StormTac
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An operative watershed management model for estimating actual and acceptable pollutant loads on receiving waters and for the design of the corresponding required treatment facilities

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Abstract

We require to have a better understanding of whether the designed or constructed Best Management Practices (BMPs) are cost-effective and have the desired effects on the receiving waters or if complementary or alternative measures are needed. The operative Excel model StormTac integrates watershed, transport, recipient and BMP processes. The aim is to present the key equations and parameters. StormTac has been implemented in many case projects for planning-level studies with a small amount of input data, as well as for detailed design considering the impacts on the recipients. Obligatory required input data are area per land use, water volume and mean water area of the recipient. Examples of parameters for which default data can be used or overwritten are precipitation intensity, land use specific runoff coefficients and storm water pollutant concentrations, measured and critical pollutant concentrations in the water of the recipient and average daily traffic intensity for larger roads.

Many stormwater treatment facilities have been and are being constructed in Sweden and abroad. However, we have no easy-to-use tool for indicating if these facilities will have the desired effects on the receiving waters. The stormwater management model StormTac employs static equations for setting up water and mass balances and for the estimation of yearly acceptable pollutant loads on receiving waters. The model objective is the planning and designing of required treatment facilities for reaching the desired load and concentration reduction to and in the receiving water. Here, the main equations in StormTac are presented, including similar models from literature studies. Specific results from the sub model “Recipient model”, from 7 Swedish lake recipients/watersheds within the Stockholm region, are presented for phosphorus (P). Calculations have also been performed for the substances nitrogen, lead, copper, zinc, cadmium, chromium, nickel, mercury, suspended solids, oil and PAH. Preliminary verification of model results to the measured data and comparisons with other models show that the model is useful for estimating yearly pollutant concentrations and acceptable pollutant loads in receiving waters, loads to/from the sediments, the required reduction and dimensions of stormwater treatment facilities to meet water quality criteria.

Keywords

BMP; design; model; receiving waters; storm water; acceptable; load; stormwater; treatment; watershed; lake

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Introduction

The EC Water Directive (2000/60/EC) is being implemented in Europe. The purpose of this directive is to establish a framework for the protection of inland surface waters, coastal waters and groundwater. In order to reach the aims of the directive, early actions and long-term planning of protective measures are required. The management tool and operative storm water and recipient model StormTac (Larm, 2000) focuses on the design of storm water treatment facilities or Best Management Practises (BMPs) with consideration to preset goals for the receiving waters. The most important equations and parameters in the model are presented. Finally, the required parameters, amended or added equations and complementary data are identified.

The unique property of this model is that it integrates the watershed properties and the pollutant transport calculations with the relevant "recipient" (here equal to receiving surface waters; e.g. lakes and water courses) processes and the design facilities. For calculating yearly pollutant loads to the recipients, land use specific standard values of concentrations and runoff coefficients are employed. They are based on long-term flow proportional data and may be calibrated to better reflect site-specific conditions in the studied watershed. Standard values are generally more reliable and relevant to apply rather than values from grab samples and shorter periods.

The presented operative recipient model is "semi-empirical". The only obligatory input data needed are the land use specific watershed areas, the volume and the area of the recipient. More reliable estimations can be performed if using more input data, such as measured pollutant concentrations in the water mass of the receiving water. When measured concentrations are not available, calculated values of e.g. lake water pollutant concentrations are used. The reduction efficiencies (positive if a net sediment load or negative if an internal load) of the recipient are also estimated. However, the model cannot be used for and is not intended for dynamic/short-term predictions. The objectives of this report are to present the stormwater and recipient model StormTac and the included main equations. The recipient submodel is applied on 7 Swedish lakes and the presented results are acceptable loads on the lakes, calculated and measured lake water concentrations, sedimentation coefficients, lake retention and required load reduction. The two first mentioned results have been compared to results of similar models. The latter models are included in StormTac for comparative purposes. Calculations have been performed for the substances phosphorus (P), nitrogen (N), lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd), chromium (Cr), nickel (Ni), mercury (Hg), suspended solids (SS), oil and poly cyclic aromatic hydrocarbons (PAH). P is selected for presentation.

1. Methods

Several nutrients and pollutants are calculated in the Excel model StormTac, see www.stormtac.com. Either quick and simplified or more detailed calculations for construction drawings can be performed with the help of the model tool. However, the model cannot and is not intended for dynamic/short-term predictions. The unique property of the model is that it in a user-friendly and simplified way integrates the watershed properties and the pollutant transport calculations (I) with the relevant recipient processes (II) and the design of facilities in the storm water treatment model (III). For each part, key equations will be presented. Figure 1 presents a simplified flowchart of the model.

