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

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## Abstract

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 recently developed recipient sub model, in 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. This paper presents the main equations of the recipient model including similar models from literature studies. Specific model results, especially for phosphorus (P), from 7 Swedish lake recipients/watersheds within the Stockholm region are presented. 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

acceptable, load, stormwater, treatment, watershed, lake

## Introduction

The watershed management model StormTac is focused on stormwater transport and the design of stormwater treatment facilities and these parts have been reviewed internationally (Larm, 2000). 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 paper is to present the recipient model in StormTac and the included main equations. The model 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 in this paper.

## Methods

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. (1) and the processes in Fig. 1.

$$L_{in} = L + L_b + L_a + L_{point} + L_{rel} \qquad (1)$$

$L_{in}$ total pollutant load on the recipient from stormwater, ground water, atmospheric deposition on the recipient, the sediments of the recipient and other pollutant sources, e.g. point loads from upstream recipients [kg/year]
$L$ stormwater pollutant load [kg/year]
$L_b$ base flow/groundwater pollutant load on the recipient [kg/year]
$L_a$ atmospheric deposition [kg/year]
$L_{point}$ point pollutant load on the recipient from other sources than stormwater and base flow/ground water [kg/year]
$L_{rel}$ internal load from the sediments to the water of the recipient [kg/year]

All loads included in Eq. (1) 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.

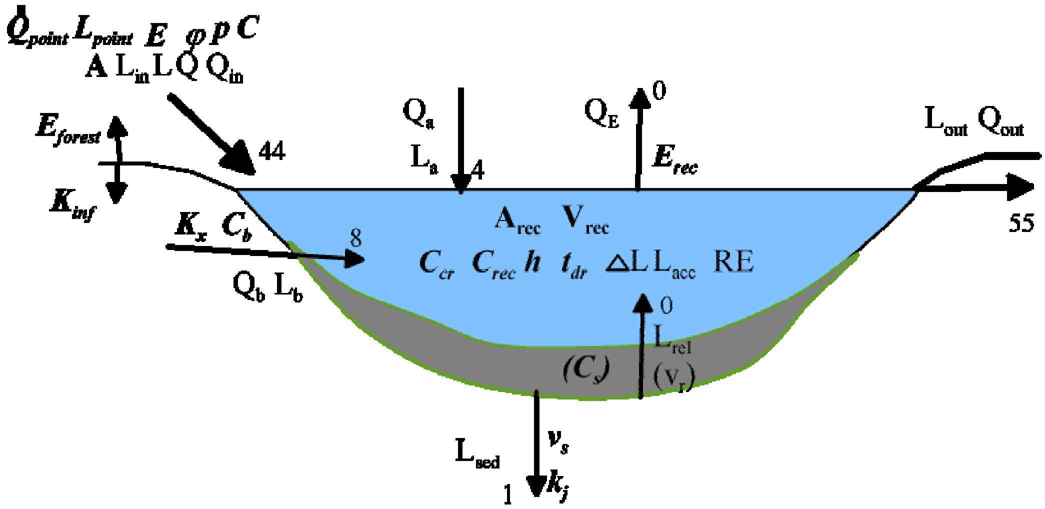


Figure 1 Processes and parameters in the recipient model in the stormwater management model StormTac. **Bold**: obligatory input data, where: A=watershed area per land use [ha], $V_{rec}$=recipient volume [$m^3$] and $A_{rec}$=recipient area [ha]. *Cursive*: other input data. Normal: output data. The parameters within (parenthesis) are to be used for comparative calculations in a future model version.

