parameters for the individual sedimentation trials. The turbidity was well correlated ($r^2 > 0{,}90$) to TSS in the study. The parameters a and b can be calculated from the initial concentration of TSS in the runoff.

RESULTS

(I). The permanent volume and area of the STF.

From the total data set presented in Figure 1, the reduction efficiency (RE, %) can be calculated (3). From (3) V_p can be calculated (4).

$$RE=11.1\ \ln(V_p/V_r) + 59.5 \qquad (3)$$

$$V_p=V_r\ 0.29\ e^{0.029RETSS} \qquad (4)$$

In (5) and (6), RE is calculated from the permanent area (A_p, m^2) and the reduced catchment area (A_{red}, ha).

$$RE=9.9\ \ln(A_p/A_{red}) + 20.1 \qquad (5)$$

$$A_p=A_{red}\ 8.7\ e^{0.0395RETSS} \qquad (6)$$

The empirical relationship between the found relative reduction RE (%) and the used design ratio between a permanent volume (V_p) and the average yearly runoff volume (V_r) displays notable variations in between the STF:s. The fit to TSS, P and Cu data was poor for both functions of V_p/V_r and A_p/A_{red} ($R^2<0.4$), indicating the effects of other parameters influencing RE.

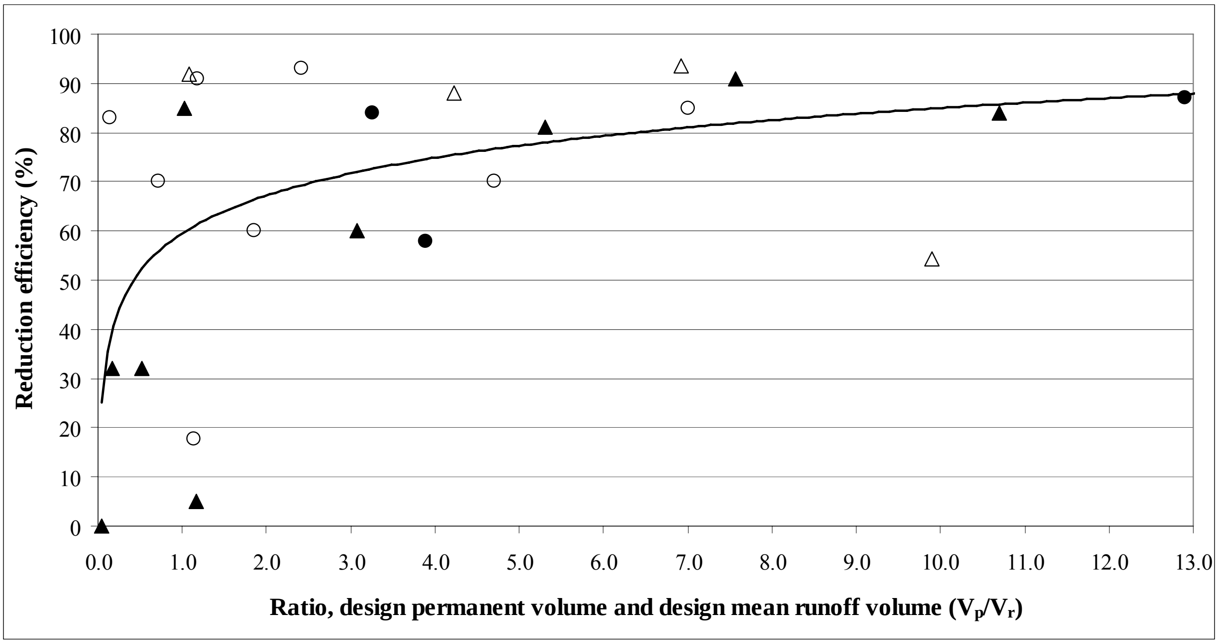

Figure 1 Reduction efficiency (RE, %) of TSS as a function of the ratio V_p/V_r for the Swedish case studies of this paper [unfilled circles], the wet ponds Järnbrott (the smaller of the two Järnbrott ponds) and Krubban (Pettersson, 1999) [filled circles], American case studies from the BMP database (ASCE and USEPA, 2008) [unfilled triangles] and the NURP study (Walker, 1987) [filled triangles]. A trend line for the total data set is presented.

