Revised design criteria for stormwater facilities to meet pollution reduction and flow control requirements, also considering predicted climate effects

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Abstract

There is a need to revise existing design methods for stormwater pollutant treatment, flow transport and detention facilities. The aim is to increase the accuracy in predicting the performance compared with design only based upon areal and volumetric functions and to optimize design by considering more site-specific data, receiving water quality criteria and forecasted climate effects. During the latest years, flow proportional concentration data from in- and outlets from wet ponds and constructed wetlands, have been compiled. Furthermore, other kind of data from the specific facilities have been compiled, such as areas, volumes, proportion of vegetation, outlet design details and length:width ratio. The parameters are used to revise design methods and are implemented in the operative stormwater and recipient software model StormTac. Design criteria and parameters for calculating design flow and sizing required detention volume are also presented. The climate effects on some of the studied parameters, e.g. design flow and inlet concentration, are discussed. The paper presents the climate factor based upon the hypothesis that it is a function of the design rain duration and reoccurrence time.

Keywords

climate factor, design criteria, flow detention, StormTac, stormwater, treatment

Introduction

The most commonly used design methods for stormwater treatment are based on volume or area related correlations (Larm and Hallberg, 2008). Over the last years, the following-up of treatment systems for stormwater has been improved through consistent flow proportional sampling. This has highlighted the need for updated tools for designing ponds, wetlands and detention basins regarding site-specific conditions.

Larm and Hallberg (2008) evaluated these methods using data from 18 stormwater facilities in Norway and Sweden. One of the conclusions was that consideration of a minimum concentration at the inlet must be taken into consideration. Larm and Hallberg (2008) also discussed the uncertainty in the overall design and the impact of vegetation in stormwater systems. Also Persson and Pettersson (2009) and Pramsten (2010) considered these methods to be insufficient, the methods need to be complemented by taking into account more site-specific parameters.

The aim of this paper is, by evaluating new data, to develop site-specific parameters to improve the design of stormwater treatment facilities. In this paper, data are presented for suspended solids (SS), phosphorus (P), copper (Cu) and zinc (Zn). These 4 substances are selected since there are much available data and since these are generally of priority in different countries used as water quality criteria and as basis for designing stormwater treatment facilities.

The updated design methods with these site-specific parameters can be used to design new facilities or to re-design existing facilities to meet requirements.

Method

To develop site-specific parameters, data from total of 46 facilities (20 Scandinavian, one Irish and 25 American) have been processed in the compilation (StormTac 2013; Larm and Hallberg, 2013). The following data is available for each facility: watershed area, runoff coefficient, permanent water area and water volume, permanent water area / reduced watershed area, permanent water volume / average runoff volume, surface loading, percentage of vegetation, bypass or not, treatment effects, the inlet and outlet concentrations.

The studied facilities are implemented in the watershed management model StormTac (Larm T., 2000). The model is based on the 5 "boxes" Runoff, Pollutant transport, Detention, Stormwater treatment and Receiving water, see Fig. 1.