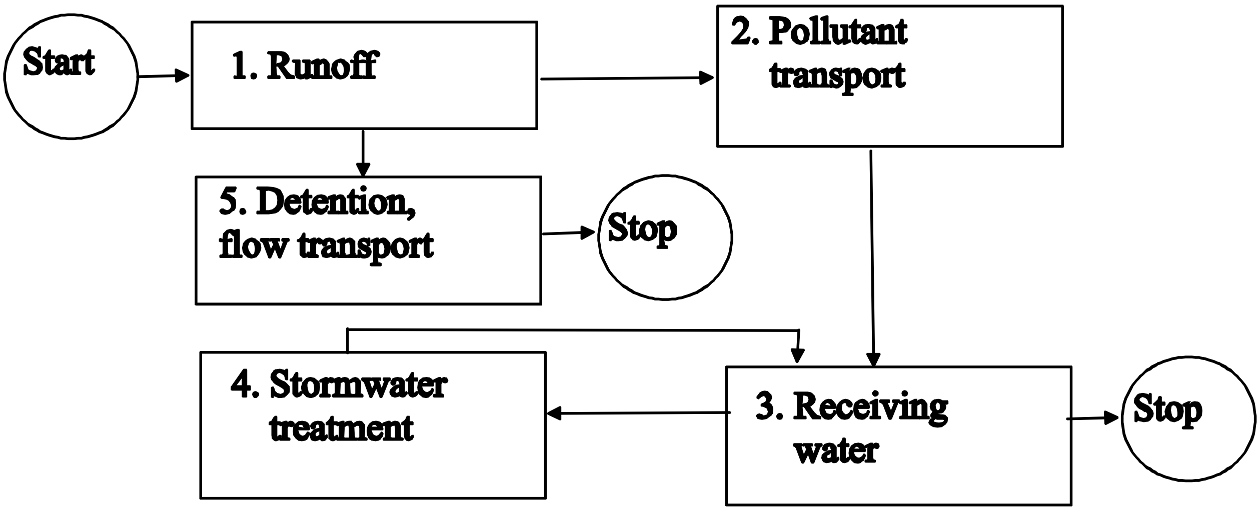

Figure 1. Simplified flowchart of the model StormTac.

For calculating yearly pollutant loads to the receiving waters, land use specific standard values are employed. They are based on long-term flow proportional data and may be calibrated to better reflect site-specific conditions in the studied watershed. The external pollutant loads (kg/year) on the recipient from urban and rural runoff (storm water and base flow), atmospheric deposition on the recipient and groundwater are calculated according to Larm (2000). The recipient model may be used to calculate the acceptable pollutant load (kg/year) for goal concentrations in the water body and to calculate required reduction of pollutant loads (Larm, 2003). Mean values of measured pollutant concentration in the water mass of the receiving water are preferred for more reliable estimations. However, concentrations are also calculated by different models for comparison to measured data and the calculated values are used in lack of such data. Furthermore, the need of reduced load to reach the desired water quality criteria is calculated. An example of such a criteria is to decrease the phosphorus concentration to decrease algal blooms. Several design methods are applied in the model and these have been used and evaluated in Swedish projects and case studies. This paper presents one selected method for planning-level design of wet ponds and another for detailed design of the permanent and detention volumes in these ponds. The equation for calculating the corresponding reduced pollutant concentrations in the receiving water is also presented. Three methods of sensitivity and uncertainty analysis (Monte Carlo simulation) were applied to StormTac's sub models for runoff, pollutant transport and recipient for a Swedish case study area (Stenvall, 2004).

1.1 Water fluxes

$$Q_{in} = Q + Q_b + Q_a + Q_{point} \tag{01}$$

Q_{in}	total inflow [m^3/year]
Q	runoff water flow [m^3/year]
Q_b	base flow/ground water flow to the recipient [m^3/year]
Q_a	atmospheric deposition on the recipient [m^3/year]
Q_{point}	point flow to the recipient other than from stormwater and base flow/ground water flow [m^3/year]

The runoff water flow Q is calculated in Eq. (2) (Larm, 2000).

$$Q = 10p\sum_{i=1}^{N}(\varphi_i A_i) \tag{2}$$

p	corrected precipitation intensity data (rain+snow) [mm/year]
φ	runoff coefficient
i	land uses, $i = 1,2,\ldots N$
A	land use area [ha]

$$Q_b = 10pK_x\sum_{i=1}^{N}(K_{\inf,i} A_i) \tag{03}$$

K_x	share of K_{inf} that reaches the base flow
K_{inf}	fraction of the yearly precipitation that is infiltrated

$$K_{\inf} = \frac{p - (p\varphi) - E}{p} \tag{04}$$

E	potential evapotranspiration intensity [mm/year]

Equations (05) - (08) are preliminary and are to be changed. For instance, E cannot be a function of only φ.