***Water fluxes****:* The outflow from the recipient is calculated in Eq. (2):

$$Q_{out} = Q_{in} - Q_E \tag{2}$$

$Q_{out}$ total outflow from the recipient [$m^3$/year]
$Q_{in}$ total inflow to the recipient [$m^3$/year]
$Q_E$ evapotranspiration flow from the recipient [$m^3$/year]

***Mass fluxes to/from the sediments****:* The sediment load is calculated as:

$$L_{sed} = L_{in} - L_{out} \tag{3}$$

$L_{sed}$ 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. (4) is used to calculate mass fluxes from the recipient:

$$L_{out} = \frac{Q_{out} C^*{}_{rec}}{1000} \tag{4}$$

$L_{out}$ total outflow pollutant load from the recipient [kg/year]
$C_{rec}$ pollutant concentration in the water mass of the recipient [mg/l]
* measured

For those substances for which there are no measured concentrations, calculated $C_{rec}$ replaces $C^*_{rec.}$ $C_{rec}$ is calculated from Eq. (12), 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 $L_{in}$ in Vallentunasjön, 5-11% of $L_{in}$ in Norrviken (Ahlgren et al, 1994) and in average 33% of $L_{in}$ 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. (5) is used for comparison to the results of Eq. (3):

$$L_{sed} = \frac{C^*_{rec} k_j V_{rec}}{1000} \tag{5}$$

$k_j$ sedimentation coefficient for pollutant j [1/year]
$V_{rec}$ water volume of the recipient [$m^3$]

The sedimentation coefficient $k_j$ is calculated in Eq. (6) and is derived from Eq. (8) assuming $C_{cr}=C^*_{rec}$ and $L_{acc}=L_{in}$:

$$k_j = \frac{1000 L_{in}}{C^*_{rec} V_{rec}} - \frac{Q_{out}}{V_{rec}} \tag{6}$$

$k_j$ can also be calculated from Eq. (7) if $v_s$ is known:

$$k_j = \frac{v_s}{h} \qquad (7)$$

$v_s$ sink velocity for a specific pollutant [m/year]
h recipient mean water depth [m]

From the application of Eq. (6) on the 7 case studies we have estimated values on $k_j$ for different pollutants, see Fig. 4. These values will be updated to new case studies and the 7 case studies, included in this paper, if being revised.

***Acceptable load**:* The acceptable (critical) load is principally calculated from Eq. (8) which is derived from Vollenweider's Eq. (15) from 1969 if we assume $C_{rec}=C_{cr}$, $L_{in}=L_{acc}$ and $v_s=k_jh$.

$$L_{acc} = \frac{C_{cr}(Q_{out} + k_j V_{rec})}{1000} \qquad (8)$$

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

Eq. (8) has the advantage of including $k_j$ which makes it possible to calculate $k_j$ in an alternative way than from Eq. (6). For those substances for which there are no measured recipient concentrations, Eq. (8) is used, with $k_j$ according to Fig. 4 or Eq.(6). 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. If $C^*_{rec}$ is known and we use $k_j$ from Eq. (6) in Eq. (8) and assume $C_{cr}=C^*_{rec}$ and $L_{acc}=L_{in}$, Eq. (9) is derived, which provides the same results as Eq. (8).

$$L_{acc} = \frac{C_{cr} L_{in}}{C_{rec}^*} \qquad (9)$$

The simple "dilution" equation (Eq. (9)) is used when measured $C^*_{rec}$ are available.

***Required reduction**:* The required reduction for meeting the recipient water quality criteria is calculated in Eq. (10):

$$\Delta L = L_{in} - L_{acc} \qquad (10)$$

?L the mass load to be reduced to reach the acceptable load $L_{acc}$ [kg/year]

***Retention (reduction) in the recipient**:* For those pollutants for which there are measured concentrations in the water mass of the recipient, we have:

$$RE = 100 - \frac{C_{rec}^* Q_{out}}{10 L_{in}} \qquad (11)$$

RE retention (reduction efficency) in the recipient [%] (e.g. sedimentation and plant uptake)

For case studies for which there are no measured concentrations, $C^*_{rec}$ in Eq. (11) is replaced with calculated $C_{rec}$, see Eq. (12).

***Calculated pollutant concentration in the water mass of the recipient:***

$$C_{rec} = \frac{1000 L_{in}}{(Q_{out} + 10000 k_j h A_{rec})} \quad (12)$$

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

$k_j$ is calculated from Eq. (6). A median value of $k_j$ (Fig. 4) from the case studies is used in Eq. (12).