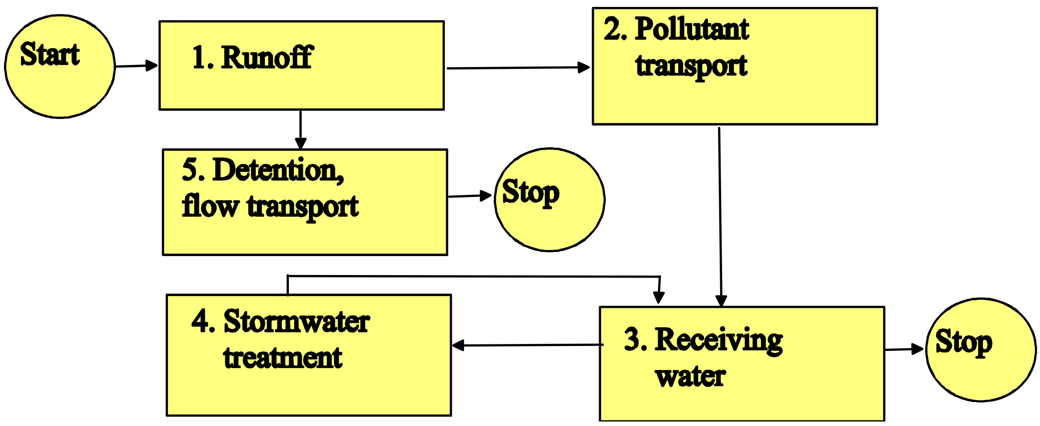

Figure 1 Simplified flowchart of the watershed management model StormTac.

Revised design criteria

"Runoff" and climate change

The design flow Q_{dim} is calculated in Eq. (1), developed by and presented in Larm (2013). It is used for the design of storm sewer, concrete channels, ditches etc.

$$Q_{dim} = Q_{dim+} + f_c * i * \varphi_s * A_s, \text{ where:} \quad (1)$$

Q_{dim}	Design flow (l/s)
Q_{dim+}	Additional inflow i.e other constant, pumped inflow or base flow Q_b
f_c	Climate factor
i	Rain intensity (l/s/ha) for specific value of t_r and N, t_r>10 min
t_r	Design rain duration (min)
N	Reoccurrence time (years)
φ	Specific runoff coefficient
A_s	Specific watershed area (ha)

The design rain duration t_r is calculated in Eq. (2).

$$t_r = L/(60v) \tag{2}$$

L	Length, transport distance (m)
v	Mean water velocity (m/s)

If there are physical flow limitations in the transport system upstream the design point can be considered in StormTac. It is common in Sweden that 10 minutes rain duration always is used when calculating design flows. This often results in oversized transport systems and too small detention volumes. The design rain duration should be the calculated transport time (Eq. 2) if it is longer than, or at minimum 10 minutes (Swedish Water, 2011). Chosen N depends on how often the transport system can be accepted to be flooded.

Climate factor f_c

The climate factor f_c is the ratio between the expected future and the present design rainfall intensities. In northern Europe more frequent and more severe storms are expected and the design intensities are expected to increase with a factor of 1.1-1.5 within the next 100 years (Arnbjerg-Nielsen, 2008). According to the recommendations by Swedish Water Association, estimated short-term precipitation will increase by a factor of 1.05 to 1.3 in Sweden, while annual runoff volume is estimated to increase by a factor of 1.1-1.2 (Swedish Water, 2011). This is based on the climate scenario A2 and SMHI recommendations.

Based on extrapolation of annual precipitation increases from data from SMHI 1860-2012, the annual precipitation will increase from the period 1961-1990 to 2071-2100 corresponding the climatic factor 1.20, and from today (2013) 1.15.

The rain reoccurrence time and duration may effect the size of the climate factor (Arnbjerg-Nielsen, 2008; Swedish Water, 2011). In order to forecast the impact of climate effects on design flows and flow detention volumes, we need to calculate the climate factors on the basis of case specific design return periods and durations. We have, based on data from Swedish Water (2011), SMHI and data compiled by Arnbjerg-Nielsen (2008), developed draft equations for calculating the climate factor based on these parameters. The equations show that the climate factor increases with increasing return period and decreases with increasing duration.

The Danish study recommends the use of different factors for different reoccurrence time, i.e. $f_c = 1.2$ for N = 2 years, $f_c = 1.3$ for N = 10 years and $f_c = 1.4$ for N = 100 years, while Swedish recommendations suggest the use of $f_c = 1.05$ to 1.3 depending on regional climate conditions (Swedish Water, 2011). Based on the Danish correlations between climate factor and return period a similar Swedish curve was adapted by a parallel shift downwards of the Danish curve. A trend line for a logarithmic function provided the best match to data, using the minimum value at N = 1 is 1.05 (assumption) and the maximum value at N = 100 is 1.3 (Larm, 2013). Based on these Danish data, shares (K_{tr}) of the climate factor ($f_{c,tr}$) for different durations (1-12 h) are calculated, which assumed that the proportion of 1.0 is used for shorter durations than 1 hour, according to what the data shows. The latter means that no reduction factor is made for durations up to 1 hour. Over the duration of one hour is thus a reduced climate factor used. A trend line was created for data in scenario A (Arnbjerg-Nielsen, 2008) and it is assumed that its function provides the effect of duration on the climate factor (Larm, 2013). We obtain the following relationship between climate factor, the return period and duration, valid for the Swedish climate conditions (Larm, 2013), see Fig. 2