(II) Inflow concentrations and relative reduction

The inflow concentrations influence the reduction efficiency (%). TSS concentrations below 100 mg/l yielded in general lower reductions efficiencies, i.e. there is an emphasised increase in reduction efficiency below 100 mg/l (Fig. 2). TSS concentrations exceeding 75 mg/l result in reduction efficiencies over 80 % (Fig. 2).

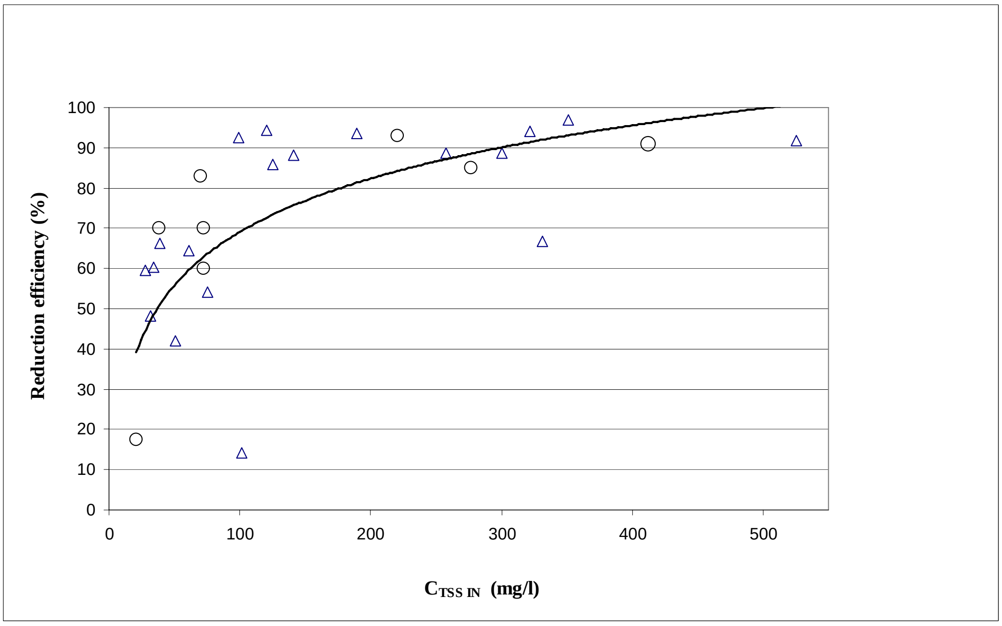

Figure 2 Inflow yearly average concentration of TSS (C_{TSS_IN}) and reduction efficiency for the Scandinavian STF in this study [open circles] and the BMP database (ASCE and USEPA, 2008) [open triangles]. A trend line for the total data set is presented.

The reduction efficiency seems rather constant, not increasing much, from around 100 mg/l TSS and higher.

The yearly average inflow concentrations of P and Cu in the STF:s show a similar trend of higher reduction efficiency with higher inflow concentrations as for TSS.