If $\varphi \leq 0.90$:

$$E = 1000(0.50 - 0.55\varphi) \tag{05}$$

If $\varphi > 0.90$:

$$E=0 \tag{06}$$

The equations above are assumed for all land uses except for forests and recipients/lakes for which the following are assumed E_{forest} and E_{rec}:

$$E_{forest} = 445 \text{ (input data)} \tag{07}$$

E_{forest}	potential evapotranspiration intensity for forests [mm/year]

E_{rec} = 590 (input data) (08)

E_{rec} potential evapotranspiration intensity for a surface water body [mm/year]

$$Q_a = 10pA_{rec} \tag{09}$$

A_{rec} mean water area of the recipient [ha]

$$Q_E = 10E_{rec}A_{rec} \tag{010}$$

Q_E evapotranspiration flow from the surface water body [m^3/year]

The outflow from the recipient is calculated in Eq. (11):

$$Q_{out} = Q_{in} - Q_E \tag{11}$$

Q_{out} total outflow [m^3/year]

1.2 Mass fluxes

The external pollutant loads (kg/year) on the recipient from urban and rural runoff (stormwater and base flow), atmospheric deposition on the recipient and groundwater are calculated from, e.g., land use specific standard runoff coefficients, areas (ha) and standard concentrations (mg/l or µg/l), precipitation intensity (mm/year) and evapotranspiration intensity (mm/year) according to Larm (2000). The corresponding loads are presented in Eq. (12) and the processes in Fig. 1.

$$L_{in} = L + L_b + L_a + L_{po\,\mathrm{int}} + L_{rel} \tag{12}$$

L_{in}	total pollutant inflow load [kg/year]
L	stormwater pollutant load [kg/year]
L_b	base flow/groundwater pollutant load [kg/year]
L_a	atmospheric deposition [kg/year]
L_{point}	point pollutant load to the recipient from other sources than stormwater and base flow/ground water [kg/year]
L_{rel}	internal pollutant load from the sediments to the water of the recipient [kg/year]

All loads included in Eq. (12) play an important role for the calculation of the acceptable loads on the recipient. However, the focus of this paper is to present the specific equations for calculating acceptable loads on the recipient, the resulting sediment/internal loads and the required reduction of external loads.

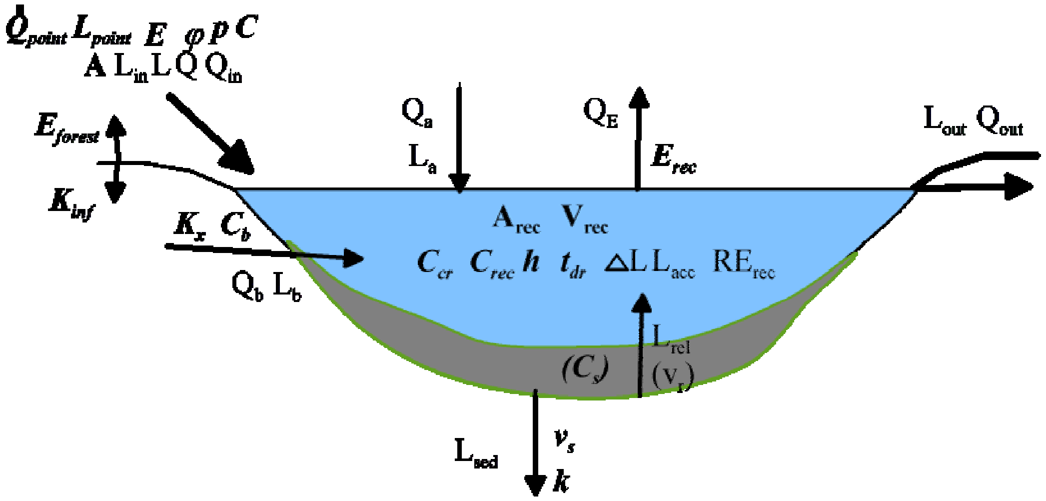

Figure 2. Processes and parameters in the recipient model in the stormwater management model StormTac. **Bold**: obligatory input data, where: A=watershed area per land use [ha], V_{rec}=recipient volume [m^3] and A_{rec}=recipient area [ha]. Cursive: other input data. Normal: output data. The parameters within (parenthesis) are to be used for comparative calculations in a future model version.