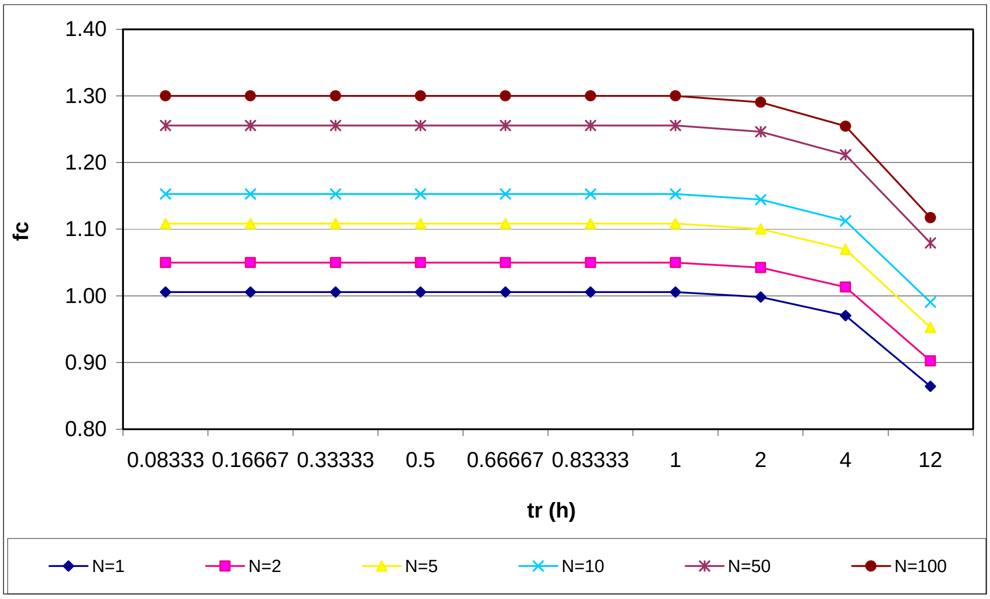

Figure 2 The overall climate factor (fc) and its dependence on both the return period N (years) and duration tr (h). Larm (2013).

For the 10-year storm (which is common design in Sweden) and from a small area with a design flow time of 10 minutes, the climate factor 1.15 can be used for the design of e.g. stormwater sewers. For a detention basin with the design duration of 5 hours, the climate factor of 1.10 can be used, see Fig. 2.

"Detention"

Facilities may need to be designed with a capacity for detention of intense flows to reduce flow due to capacity of the transport system downstream to prevent flooding. The detention volume (V_d) can be sized for a rain with a particular return time N (Larm, 2013). Eq. (3) and Eq. (4) were developed by and presented in Larm (2013). The design discharge (outflow Q_{out}) from a detention basin control required detention volume, which is the maximum volume between the design inflow (Q_{dim}) and outflow at the rainfall duration (t_r) that gives the maximum volume (V_d) at the design return period, Eq. (3). The design outflow, Eq. (4), is not the maximum but the mean outflow (Swedish Water, 2011).

$V_{dmax} = 60 * t_r * (Q_{dim} – Q_{out,ave})$, where: (3)

$Q_{out,ave}$ $Q_{out} * f_{Qred}$, where (4)

V_{dmax} Maximum required detention volume (m^3)

$Q_{out,ave} =$ Design outflow, mean outflow (Swedish Water, 2011) (l/s)

Q_{out} Maximum outflow (l/s)

f_{Qred} Factor for reducing the design outflow considering that the outflow is not at a maximum other than at maximum detention level. Normally: 2/3, if flow regulator: 0.95, if pumped outflow: 1.0.