***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. In opposite to the main equations, the comparative equations (13), (14), (16) and (17) are only to be applied for phosphorus calculations. Two equations for comparisons to the results of Eq. (8) and (9) are Eq. (13) by Vollenweider (1976) and the OECD Management Model in Eq. (14) presented by Vollenweider and Kerekes (1982):

$$L_{acc} = \frac{V_{rec} C_{cr} (1 + t_{dr}^{0.5})}{1000 t_{dr}} \quad (13)$$

$$L_{acc} = \frac{V_{rec} \left(\frac{C_{cr}}{1.55}\right)^{1/0.82} (1 + t_{dr}^{0.5})}{1000 t_{dr}} \quad (14)$$

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

The equations (13) and (14) exclude a specific term for net sedimentation load or internal load else than that the sediment part may be empirically included in the term $(1+t_{dr}^{0.5})/t_{dr}$. For comparison of the result of Eq. (12), Vollenweider's equation from 1969 is used:

$$C_{rec} = \frac{1000 L_{in}}{(Q_{out} + 10000 v_s A_{rec})} \quad (15)$$

If no value of $v_s$ is available, $v_s$ is calculated from Eq. (7), in which $k_j=t_{dr}^{-0.5}$ (Vollenweider, 1976). Then the same results is obtained as by Vollenweider's equation from 1976:

$$C_{rec} = \frac{1000 L_{in}}{Q_{out} (1 + \sqrt{t_{dr}})} \quad (16)$$

Another widely used model is the OECD Management model (Vollenweider and Kerekes, 1982):

$$C_{rec} = 1.55\left(\frac{C_{in}}{1 + \sqrt{t_{dr}}}\right)^{0.82} = 1.55\left(\frac{1000 L_{in}}{Q_{in} (1 + \sqrt{t_{dr}})}\right)^{0.82} \quad (17)$$

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

***Case studies:*** The described models and equations have been applied on 7 more or less eutrophied lakes in the Stockholm region. For these case studies the following data have been collected: land use specific areas [ha], measured lake water concentrations [mg/l], measured concentrations in in-flows and outflows to/from the lakes [mg/l], mean lake water depth [m], lake area [ha] and lake volume [$m^3$]. In some case studies, the stormwater pollutant load has been reduced for sub water-sheds with existing treatment facilities (the wetland Nora Träsk and the stormwater tunnels Järva-tunneln and Sollentunatunneln next to Edsviken and the wetland Lillsjön next to Flaten). This paper presents the results mainly for phosphorus (P), even if many other substances have been calculated and to some extent presented here. P is in focus since it is of great importance for the conditions of the studied lakes. Furthermore, several literature reference methods presented are only valid for P and there exists more data of nutrients (P and N) than of metals in the lakes. $C_{cr}$ = 50 µg/l (P) is assumed for the case studies, corresponding to the upper limit for high concentrations and an eutrophic water (the goal is to reach "class 3" set by the Swedish Environmental and Protection Agency; "Naturvårdsverket", in 1999). Specific values for each lake should be studied more detailed in later stages depending on recipient goals and reasonable reductions that may be achieved for reasonable costs.

## Results and discussion

Figure 2-7 present selected results.