In Eq. (13) the storm water pollutant load L_j is calculated (Larm, 2000).

$$L_j = \frac{\sum_{i=1}^{N}(Q_i C_{ij})}{1000} \qquad (13)$$

C standard concentration for stormwater [mg/l]
j pollutant

If measured storm water pollutant concentrations, C_j*, exist, they can be used instead of $\Sigma C_{i,j}$ (Larm, 2000):

$$L_{b,j} = \frac{C^*_{b,j}\sum_{i=1}^{N} Q_{b,i}}{1000} \qquad (014)$$

C_b * measured base flow pollutant concentration [mg/l]

If not the measured base flow pollutant concentration, $C_{b,j}$*, exists, an empirical value from a data base, $\Sigma C_{b,i,j}$, is used.

$$L_a = \frac{Q_a C_a}{1000} = \frac{10 p A_{rec} C_a}{1000} \qquad (015)$$

C_a concentration in atmospheric deposition [mg/l]

1.3 Recipient processes

1.3.1 Mass fluxes to/from the sediments

The sediment load is calculated as:

$$L_{sed} = L_{in} - L_{out} \tag{16}$$

L_{out} total outflow pollutant load [kg/year]
L_{sed} pollutant load to the sediments of the recipient from its water mass [kg/year]

For those substances for which there exist measured concentrations in the water, Eq. (17) is used to calculate mass fluxes from the recipient:

$$L_{out} = \frac{Q_{out} C^{*}{}_{rec}}{1000} \tag{17}$$

C_{rec}* measured pollutant concentration in the water mass of the recipient [mg/l]

For those substances for which there are no measured concentrations, calculated C_{rec} replaces $C^{*}{}_{rec}$. C_{rec} is calculated from Eq. (28), using empirical output data from the 7 case studies. For nitrogen (N) L_{sed} includes loss of nitrogen through denitrification from the water surface to the atmosphere. The share of denitrification loss has been estimated to 12-25% of Lin in Vallentunasjön, 5-11% of L_{in} in Norrviken (Ahlgren et al, 1994) and in average 33% of Lin in Danish lakes, according to Jensen J.P. et al, 1990 (Ahlgren et al, 1994). For other substances, the loss to the atmosphere is neglected or is included in L_{sed}.

Eq. (18) is used for comparison to the results of Eq. (16):

$$L_{sed} = \frac{C^{*}_{rec} k\, V_{rec}}{1000} \tag{18}$$

k sedimentation coefficient [1/year]
V_{rec} water volume of the recipient [m^3]

The sedimentation coefficient k_j is calculated in Eq. (19) (Larm, 2003) and is derived from Eq. (26), assuming $C_{cr}=C^{*}{}_{rec}$ and $L_{acc}=L_{in}$. The last term Q_{out}/V_{rec} expresses the “flushing rate”.

$$k_j = \frac{1000 L_{in}}{C^{*}_{rec} V_{rec}} - \frac{Q_{out}}{V_{rec}} \tag{19}$$

For comparison $k_P=t_{dr}^{-0.5}$ (Vollenweider, 1976). If instead k_j had been calculated from the sink velocity (m/year) divided by the recipient mean water depth (m), the residence time would have been neglected. k can also be calculated from Eq. (20) if v_s is known:

$$k = \frac{v_s}{h} \tag{20}$$

v_s sink velocity [m/year]
h recipient mean water depth [m]

From the application of Eq.(19) on the 7 case studies we have estimated values on k for different pollutants, see Fig. 5. These values will be updated to new case studies and the 7 case studies, included in this paper, if being revised.

1.3.2 Acceptable load

The acceptable (critical) load is calculated in Eq. (21), derived from the OECD Management model (Vollenweider and Kerekes, 1982).

$$L_{acc} = \frac{V_{rec}\left(\frac{C_{cr}}{x_j}\right)^{1/y_j}(1+t_{dr}{}^{0.5})}{1000t_{dr}} \qquad (21)$$

If C^*_{rec} is known and we use k_j from Eq. (19) in Eq. (26), Eq. (22) (Larm, 2003) is derived, which under this assumption provides the same results as Eq. (26).

$$L_{acc} = \frac{C_{cr}L_{in}}{C^*_{rec}} \qquad (22)$$

In cases where upstream lakes exist, the input to the downstream lake is calculated as "load to lake=monitored upstream lake concentration+calculated upstream lake volume output+load for those subwatersheds between the upstream lake outlet and the modeled lake" (MCWD H/H and Pollutant Loading Study, 2003).

1.3.3 Required reduction

The required reduction for meeting the recipient water quality criteria is calculated in Eq. (23):

$$^{\Delta}L = L_{in} - L_{acc} \qquad (23)$$

$^{\Delta}L$ pollutant load to be reduced to reach the acceptable load L_{acc} [kg/year]

1.3.4 Retention (reduction) in the recipient

For those pollutants for which there are measured concentrations in the water mass of the recipient, we have:

$$RE_{rec} = 100 - \frac{C_{rec}{}^{*}Q_{out}}{10L_{in}} \qquad (24)$$

RE_{rec} pollutant reduction efficiency in the recipient [%] (e.g. sedimentation and plant uptake)

For case studies for which there are no measured concentrations, $C_{rec}*$ in Eq. (24) is replaced with calculated C_{rec}, see Eq. (28).