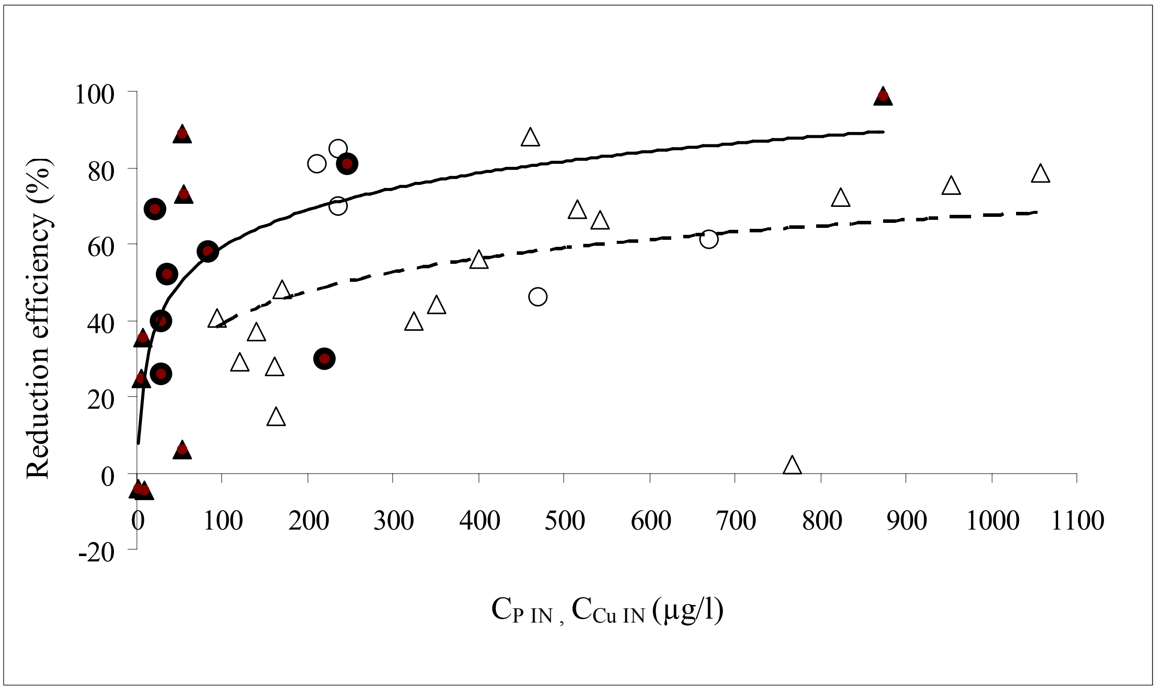

Figure 3 Inflow yearly average concentration of P (C_{P_IN}) and Cu (C_{Cu_IN}) and reduction efficiency (%) for the Scandinavian STF:s in this study [circles, Cu filled and P open] and the BMP database [triangles, Cu filled and P open]. Trend lines for the total data set of P [dotted line] and Cu [line] are presented.

(III) Outflow concentrations.

In this study, the average outflow concentrations of TSS for the ponds ranged from 13 mg/l to 32 mg/l. The corresponding values for P ranged from 44 µg/l to 144 µg/l and for Cu from 6 µg/l to 34 µg/l (Table 1).

Table 1. Inflow (C IN) and outflow (C OUT) EMC concentrations in the STF . *) 4.71 for wet pond+wetland.

STF	V_p/V_r	C IN Range	C OUT Range	C IN Median	C OUT Median	C OUT Average	C OUT Std. Dev.	Samples
TSS (mg/l)								
Bäckaslöv (wet pond)	1.86	7-620	4-70	43	15	21	16	25
Bäckaslöv (wetland)	2.85*	4-70	2-15	15	5	5	3	22
Järnbrott	0.71	16-58	5-26	40	22	17	8	7
Kolardammen	1.14	10-38	6-38	16	15	18	15	4
Lilla Essingen	2.42	4-280	2-60	20	7	15	15	35
Välenviken	0.14	9-153	6-25	25	10	13	9	6
Skullerudkrysset	7.03	39-606	5-133	183	11	23	28	24
Fredhäll	1.18	148-1453	15-54	486	29	32	14	6
P (µg/l)								
Bäckaslöv (wet pond)	1.86	8-833	14-470	150	100	130	95	25
Bäckaslöv (wetland)	2.85*	14-470	10-420	100	36	57	80	25
Kolardammen	1.14	41-790	20-150	165	31	44	30	26
Skullerudskrysset	7.03	34-2000	8-650	500	71	144	167	28
Cu (µg/l)								
Bäckaslöv (wet pond)	1.86	13-61	7-48	26	21	23	12	24
Bäckaslöv (wetland)	2.85*	7-48	2-87	21	11	17	18	26
Järnbrott	0.71	32-48	19-38	46	20	25	9	5
Kolardammen	1.14	3-56	3-12	15	6	6	2	26
Välenviken	0.14	16-51	9-25	32	16	16	5	6
Skullerudskrysset	7.03	25-133	13-77	84	34	34	13	28

(IV) The detention times in regard to TSS removal during and between runoff events.