It is common in Sweden to generally design flow detention volumes using the rain duration 10 minutes. This results in too small detention volumes with more frequent floodings. According to Swedish Water (2011), the rain duration together with the specific rain intensity for that duration that result in the largest detention volume V_{dmax} shall be used, see Eq. (3). For small outflow values, very long rain durations shall be used, up to 24 hours (Swedish Water, 2011).

”Pollutant transport”

Stormwater discharge is identified as one of the major pollutant emissions in urban areas (Alm et al., 2010). There is a correlation between annual mean concentration and specific landuse in the catchments (Alm et al., 2010). The specific concentrations in stormwater water vary between different rain occasions (event mean concentration), during the specific rainfall occasions and between the different substances. StormTac uses annual mean data to cope with these variations. These “standard concentrations” per land use are used to calculate specific concentrations at the inlet and pollution loads on recipient. With the expected climate change, the total precipitation will increase (in Sweden), maximum flows will increase and the period without precipitation will be longer. This is expected to result in higher peak concentrations and event mean concentrations, and an increased total load (Sharma et al, 2011) which may lead to that existing treatment facilities are undersized.

Table 1 Standard concentrations of stormwater and base flow for selected substances (total fractions) and land uses.

	Storm water				Base flow			
Land use	P	Cu	Zn	SS	P	Cu	Zn	SS
	mg/l	µg/l	µg/l	mg/l	mg/l	µg/l	µg/l	mg/l
Road 10 000 vehicles/day	0.18	38	164	87	0.052	13	77	25
Parking	0.10	40	140	140	0.029	11	47	35
Residential area	0.20	20	80	45	0.058	5.5	27	11
Terraced house area	0.25	25	85	45	0.073	6.9	28	11
Multi-family area	0.30	30	100	70	0.087	8.3	33	17
Downtown area	0.28	22	140	100	0.081	6,1	47	25
Industrial area	0,30	45	270	100	0.087	12	90	25
Park grounds	0.12	15	25	49	0.035	4.1	8,4	12
Forest	0.035	6.5	15	34	0.030	4.0	10	1.5
Agricultural property	0.22	14	20	100	0.22	14	20	100
Meadow	0.20	15	30	45	0.17	9.2	20	2,0

“Storm water treatment”

With Eq. (5) the permanent pool area for a wet pond and a constructed wetland is calculated (Larm, 2000; Persson and Pettersson, 2009).

$$A_p = \varphi A K_{A\varphi} \qquad (5)$$

A_p Area of permanent pool [m^2]

$K_{A\varphi}$ Regression constant, normally 150 (70-400) for wet ponds and 300 (100-800) for wetlands (StormTac, 2013)

Figure 3 presents the correlation between $K_{A\varphi}$ (=A_p/A_{red}=$A_p/A\varphi$) and the reduction efficiency of studied substances from the studied treatments facilities, without using other site-specific parameters.