1.4 Calculated pollutant concentration in the water mass of the recipient

It has been found that nutrient concentrations in a cross-section of lakes are a simple function of annual nutrient loading, lake mean depth and water residence times. Basically, all lake models include these components (MCWD H/H and Pollutant Loading Study, 2003). The pollutant concentration in the water mass of the recipient is calculated in consideration to the recipient residence time with the OECD Management model (Vollenweider and Kerekes, 1982), as formulated in Eq. (25):

$$C_{rec} = x_j \left(\frac{C_{in}}{1+\sqrt{t_{dr}}}\right)^{y_j} = x_j \left(\frac{1000 L_{in}}{Q_{in}(1+\sqrt{t_{dr}})}\right)^{y_j} \qquad (25)$$

C_{rec} calculated pollutant concentration in the water mass of the recipient [mg/l]
C_{in} pollutant concentration in inflow water [mg/l]
Q_{in} total inflow [m^3/year]
t_{dr} recipient residence time [year], $t_{dr}=V_{rec}/Q_{out}$
x_j, y_j coefficients for pollutant j

Different values of the coefficients x_j and y_j are used in StormTac, see Table 1, resulting in a range of calculated recipient concentrations.

Table 1. Coefficient values of x_j and y_j for Eq. (25) from Vollenweider and Kerekes (1982). These values and the sedimentation coefficient k_j for Eq. (28) for 7 studied lakes in the Stockholm region (StormTac, version 2005-01). The latter include metals, are uncertain and are soon to be complemented with 14 lakes, presenting R^2-values.

	P	N	Pb	Cu	Zn	Cd	Cr	Ni
Combined OECD data, x_j	1.55	5.34						
Combined OECD data, y_j	0.82	0.78						
Lakes with internal loading, x_j	1.22	3.25						
Lakes with internal loading, y_j	0.87	0.85						
Shallow lakes and reservoirs, x_j	1.02							
Shallow lakes and reservoirs, y_j	0.88							
Baltic and North Sea areas, x_j	1.12							
Baltic and North Sea areas, y_j	0.92							
Stockholm region, x_j	1.47	4.80	1E-04	0.0037	0.0003	5E-05	0.0006	0.25
Stockholm region, y_j	0.95	0.40	-0.27	0.30	-0.59	0.29	0.17	1.29
Stockholm region, kj	0.022	0.23	22	7.4	13	5.2	0.95	0.40

The predicted lake concentration after reduction in the facility is estimated by subtracting L_{in} in Eq. (25) and/or Eq. (28) with $L_{in,BMP}RE_{BMP}/100$, where $L_{in,BMP}$ is the pollutant load in to the BMP (kg/year) and RE_{BMP} is the pollutant reduction efficiency in a BMP (%).

1.5 Comparative models for acceptable loads and lake concentrations

The following equations are presented and included in StormTac for comparison of results from the earlier presented main equations of StormTac.

The acceptable (critical) load is as comparison calculated from Eq. (26), Vollenweider's equation from 1969, as formulated in Larm (2003), assuming $Q_{out}=Q_{in}$, $C_{rec}=C_{cr}$ and $L_{in}=L_{acc}$:

$$L_{acc} = \frac{C_{cr}(Q_{out} + kV_{rec})}{1000} \qquad (26)$$

L_{acc} acceptable (critical) pollutant load to the recipient [kg/year]
C_{cr} critical pollutant concentration in the water mass of the recipient for negative effects [mg/l]

Eq. (26) has the advantage of including k which makes it possible to calculate k in an alternative way than from Eq. (19). For those substances for which there are no measured recipient concentrations, Eq. (26) is used, with k according to Fig. 4 or Eq.(19). In StormTac it is possible to choose an optional C_{cr}-value. The chosen value depends on the corresponding biological or eutrophical effects and reasonable load reduction goals.