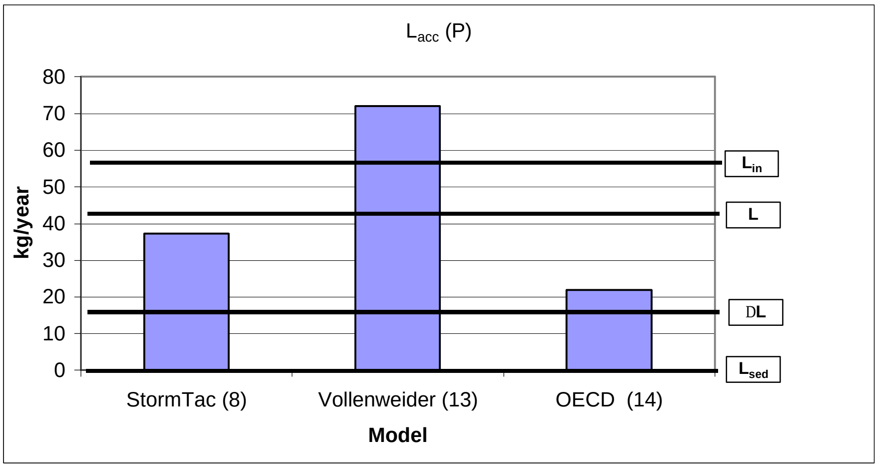


Figure 2 Acceptable P load (kg/year) for the case study Flaten and for the presented models. The total load ($L_{in}$), the stormwater load (L), the required load reduction (? L) and the sediment load ($L_{sed}$) are presented as horizontal lines. Equation numbers in parenthesis.

The acceptable load (Fig. 2) is specific for each individual recipient which is evident from the parameters included in Eq. (6), (8) and (9) (e.g. lake volume and measured pollutant concentrations). Since the acceptable loads are calculated from measured concentrations in StormTac, else if these are not available from empirically estimated data from nearby sites, the values are more site specific and probably more relevant compared to the other methods presented. An analysis of the calculated acceptable loads from different methods indicated that by using Vollenweider the acceptable P load were higher than for StormTac for the lakes with the highest P concentrations (ending with Flaten, see Fig. 2) and lower for the other lakes (except for Fysingen). The results from the OECD model indicate no such trend and are higher or lower for different lakes. Furthermore, typically exemplified by Figure 3, the results indicate that the model by Vollenweider (Eq. (16)) resulted in larger deviation from the measured P concentration values in 4 of 5 more eutrophic lakes studies compared to the results from StormTac.

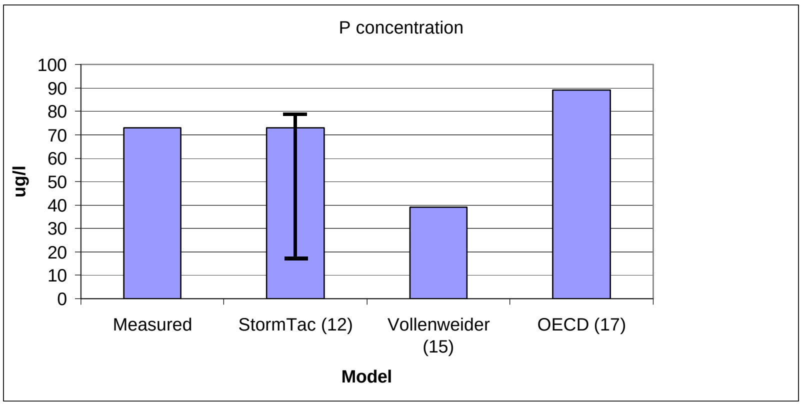


Figure 3 Measured compared to calculated P concentrations (µg/l) for the case study Flaten and for the presented models. Equation numbers in parenthesis.

However, Vollenweider did the better job of predicting the concentrations in the two less eutrophied lakes. StormTac generally resulted in higher predicted concentrations than Vollenweider but lower than the OECD model. The OECD model resulted in larger deviations than StormTac for 5 of the 7 case studies. Fig. 4 shows that there is a very good match between measured and with StormTac calculated P concentrations for the 4 more eutrophied lakes and that StormTac overestimated the concentrations for the less eutrophied lakes.