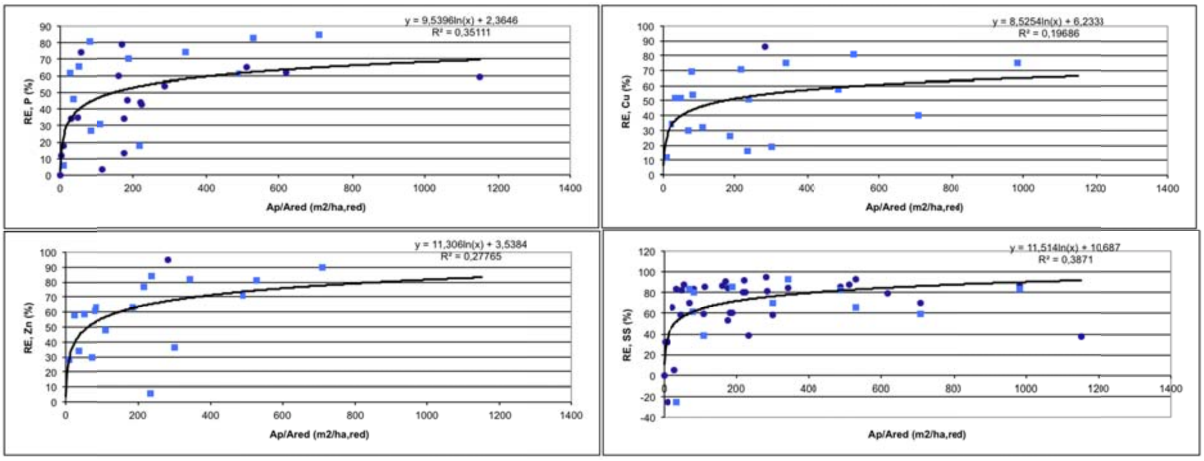

Figure 3 Diagram of treatment effects based on sampling and trendline empirical relationships A_p/A_{red}, where A_{red}= $A\varphi$. Blue squares show data from the Scandinavian facilities, black dots show facilities from U.S. and one facility from Ireland.

The fit of the data for the studied substances was less good (regression coefficients R^2<0.4), see Fig. 3, indicating the influence of other parameters on treatment efficiency.

In Eq. (6) the reduction efficiency is calculated based on the correlations in Fig. 3, but complemented with different factors, representing included site-specific parameters (StormTac, 2013).

$$RE = [k_1 * \ln (A_p / A\varphi) + k_2] * f_{Cin} * f_{veg} * f_{bypass} * f_{Vd} * f_{Cirr} * f_{temp} * f_{shape} \qquad (6)$$

RE	Reduction efficiency for wet ponds and constructed wetlands [%]
k_1, k_2	Regression coefficients for each pollutant
f	factor
Cin	inlet concentration
veg	vegetation
bypass	bypass
Vd	detention volume
Cirr	irreducible concentration
temp	temperature
shape	shape

The treatment effect can also be a function of permanent facility water volume (V_p) and the average runoff volume (V_r). V_p/V_r can in StormTac be used to replace $A_p/A\varphi$ in Eq. (6). However, generally the fit to data was better for $A_p/A\varphi$.

Inlet concentration (f_{Cin})

The inlet concentrations C_{in} affect the relative treatment effect, see Fig. 4. From the presented diagram of SS, one observation is that the reduction efficiency is over 80% for all facilities with higher inlet concentration than 100 mg/l.