In opposite to the main equations, the comparative equations (27), (29) and (25) are only to be applied for phosphorus calculations. One equation for comparisons to the results of Eq. (26) and (22) is Eq. (27) by Vollenweider (1976):

$$L_{acc} = \frac{V_{rec} C_{cr} (1 + t_{dr}^{0.5})}{1000 t_{dr}} \tag{27}$$

t_{dr} recipient residence time [year], $t_{dr}=V_{rec}/Q_{out}$

In StormTac, the resulted recipient concentrations from Eq. (25) are evaluated and compared to results from calculations with Eq. (28) from Vollenweider, 1969 (Vollenweider, 1976), as formulated in Larm (2003):

$$C_{rec} = \frac{1000 L_{in}}{(Q_{out} + 10000 v_s A_{rec})} = \frac{1000 L_{in}}{(Q_{out} + 10000 k_j h A_{rec})} = \frac{1000 L_{in}}{(Q_{out} + k_j V_{rec})} \tag{28}$$

Q_{out} total outflow [m^3/year]
v_s sink velocity [m/year], $v_s=k_jh$ if no data of v_s. k is calculated from Eq. (19).
A_{rec} mean water area of the recipient [ha]
k_j sedimentation coefficient for pollutant j [1/year]
h recipient mean water depth [m]
V_{rec} water volume of the recipient [m^3]

Eq. (28) employs a median value of k_j from case studies, se Table 1. k_j is calculated from Eq. (19). Equation (27) excludes a specific term for net sedimentation load or internal load else than that the sediment part may be empirically included in the term (1+tdr0.5)/t_{dr}.

If no value of v_s is available, v_s is calculated from Eq.(20), in which $k=t_{dr}$-0.5 (Vollenweider, 1976). Then the same results are obtained as by Vollenweider's equation from 1976:

$$C_{rec} = \frac{1000 L_{in}}{Q_{out}(1 + \sqrt{t_{dr}})} \tag{29}$$

The empirical models by Vollenweider and OECD are based on data from a large number of lakes in Europe and North America.

1.6 Design of stormwater treatment facilities

1.6.1 Wet ponds

Method 1: Planning-level design; share-area

The permanent pool water area is designed as a certain share of the reduced watershed area (reduced area = area x runoff coefficient), expressed by the constant $K_{A\varphi}$., see Eq. (30) (Larm, 2000). Generally for constructed Swedish wet ponds $K_{A\varphi}$ is around 150 (70-300), depending on available place on site and chosen design method. Empirical studies including estimated reduction efficiencies show that there prevails a function that may be used with relatively good fit between the reduction efficiency and $K_{A\varphi}$ and that ponds can be designed for a $K_{A\varphi}$-value depending on desired reduction efficiency.

$$A_p = \varphi A K_{A\varphi} \tag{30}$$

A_p permanent facility water area [m^2]
$K_{A\varphi}$ constant dependent on the desired reduction efficiency

Method 2: Detailed design; reduction efficiency

One of the more detailed design methods in StormTac for designing wet ponds is an empirical method based on desired reduction efficiency as a function of the relation between permanent pool volume (V_p) and runoff volume (V_r). P and SS are the substances for which there are most data available. For suspended solids (SS) empirically we have (StormTac, version 2005-01):

$$V_p = \mathrm{V_r} 0.178\mathrm{e}^{0.0395\mathrm{RE_{BMP}}} \tag{31}$$

V_p permanent water volume in a BMP [m^3]
V_r water volume of runoff at an average runoff event [m^3]

For phosphorus (P) empirically we have (StormTac, version 2005-01):

$$V_p = \mathrm{V_r} 0.231\mathrm{e}^{0.0509\mathrm{RE_{BMP}}} \tag{32}$$

The largest V_p from Eq. (31) and (32) is chosen. The two equations are to be changed with complementary data from added case studies. One or two detention volumes may be designed. The first detention volume (V_{d1}) is designed for an emptying time (t_{out}) of 12-24 hours, i.e. the outflow $Q_{out,1}$ is chosen/designed to get a suitable emptying time. The corresponding detention depth (h_{r1}) is also to be checked, not to risk upstream floods. The yearly average rain depth (r_{da}) is used (WEF and ASCE, 1998), as formulated in Larm, (2000):

$$V_{d1} = 10\varphi A r_{da} \tag{33}$$

V_{d1} first detention volume in a BMP [m^3], first volume above the permanent volume
A watershed area [ha]
r_{da} yearly mean precipitation depth [mm]

The emptying time is calculated in Eq. (34) (Larm, 2000).

$$t_{out} = \frac{V_{d1}}{3.6 Q_{out1}} \tag{34}$$

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

The second detention volume (V_{d2}) is designed for a chosen rain return time in respect of flood risks, e.g. 1-year, 2-year, 5-year, 10-year or 100-year return time. The maximum V_{d2} is chosen, testing different rain durations (t_r), assumed equal to the maximum transport time, and different outflows ($Q_{out,2}$). This is an iterative process which may be automatically processed in Excel models, such as in StormTac.

$$V_{d2} = \frac{\max(60 t_r (Q_{\dim} - Q_{out,2}))}{1000} \tag{35}$$

V_{d2} second detention volume [m^3]
t_r rain duration [min]
Q_{dim} design inflow to facility [l/s]
$Q_{out,2}$ Outflow for the second detention volume in a BMP [l/s]

