# Designing BMPs considering water quality criteria

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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. Complementary studies and uncertainties are briefly discussed. 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. The uncertainty studies have identified some parameter values, their ranges and processes to be changed, e.g. the base flow equations. Further studies will be performed especially regarding uncertainty estimations and by adding pollutant concentration data to decrease uncertainty and reflect time trends. 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.

## KEYWORDS

BMP; design; model; receiving waters; storm water

## 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 paper presents the management tool and operative storm water and recipient model StormTac (Larm, 2000) and focuses on the design of storm water treatment facilities or Best Management Practises (BMPs) with consideration to preset goals for the receiving waters. Some of the most important and recently updated equations and parameters in the model are presented. The uncertainty of selected processes and parameters is briefly discussed (Stenvall, 2004). Finally, the required parameters, amended or added equations and complementary data are identified.

## 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 is presented under Results and discussion. Figure 1 presents a simplified flowchart of the model.

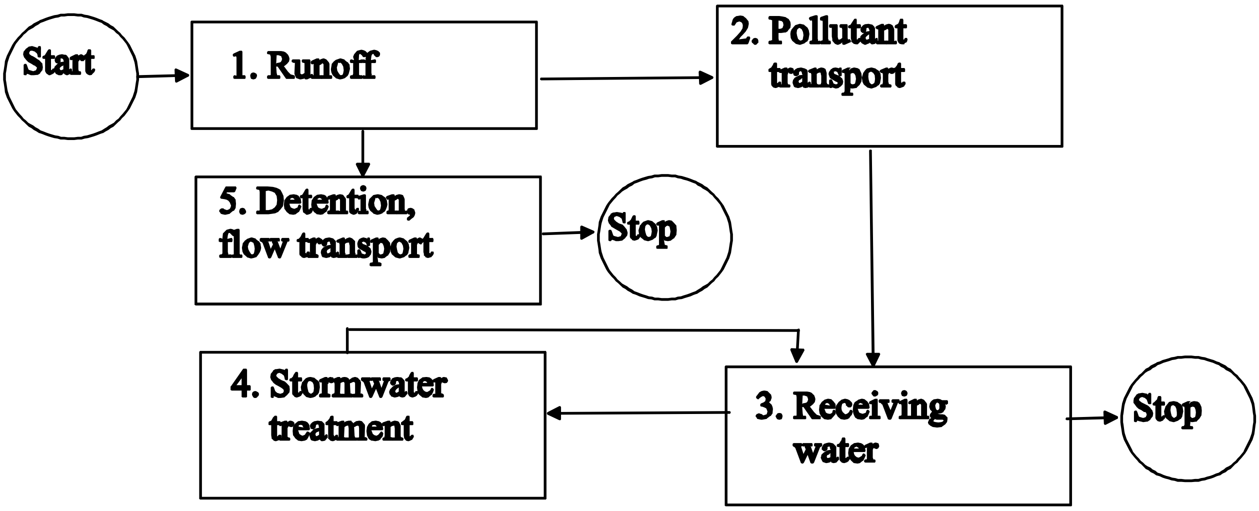

**Figure 1**. Simplified flowchart of the model StormTac.

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).

## RESULTS AND DISCUSSION

The results focus on presenting the key equations and parameters.

### Pollutant transport (I)

The pollutant loads are calculated in Eq. (1) (Larm, 2003).

$$L_{in} = L + L_b + L_a + L_{point} + L_{rel} \tag{1}$$

| | |
|---|---|
| $L_{in}$ | total pollutant inflow load [kg/year] |
| $L$ | storm water 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 storm water and base flow/ground water [kg/year] |
| $L_{rel}$ | internal pollutant load from the sediments to the water of the recipient [kg/year] |

In Eq. (2) the storm water pollutant load $L_j$ is calculated (Larm, 2000).

$$L_j = \frac{\sum_{i=1}^{N}(Q_i C_{ij})}{1000} \tag{2}$$

| | |
|---|---|
| $C$ | standard concentration for storm water [mg/l] |
| $Q$ | runoff water flow [$m^3$/year] |
| $i$ | land uses, $i = 1,2,\ldots N$ |
| $j$ | pollutant |

If measured storm water pollutant concentrations, $C_j^*$, exist, they can be used instead of $\Sigma C_{i,j}$. The runoff water flow Q is calculated in Eq. (3) (Larm, 2000).

$$Q = 10p\sum_{i=1}^{N}(\varphi_i A_i) \tag{3}$$

| | |
|---|---|
| $p$ | corrected precipitation intensity data (rain + snow) [mm/year] |
| $\varphi$ | runoff coefficient |
| $A$ | land use area [ha] |

**Recipient processes (II)**

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. (4):

$$C_{rec} = x_j\left(\frac{C_{in}}{1+\sqrt{t_{dr}}}\right)^{y_j} = x_j\left(\frac{1000L_{in}}{Q_{in}(1+\sqrt{t_{dr}})}\right)^{y_j} \tag{4}$$

| | |
|---|---|
| $C_{rec}$ | 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. (4) from Vollenweider and Kerekes (1982). These values and the sedimentation coefficient $k_j$ for Eq. (5) 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 |

In StormTac, the resulted recipient concentrations from Eq. (4) are evaluated and compared to results from calculations with Eq. (5) from Vollenweider, 1969 (Vollenweider, 1976), as formulated in Larm (2003):

$$C_{rec} = \frac{1000L_{in}}{(Q_{out} + 10000 v_s A_{rec})} = \frac{1000L_{in}}{(Q_{out} + 10000 k_j h A_{rec})} = \frac{1000L_{in}}{(Q_{out} + k_j V_{rec})} \tag{5}$$