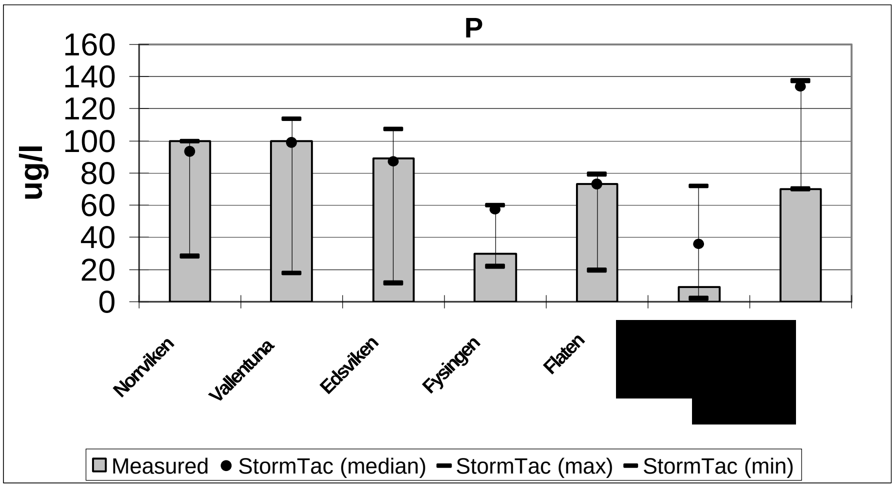


Figure 4 Measured ($C^*_{rec}$) and calculated ($C_{rec}$) lake P concentrations (µg/l). $C_{rec}$ is calculated according to Eq. (12). The "median", "max" and "min" concentrations have been calculated from the corresponding median, min- and maximum $k_j$-values in Fig. 5.

Other model results indicate that there prevails net sediment loads for each substance and each lake, with the following exceptions; P in Norrviken, Ni in Vallentuna and Cr and Ni in Fysingen. In the latter cases, there are probably negative sedimentation coefficients (see Fig. 5) and net internal loads from the sediments to the water mass of the lakes (as a yearly average situation). However, for metals there were too few measurements for drawing any conclusions whether the sediments act as sources or sinks. The agreement between calculated and measured concentrations were nevertheless approximately the same for nutrients and metals.

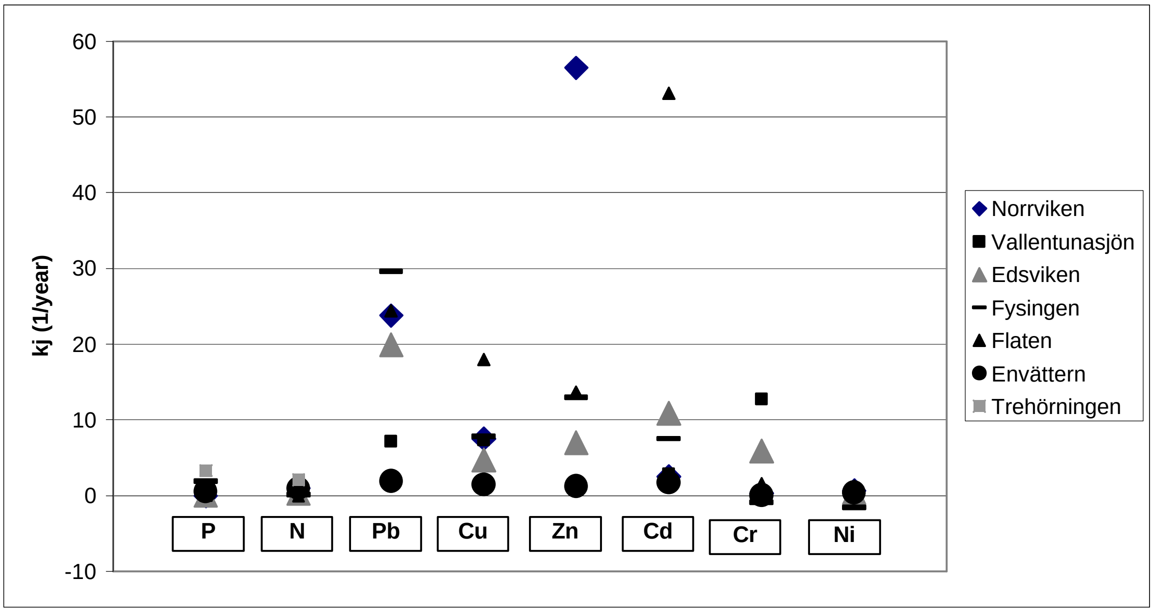


Figure 5 Calculated sedimentation coefficients ($k_j$) based on measured lake concentrations $C^*_{rec}$. $k_j$ is calculated according to Eq. (6)