The design inflow to the facility is calculated in Eq. (36). Different specific runoff coefficients (φ_s) for different areas are considered (Larm, 2000).

$$Q_{\dim} = i \varphi_s A_s \tag{36}$$

i rain intensity for chosen return time [l/s/ha]
φ_s specific runoff coefficient for A_s
A_s specific watershed area that contributes to runoff during the design rain duration [ha]

The total detention volume V_d is calculated:

$$V_d = V_{d1} + V_{d2} \tag{37}$$

V_d total detention volume [m^3]

The corresponding detention depth (h_{r2}) must also be checked so as not to risk upstream floods. The total detention depth (h_r) is to be considered in the iterative calculations.

$$h_r = h_{r1} + h_{r2} \tag{38}$$

h_r total detention depth [m]
h_{r1} maximal water depth for the first detention volume in a pond [m]
h_{r2} maximal water depth for the second detention volume in a pond [m]

Approximately, we can calculate hr such as:

$$h_r = \frac{V_d}{A_p} \tag{39}$$

A_p permanent volume of a STF [m^3]

Method 3: Runoff depth

In Method 3, the detention volume (V_d) and the permanent pool volume (V_p) are designed for a desired rain depth multiplied with the runoff coefficient (i.e. Runoff depth). N_d is a constant dependent on the desired reduction efficiency. Generally N_d is between 1and 3.

$$V_d = 10\varphi A r_d \tag{40}$$

r_d rain depth [mm]

$$V_p = N_d V_d \tag{41}$$

N_d constant dependent on the desired reduction efficiency

$$V = V_p + V_d \tag{42}$$

Method 4: Surface load
In Method 4, the permanent pool area is designed as a function of a design flow and a design sink velocity of particles. The method is not recommended in every case, but can be used in cased when the flow does not fluctuate so much, e.g. when pumping (or leading by gravity) a partial flow to the pond.

$$A_p = \frac{3.6Q_{\dim}}{v_p} \tag{43}$$

vp design sink velocity of particles (m/h)

2. Conclusions

Preliminary verification of model results to measured data of the case studies and of specific data (e.g. lake concentrations) to other models and literature values show that the model can be used when the objective is to estimate yearly and acceptable pollutant loads on receiving waters. It can also be employed to estimate loads to/from the sediments of the recipient and the required reduction and dimensions of stormwater treatment facilities to reduce the pollutant lake concentrations from one value to another. In this aspect StormTac with its sub models is a user-friendly planning level model to select treatment measures that consider the specific recipient conditions/goals (Larm, 2003).

The advantage of StormTac is that it is a watershed management tool calibrated to other substances than phosphorus, i.e. the model is used to predict acceptable loads and concentrations also of e.g. nitrogen and different metals in Swedish lakes.

The presented model and equations assume steady state conditions on an annual basis, bearing in mind that there are considerable year-to-year load variations. Local conditions may deviate considerable, both temporally and spationally. Predictions of the uncertainties are to be performed in the near future. However, in spite of the uncertainties involved, the estimates are probably accurate enough for planning and management purposes. The employed methodology has the capability to study the relevance and importance of the measures to the recipient effects and conditions. The recipient model in StormTac is continuously being updated with revised and new equations and parameter values see http://www.stormtac.com/.

The aim with the model calculations is not to calculate exact numbers of loads, reduction efficiencies of BMPs and recipient effects. The objective is to provide the user with a tool that considers and uses the usually sparse amount of data for the choice of a cost-effective measure. This measure is to be located on a site that is large enough to contain it and in which a large enough quantity of pollutants may be treated in consideration to preset goals for the recipient. The advantage is that the model considers acceptable recipient loads and desired changed recipient pollutant concentrations rather than employing limit storm water concentration values or the identified watershed land uses as basis for storm water abatement strategies. The model is continuously being updated with equations, parameters and data. After discussions, continued literary studies and reviews to come, it is easy to change equations and add data in order to decrease the uncertainty and to consider trends in changed concentrations. The largest contribution of the tool is the model flowchart and how the boxes and sub models are linked. Key findings from the study concern required input data for designing BMPs with consideration to water quality criteria, which may be compared with similar models:

Obligatory input data:

A	area per land use [ha]
V_{rec}	water volume of the recipient [m^3]
A_{rec}	mean water area of the recipient [ha]

Other important input data for which default data may be used:

p	corrected precipitation intensity data (rain + snow) [mm/year]
φ	runoff coefficient
C	land use specific standard concentration for storm water [mg/l]
C^*_{rec}	measured pollutant concentration in the water mass of the recipient [mg/l]
C_{cr}	critical pollutant concentration in the recipient water mass for negative effects [mg/l]
ADT	average daily traffic intensity [vehicles/day]

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Appendix 1 List of parameters