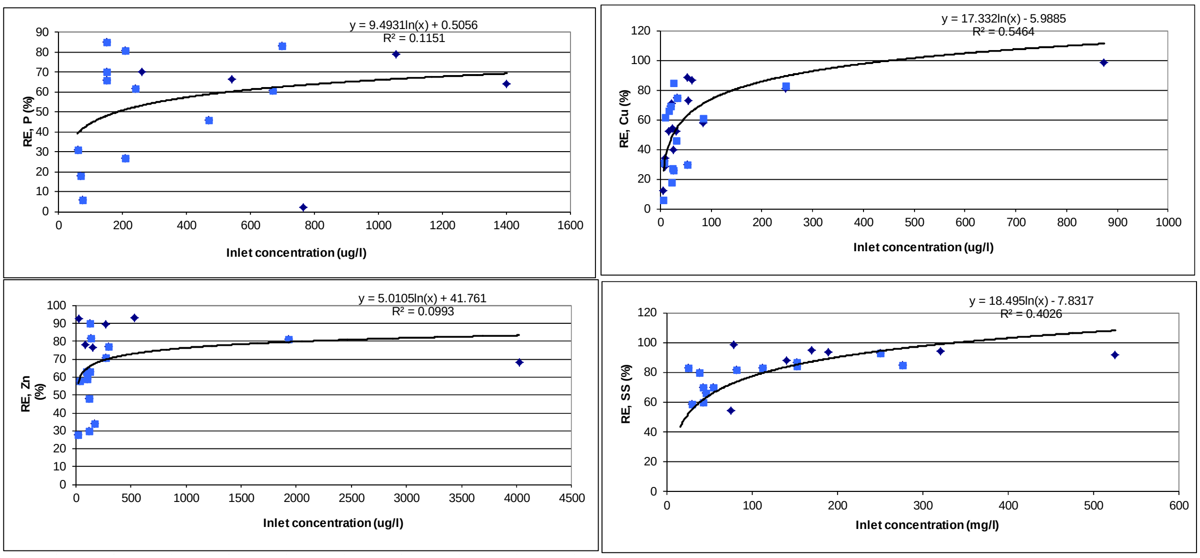

Figure 4 Diagram of treatment effects based on sampling and trendline empirical relationship of inlet concentrations C_{in}. Blue squares show data from the Scandinavian plants, black dots show plants from U.S. and one facility from Ireland.

Irreducible concentration (f_{Cirr})

The minimum outlet concentration, the "irreducible concentration", is affected by incoming content and internal processes in plants (decomposition of plants, leakage from the bottom due to lack of oxygen, the exchange with sediment, stirring sediment because benthic animals, etc). In StormTac, the reduction efficiency is adjusted so that not less than its minimum concentration is obtained at the outlet. The model contains relationships for each subject between the percentage of vegetation and the irreducible concentrations. However, it is possible to unlock this restriction if it is believed possible to achieve lower levels by adapting the choice of plants or add filters or the like. The irreducible concentrations have been estimated from outflow concentration data from the studied facilities. These are C_{irr} (P) = 20-30 ug/l, C_{irr} (Cu) = 6-7 ug/l, C_{irr} (Zn) = 14-25 ug/l and C_{irr} (SS) = 5-10 mg/l.

Vegetation (f_{veg})

Increased proportion of vegetation of the facility area is expected to provide higher treatment effects (Larm and Hallberg, 2008; Persson and Pettersson, 2009). The vegetation reduces water velocity and stops particles and thus increases the effect of the sedimentation process. Vegetation also reduces resuspension of particles and provides an uptake of nutrients and metals that can be separated if the vegetation is harvested. Vegetation also provides large areas for microorganisms and contributes to the uptake of pollutants. The pollutants are mostly taken up in the roots where the contaminant concentration is highest (SMRC, 2012). The roots oxygenate even surrounding sediments which increase microbial uptake of pollutants (Stottmeister et al., 2003). More data is needed and the relationship is uncertain, but an increase in treatment effect was observed for Zn, Cu and SS. The correlations indicate a negative effect of P, but this may be due to the influence of other parameters. An assessment is that vegetation has no effect on phosphorus. How the facilities are maintained is considered to play a major role, in some facilities have no harvest of vegetation occurred while harvest has taken place in others.

Bypass (f_{bypass})

Pollutants in bypassed flows (overflow)-are not treated within the facility. Bypass results in an increased pollutant reduction efficiency (%) within the facility since the flow to the facility is decreased. However, the total load to the recipient may increase (Vikström et al., 2004; Pramsten, 2010;). The part of the total yearly runoff volume that bypasses (untreated) the facility is calculated in StormTac.-The developed flow model calculates the share of bypass of the total volume from this historical precipitation data, calculated time of concentration (minutes) and the bypassed flow divided by the reduced watershed area, i.e. the reduced flow Q_{red} (l/s, ha_{red}).

Detention volume (f_{det})

There is often a need of both flow detention and pollutant treatment which can be achieved in the same facility (Whipple and Hunter, 1981). By limiting the outflow an increased detention time and sedimentation time during the runoff events is generated, although it is generally accepted that most of the treatment occurs between the runoff events. This regulation implies that a greater portion of the facility is involved in the treatment; better mixing occurs and less risk of short circuit currents occurs. This might indicate a correlation with f_{shape}.