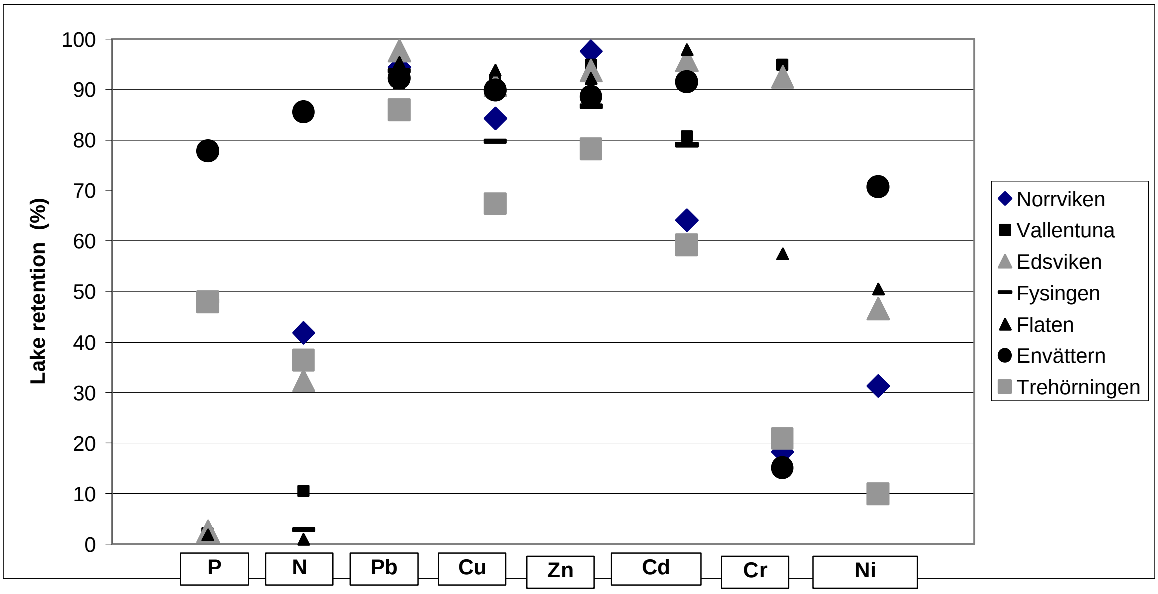


Figure 6 Calculated lake retention (%), according to Eq. (11). The following values are negative and not included in the diagram; P: Norrviken (-6%), Ni: Vallentuna (-59%) and Fysingen (-442%), Cr: Fysingen (-82%).

Figure 6 presents the calculated lake retention (%) for the different case studies and substances. Generally, the lakes result in a load reduction of 60-98% for the metals Pb, Zn, Cu and Cd. The nutrients P and N, and the metals Cr and Ni, show more varied results with a few negative values for some of the lakes (not for N). The negative values indicate a net internal load from the sediments. The required reduction need is estimated from the load that is higher than this acceptable load. If the load is higher than the acceptable load and the share of stormwater is large compared to e.g. atmospheric deposition and eventual net internal loads from the lake sediments, then a reduction of external loads on the recipient is recommended or considered. According to the main recipient model in StormTac, the pollutant loads to the studied lakes need to be reduced regarding P for all lakes, except for Fysingen and Envättern (the lakes with the lowest P concentrations), and regarding N (critical concentration 1.25 mg/l for reaching class 3) for the lakes Vallentunasjön, Fysingen and Flaten. No reduction for the same criteria class was required for the studied metals Pb, Cu, Zn, Cd, Cr and Ni. This is equivalent to that the concentrations were below the limit values resulting in increased risk for biological effects. The calculated need of load reduction is only valid to meet the specific water quality criteria studied. Calculations can be performed for other criteria, e.g. to reduce the lake concentration by, for instance, 20% which may be a more reasonable criteria in respect of cost-benefit. The selected criteria should be specific for the conditions of each specific recipient. In Flaten case study, Salem municipality has for example formed a goal to decrease the lake P concentration from a yearly average of 73 µg/l to 50 µg/l, i.e. a 30% decrease. 18 kg P/year need to be reduced and 3-4 stormwater treatment facilities are planned to reduce the load from stormwater and some of the base flow. A stormwater treatment facility is planned to be constructed in 2003 at the sub watershed Herrängsparken. It will probably consist of a wet pond followed by a filter strip. The designed pond area is 1260 $m^2$ (150-200 $m^2$/red ha; “red ha”=reduced hectares=runoff coefficient x area) and the permanent volume of the pond is 950 $m^3$ (1.9 times the average runoff volume of a yearly average rain event). The P load before reduction ($L_1$) was estimated to 9.4 kg/year.