Notation	Description	Unit	Comments
φ	Runoff coefficient		
φ_s	Specific runoff coefficient for A_s		
A	Land use area, watershed area	ha	1 ha=10 000 m^2
A_p	Permanent volume of a STF	m^3	
A_{rec}	Mean water area of the recipient	ha	
A_s	Specific watershed area that contributes to runoff during the design rain duration	ha	
C	Standard concentration for stormwater	mg/l	
C^*	Measured stormwater pollutant concentration		
C_a	Concentration in atmospheric deposition	mg/l	
C_b	Empirical base flow/ground water pollutant concentration	mg/l	
C_b*	Measured base flow pollutant concentration	mg/l	
C_{cr}	Critical pollutant concentration in the water mass of the recipient for negative effects	mg/l	
C_{in}	Pollutant concentration in inflow	mg/l	
C_{rec}	Calculated pollutant concentration in the water mass of the recipient	mg/l	
C_{rec}*	Measured pollutant concentration in the water mass of the recipient	mg/l	
E	(Potential) evapotranspiration intensity	mm/year	
E_{forest}	(Potential) evapotranspiration intensity for forests	mm/year	
E_{rec}	(Potential) evapotranspiration intensity for a surface water body	mm/year	
h	Recipient mean water depth	m	
h_r	Total detention depth	m	
h_{r1}	Maximal water depth for the first detention volume in a pond	m	
h_{r2}	Maximal water depth for the second detention volume in a pond	m	
i	Rain intensity for chosen return time	l/s/ha	
i	Land use		
j	Pollutant		
k	Sedimentation coefficient	1/year	
$K_{A\varphi}$	Constant dependent on desired reduction efficiency		
K_{inf}	Fraction of the yearly precipitation that is infiltrated		
K_x	Share of K_{inf} that reaches the base flow		
$^{\Delta}L$	Pollutant load to be reduced to reach the acceptable load L_{acc}	kg/year	
L	Stormwater pollutant load	kg/year	
L_a	Atmospheric deposition	kg/year	

L_{acc}	Acceptable (critical) pollutant load to the recipient	kg/year	
L_b	Base flow/ground water pollutant load to the recipient	kg/year	
L_{in}	Total pollutant inflow load	kg/year	
L_{inSTF}	Inflow load to a Stormwater Treatment Facility (STF)	kg/year	
L_{out}	Total outflow pollutant load	kg/year	
L_{point}	Point pollutant load to the recipient from other sources than stormwater and base flow/ground water	kg/year	
L_{rel}	Internal pollutant load from the sediments to the water of the recipient	kg/year	
L_{sed}	Pollutant load to the sediments of the recipient from its water mass	kg/year	
N_d	Constant dependent on desired reduction efficiency		
p	Precipitation intensity data (rain+snow) corrected for systematic errors	mm/year	636 (400-900) mm/year for Stockholm p=precipitation
Q	Runoff water flow	m^3/year	
Q_a	Atmospheric deposition on the recipient	m^3/year	
Q_b	Base flow/ground water flow to the recipient	m^3/year	
Q_{dim}	Design inflow to facility	l/s	
Q_E	Evapotranspiration flow from a surface water body	m^3/year	
Q_{in}	Total inflow	m^3/year	
Q_{out}	Total outflow	m^3/year	
$Q_{out,1}$	Outflow for the first detention volume in a STF	l/s	
$Q_{out,2}$	Outflow for the second detention volume in a STF	l/s	
Q_{point}	Point flow to the recipient other than from stormwater and base flow/ground water flow	m^3/year	
r_d	Rain depth	mm	
r_{da}	Yearly average precipitation depth	mm	3-8 mm in Stockholm. New rain when time between rain events >6 h. Only rain>1.0 mm (0.5-2.5 mm) contributes to runoff
RE_{rec}	Pollutant reduction efficiency in the recipient	%	
RE_{STF}	Pollutant reduction efficiency in the Stormwater Treatment Facility	%	
STF	Stormwater Treatment Facility		
t_{dr}	Recipient residence time, $t_{dr}=V_{rec}/Q_{out}$	year	
t_{out}	Emptying time, time for water to flow out from a STF	h	12-24 (6-48) h
t_r	Rain duration	min	
v_p	Sink velocity of particles	m/h	0.15 (0.04-0.25)

v_s	Sink velocity	m/year	
V_{d1}	First detention volume (maximal level-level of permanent surface of water) in the facility	m^3	d=detention
V_{d2}	Second detention volume (maximal level-level of permanent surface of water) in the facility	m^3	d=detention
V_p	Permanent volume in the facility	m^3	
V_r	Water volume of runoff at an average runoff event	m^3	
V_{rec}	Water volume of the recipient	m^3	