In Skullerudkrysset 75 % of the runoff events had a time separation over 72 hours. The average TSS in the runoff over the year was 276 mg/l, for the summer and winter period it was 191 mg/l and 339 mg/l respectively. Assessment of the TSS removal during quiescent conditions was carried out using the findings of Hallberg (2007) and assessing a water column of 0.4 m, representing either a detention volume or part of the permanent volume in the pond. After 72 hours, TSS concentrations in the water column are below 20 mg/l and 75 mg/l for summer and winter respectively (Fig. 4). The major reduction (>50%) occurs within the first 6-12 hours.

TSS concentration C_{TSS} (mg/l) for the specific data in Figure 4 is calculated in (7) and (8) for different sedimentation times t_s (h):

$C_{TSS} = -40.3 \ln(t_s) + 249$ (winter) (7)
$C_{TSS} = -26.6 \ln(t_s) + 131$ (summer) (8)

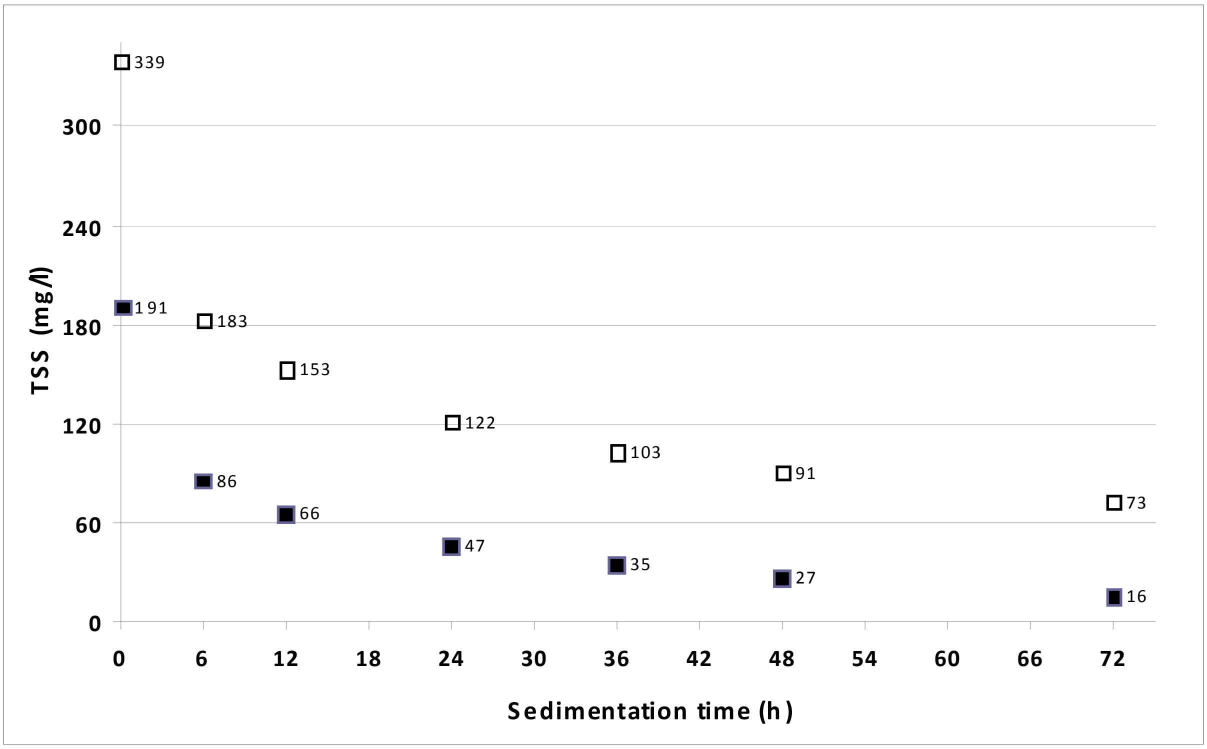

Figure 4 Calculated TSS concentration during sedimentation during quiescent conditions during winter (open squares) and summer (filled circles) in a 0.4 m water column.
TSS Summer = 191 mg/l, TSS Winter = 339 mg/l.

The STF can be designed for one or two detention volumes (V_d). The first detention volume (V_{d1}) accommodates for runoff events excluding flooding events with e.g. 2-year, 10-year or 100-year return time. The first detention volume can be calculated according to (9) and (10) as formulated in Larm (2000). Discussed detention or emptying times (t_{out}) are of 12-24 hours (Urbonas *et al.*, 1992; WEF and ASCE, 1998). As can be seen from the Skullerudkrysset example the bulk of reduction takes place within the first hours which underlines the possibilities to enhance treatment by detention volumes.

$V_{d1} = 10\ \varphi\ A\ r_{da}$ (9)

V_{d1} first detention volume in a STF [m^3], first volume above the permanent volume
r_{da} yearly mean precipitation depth (WEF and ASCE, 1998) [mm]

The emptying time is calculated in (10) (Larm, 2000).

$t_{out} = V_{d1} / (3.6\ Q_{out1})$ (10)

t_{out} emptying time for water to flow out from a STF [h]