A feature has been developed for use in StormTac based on data from the New Jersey Stormwater Best Management Practices Manual (2004), see Fig. 5. The figure shows the treatment efficiency of SS as a function of V_p/V_r. There are curves for various detention times. The treatment efficiency is then increased from the lower curve up to the percentage specified in the upper curve corresponding to a certain detention time.

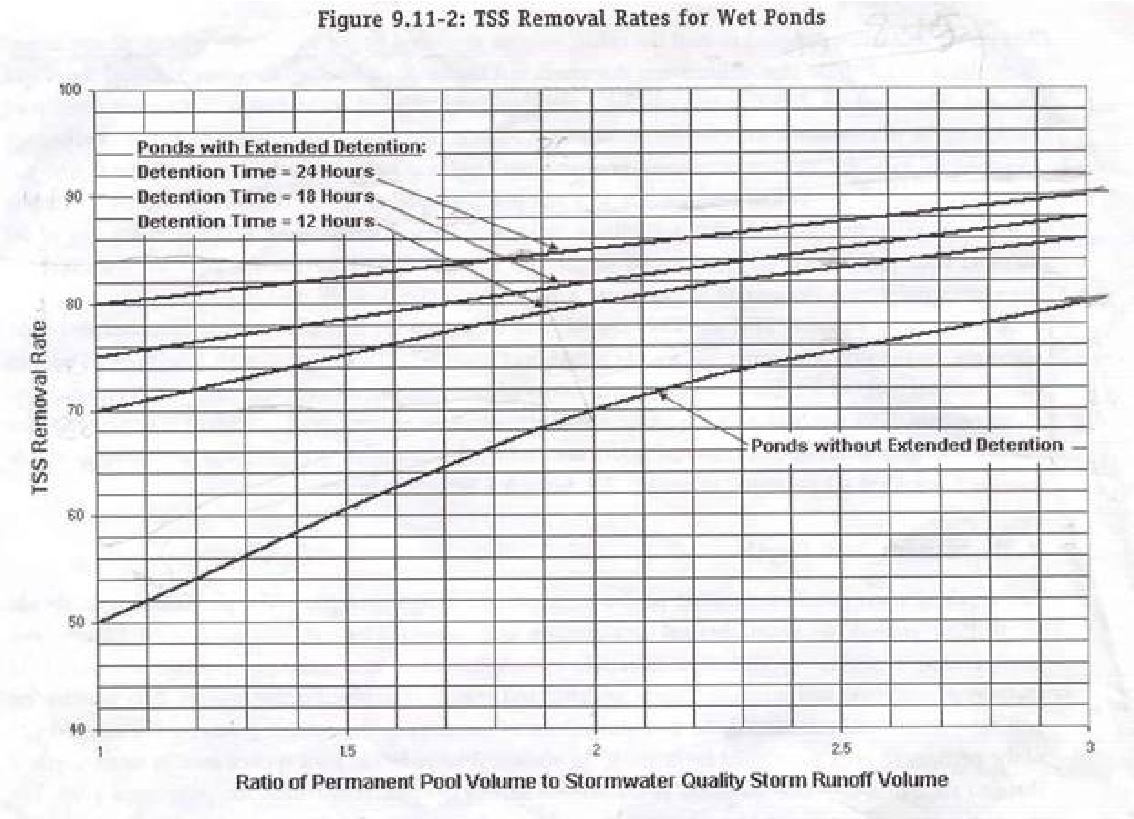

Figure 5 Reduction efficiency of SS as a function of V_p/V_r. New Jersey Stormwater Best management Practices Manual (2004).

Temperature (f_{temp})

To adapt the pollutant calculations for colder regions the runoff coefficients can be increased in StormTac to include the effects of decreased evaporation. Furthermore, the evaporation from upstream lakes and water courses in the runoff and the recipient model can be decreased. Also, the regression coefficient for calculation recipient lake pollutant concentrations using the OECD-model can be changed (lower x and higher y). These adaptions shall be further studied by comparing data from colder and warmer regions.