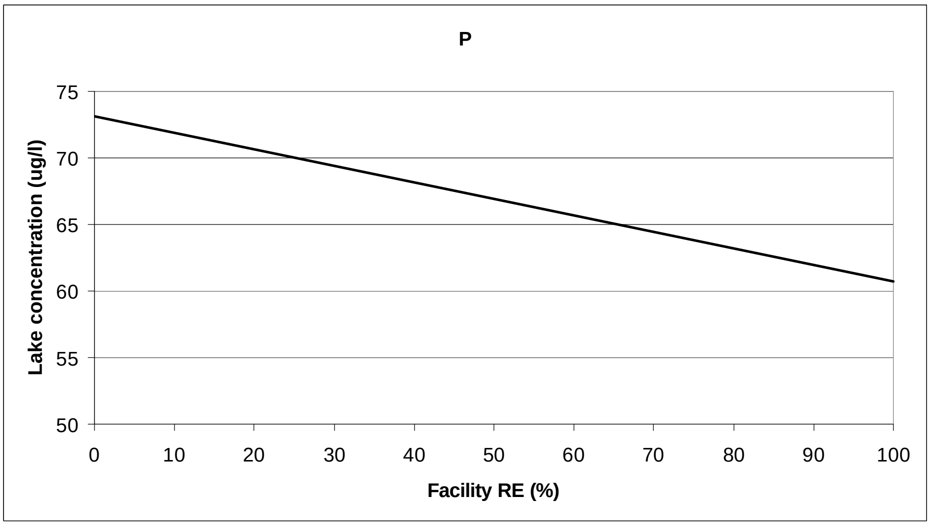


Figure 7 Reduction efficiency (%) of a stormwater treatment pond as a function of calculated lake P concentration (µg/l). Sub watershed Herrängsparken, Flaten case study.

Figure 7 shows the calculated corresponding P concentration as a function of different reduction efficiencies of the facility in Herrängsparken. If we assume that the reduction efficiency ($RE_1$) of the total facility will be 60% we get a predicted lake concentration of around 66 ug/l (Fig. 7), i.e. an average decrease of 10% due to the designed facility. The predicted lake concentration after reduction in the facility was estimated by subtracting $L_{in}$ in Eq. (12) with $L_1RE_1/100$, where $L_1$=9.4 kg/year, $RE_1$=60% (0-100%), $L_{in}$=55.9 kg/year, $Q_{out}$=751439 $m^3$/year, $k_j$=0.022 $year^{-1}$, h=2.0 m and $A_{rec}$=32.2 ha.

## 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.

The results from the case studies indicate that StormTac makes relative good predictions of pollutant concentrations in the water mass of a lake; generally better than the models of Vollenweider and OECD. One explanation is that the parameters in StormTac have been calibrated to the median measured concentrations of the case studies in Stockholm. The models of Vollenweider and OECD are probably, specifically for phosphorus calculations, better to use for predictions in other regions, since they are based on more case studies. However, the use of the Vollenweider and OECD model for prediction of P may be limited since measured values of P are available for many Swedish lakes. 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 method of employing acceptable recipient loads is clearly more relevant than, which is common in Sweden, to just employ limit stormwater concentration values or the identified watershed land uses as basis for stormwater abatement strategies. 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://hem.passagen.se/larm007/page2_stormtac.htm.

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