$Q_{out,1}$ outflow for the first detention volume in a STF [l/s]

DISCUSSION

The correlation between relative reduction and the generally used ratios V_p/V_r and A_p/A_{red} respectively were low. For STF:s with inflow concentrations approaching the irreducible concentrations the use of V_p/V_r or A_p/A_{red} is less applicable.

In this study, the mean outflow concentrations were below 35 mg/l (TSS), 150 µg/l (P) and 35 µg/l (Cu). In a study compiled in Schueler and Holland (2000) the irreducible concentrations were studied. In 24 wet ponds in Tampa Bay, Florida, the mean outflow concentration was 8.8 mg/l (TSS) and 16 µg/l (Cu), taken from grab samples 1 to 3 days following storm. In 12 wet ponds and wetlands in Tampa Bay, Florida, the mean outflow concentration was 9.1 mg/l (TSS) and 10 µg/l (Cu), also taken from grab samples 1 to 3 days following storm. In a study of 15 wetlands the mean outflow concentration was 32 mg/l (TSS) and in 16 wetlands 190 µg/l (P). In 11 wet and extended detention ponds the mean outflow concentration was 35 mg/l (TSS) and 220 µg/l (P). Based on these data, the “irreducible concentrations” for STF:s were suggested to be 20-40 mg/l (TSS) and 100-150 µg/l (P). Furthermore, the findings of Randall et al. (1982) and Urbonas and Stahre (1993) suggest a lowest reachable outflow concentration for TSS around 10-20 mg/l. This would suggest that the found mean outflow concentrations would represent irreducible concentrations for the studied STFs.

The TSS mean outflow concentrations in this study were below the effluent TSS standard for wastewater of 60 mg/l applied in the EU. The mean outflow P concentrations were below the effluent limit concentration for wastewater of 300 µg/l applied in the year 2000 by the Swedish Environmental Court. However, for comparison, the State of California Control Board in the year 2002 set a maximum P-value of 100 µg/l for stormwater release to the Lake Tahoe Basin. The highest outflow Cu concentrations were below the USEPA “benchmark” criteria of 63.6 µg/l for outflow of Cu after treatment, not risking biological recipient effects.