From data from the studied facilities, the difference in reduction efficiency (%) per degree Celcius can be calculated in StormTac. The yearly average water temperature has been estimated for the case studies. For a new calculation the yearly average air temperature is input data and a factor for increased or decreased reduction efficiency is calculated from an empirical equation from the case studies.

Shape (f_{shape})

From the case studies the mean form as length:width ratio was estimated. Input is an estimated ratio and output is a factor to increase the reduction efficiency for larger ratio or to decrease it for smaller ratio. The StormTac equations are based on data of hydraulic efficiency for different shapes from Vikström et al. (2004), assuming the same fraction for all parameters due to small differences between substances.

Results and discussions

The errors per parameter have been investigated and the parameters with most impacts are presented. Table 2 presents compiled errors for the studied facilities per parameter and substance, and the average error per parameter. The data in Table 2 indicates that there is no sufficiently good match for any single parameter, therefore a combination of parameters need to be studied and used.

Table 2 Correlation (R^2-valuee) between studied single parameters and measured reduction efficiency.

Parameter	P	Cu	Zn	SS	Mean
A_p/A_{red}	0.35	0.20	0.28	0.39	0.31
C_{in}	0.12	0.55	0.10	0.40	0.29
V_p/V_r	0.09	0.30	0.26	0.33	0.25
Vegetation	0.14	0.073	0.054	0.042	0.077

For detention volume, temperature, bypass and shape no regression coefficients could be developed because of the context and type of data used.

The strongest correlation was generally for the areametric correlation (A_p/A_{red}) for each substance. Vegetation gave weak indications of increasing treatment efficiency with increasing percentage vegetation.

The data also shows that there are irreducible concentrations from stormwater ponds and wetlands. These irreducible concentrations are interesting to compare with guidelines and environment quality standards deciding which treatment technique to be used. Furthermore, maximum treatment effects are identified and used.

Uncertainty remains high for individual parameters, so it is considered relevant to consider more parameters than not doing it. Relatively much data was used, but more data is needed in future to update the correlations.

The results can be used to design ponds and wetlands regarding a specific parameter or to identify which type of storm water treatment or combination of treatments facilities needed.

Conclusions

The paper presents a selection of design criteria for flow transport, flow detention and pollutant treatment of stormwater. The model is updated with the optional climate factor. The relations need to be reviewed and revised regularly in accordance with current knowledge from SMHI and the Swedish Water's forthcoming recommendations.

The following parameters have been selected, and can now be modelled in various combinations in StormTac for designing ponds and wetlands, and to compute their treatment effects.

- A_p/A_{red} (area related).
- V_p/V_r (volume related)
- C_{in} (inlet concentration)
- C_{irr} (irreducible concentration)
- Detention volume
- Vegetation (wetland plants, plants in the water)
- Bypass
- Temperature
- Shape

The strongest influences on the reduction efficiency are the relationship between permanent pool area and the reduced sub-watershed area (A_p/A_{red}), and the inlet concentration (C_{in}).

The following parameters are to be investigated further because of high uncertainty: the effects of vegetation, the presence of a detentions volume and bypass.

There is also a need for a statistical analysis of the various parameters influence on the treatment efficiency, to quantify uncertainty. For the latter, it is planned some form of multi criteria analysis.

Although there is considerable uncertainty for each parameter separately studied, the reduction efficiency can be explained by the influence of site-specific conditions and the updated design methods with these site-specific parameters can now be used to design new facilities or to re-design existing facilities to meet requirements~~.~~

A comparison has been performed with data from the wet ponds Ladbrodammen and Tibbledammen (Alm et al., 2010) which showed a significantly better agreement between calculated and measured treatment effects when area and volume relationships were supplemented with the site-specific parameters. Further evaluation will take place and data and the empirical equations will be continuously updated.

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