The assessment of sedimentation suggested that 50 % of TSS reduction occurred within the 6 to 12 hours during quiescent conditions (Fig. 4). This would support that the major removal of pollutants, with affinity to the particulate material, will occur between runoff events. The V_p/V_r ratios differed significantly between the case studies as did the inflow TSS concentrations. However, they displayed similar TSS outflow concentrations (Table 1). This indicates the importance of the removal between storm events. The use of a detention volume increases the treatment efficiency. Accumulation of a detention volume during a runoff event provides better mixing of the more polluted runoff with the cleaner permanent volume. Furthermore, a detention volume also results in a lesser risk of hydraulic short circuiting in the pond. The impact of different detention volumes and detention times should be investigated further, for example using on line measurements of turbidity (e.g. Hallberg, 2007).

The three case studies with larger share vegetation, i.e. Bäckaslöv wetland, Välenviken and Kolardammen, have been compared with the other STF:s. The Bäckaslöv STF consisted of a pond in series with a wetland. After the treatment in the Bäckaslöv wetland, the mean TSS concentration was reduced from 21 mg/l after the wet pond to 5 mg/l as effluent from the wetland, the corresponding reduction of P was from 130 to 57 µg/l and of Cu from 23 to 17 µg/l (Table 1). Bäckaslöv wetland and Välenviken have the lowest outflow TSS concentrations, Kolardammen and Bäckaslöv have the lowest outflow P concentrations (no data of P was found for Välenviken) and all of the three have the lowest Cu concentrations. Relating the reduction efficiency (RE) for wetlands and more vegetated wet ponds, such as the three STF:s studied, to the ratio V_p/V_r may provide a basis for improved design and estimation of the influence of vegetation on RE, even if more data is needed. For the studied STF:s, only Välenviken results in high RE of TSS in relation to V_p/V_r, but Bäckaslöv and Kolardammen results in lower RE (below the plotted trend line in Figure 1). However, this can be explained by low inflow TSS concentrations (21 mg/l into Bäckaslöv wetland and 20 mg/l into Kolardammen) i.e. in the order of “irreducible concentrations”. For P there is a clear trend with the three vegetated STF:s’ RE-values high above the other STF:s. For Cu, there is the same clear trend for Välenviken and Kolardammen, but not for Bäckaslöv. Also the latter can be explained by low inflow concentrations (average 23 µg/l), in the order of “irreducible concentrations”. Increased share of vegetation in wet ponds will probably increase the reduction efficiency for the studied substances as suggested by this study.

According to Braskerud (2001), vegetation may retain sediments and reduce resuspension. A review of the existing performance data indicated that the removal efficiencies of constructed stormwater wetlands are slightly higher than those of conventional pond systems (N.J.D.E.P., 2004). Estimated average RE for wet ponds and wetlands in the New York State Stormwater Management Design Manual (Center for Watershed Protection, 2001) were equal for TSS (RE=80%) and P (RE=50%), but higher in wet ponds for Cu (RE=60%) than in wetlands (RE=40%). A review of STF:s in Europe by the Daywater project (Middlesex University, 2003) compiled RE of TSS and Cu, with around the same RE for TSS in retention basins (RE=80-90%) and wetlands (RE=70-95%) but possibly a larger RE for Cu in wetlands (RE=40-75%) than in retention basins (RE=35-50%).

CONCLUSIONS

For STF:s with inflow TSS concentrations approaching the irreducible concentrations the use of V_p/V_r or A_p/A_{red} is less applicable as a design tool. The range of irreducible outflow concentrations was suggested to be 5-32 mg/l (TSS), 44-144 µg/l (P) and 6-34 µg/l (Cu). Assessment of TSS reduction suggested that the major removal occurs within 6-12 hours under quiescent conditions. A general equation for calculating reduction efficiency and for improved design of STF:s may be developed and is being adapted into the model StormTac. Included factors suggested are permanent volume, mean runoff volume, catchment area and runoff coefficient, detention volume, inflow and outflow concentration, share of vegetation cover and the share of the yearly flow captured by the facility.

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