$Q_{out}$ 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. (8).
$A_{rec}$ 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. (5) employs a median value of $k_j$ from case studies, se Table 1. $k_j$ is calculated from Eq. (8). 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. The predicted lake concentration after reduction in the facility is estimated by subtracting $L_{in}$ in Eq. (4) and/or Eq. (5) 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 (%). The acceptable (critical) load is calculated in Eq. (6), derived from the OECD Management model (Vollenweider and Kerekes, 1982) and as comparison from Eq. (7), Vollenweider's equation from 1969, as formulated in Larm (2003), assuming $Q_{out}=Q_{in}$, $C_{rec}=C_{cr}$ and $L_{in}=L_{acc}$.

$$L_{acc} = \frac{V_{rec}\left(\frac{C_{cr}}{x_j}\right)^{1/y_j}(1 + t_{dr}^{\ 0.5})}{1000 t_{dr}} \tag{6}$$

$$L_{acc} = \frac{C_{cr}(Q_{out} + kV_{rec})}{1000} \tag{7}$$

$L_{acc}$ 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]

The sedimentation coefficient $k_j$ is calculated in Eq. (8) (Larm, 2003) and is derived from Eq. (7), assuming $C_{cr}=C^*_{rec}$ and $L_{acc}=L_{in}$. The last term $Q_{out}/V_{rec}$ expresses the "flushing rate".

$$k_j = \frac{1000L_{in}}{C^*_{rec}V_{rec}} - \frac{Q_{out}}{V_{rec}} \quad (8)$$

$C^*_{rec}$ measured pollutant concentration in the water mass of the recipient [mg/l]

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. (8) in Eq. (7), Eq. (9) (Larm, 2003) is derived, which under this assumption provides the same results as Eq. (7).

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

The simple "dilution" equation (Eq. (9)) is used when measured $C^*_{rec}$ are available. The required reduction for the recipient water quality criteria is calculated in Eq. (10) (Larm, 2003):

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

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

**Storm water treatment model (III)**

*Planning-level design.* 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. (11) (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.

$$A_p = \varphi A K_{A\varphi} \quad (11)$$

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

*Detailed design.* 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 2006-06, around 30 values from Swedish, Danish and American case studies):

$$V_p = \mathrm{V_r} 0.178 \mathrm{e}^{0.0395 \mathrm{RE_{BMP}}} \qquad (12)$$

$V_p$ 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 2006-06, around 30 values from Swedish, Danish and American case studies):

$$V_p = \mathrm{V_r} 0.231 \mathrm{e}^{0.0509 \mathrm{RE_{BMP}}} \qquad (13)$$

The largest $V_p$ from Eq. (12) and (13) 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):

$$V_{d1} = 10 \varphi A r_{da} \qquad (14)$$

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

The emptying time is calculated in Eq. (15) (Larm, 2000).

$$t_{out} = \frac{V_{d1}}{3.6 Q_{out1}} \qquad (15)$$

$t_{out}$ 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.

$$V_{d2} = \frac{\max(60 t_r (Q_{\dim} - Q_{out,2}))}{1000} \qquad (16)$$

$V_{d2}$ 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. (17). Different specific runoff coefficients ($\varphi_s$) for different areas are considered (Larm, 2000).

$$Q_{\dim} = i\varphi_s A_s \tag{17}$$

i rain intensity for chosen return time [l/s/ha]
$\varphi_s$ 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:

$$V_d = V_{d1} + V_{d2} \tag{18}$$

$V_d$ 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.

*Case study*. In the Swedish Flaten case study, Salem municipality has formed a goal to decrease the mean lake P concentration from 73 µg/l to 50 µg/l. 18 kg P/year need to be reduced and 3-4 BMPs are planned to reduce the load from storm water and some of the base flow. A wet pond followed by a filter strip is planned in one sub watershed. The designed pond area is 1,260 $m^2$ (150-200 $m^2$/red ha; "red ha"=reduced hectares=$A_{red}$=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 fall). The calculated lake P concentration was plotted as a function of different reduction efficiencies of the facility. If we assume that the reduction efficiency ($RE_{BMP}$) of the total facility will be 60% we get a predicted lake concentration of around 66 ug/l, i.e. an average decrease of 10% due to the designed facility. The predicted lake concentration after reduction in the facility was estimated from Eq.(5), subtracting $L_{in}$ with $L_{in,BMP}RE_{BMP}/100$, where $L_{in,BMP}$=9.4 kg/year, $RE_{BMP}$=60%, $L_{in}$=55.9 kg/year, $Q_{out}$=751,439 $m^3$/year, $k_P$ =0.022 year-1, h=2.0 m and $A_{rec}$=32.2 ha (Larm, 2003).

**Uncertainty**

The sensitivity analyses indicated that the storm water flow and the base flow were most sensitive to errors in the precipitation. The Monte Carlo analyses indicated that the largest uncertainty for the storm water flow was the runoff coefficient for forests and the precipitation value. Furthermore, for some of the parameters there was an indication of interval ranges to be changed, especially the ranges for runoff coefficients for forests may be decreased from 0.05-0.4 to 0.09-0.22. The minimum runoff coefficient for detached houses may be decreased from 0.2 to 0.1 and the minimum sedimentation coefficient for copper, $k_{cu}$, may be increased from 1.4 to 10. Another finding was that the base flow should be less dependent on the variation in precipitation. However, the model employs yearly average values of precipitation and these indications of changes are only based on one case study.

## CONCLUSIONS

The uncertainties are relatively large, e.g. concerning the calculation of base flow, groundwater flow and lake water concentration. However, when measured recipient data is available, the latter calculation is not necessary. The uncertainty and sensitivity routines recently implemented in StormTac as a result of the analyses by Stenvall (2004) will be further developed. By using these routines and adding more data to the data bases of the model, more optimised parameter values and ranges may continuously be implemented, also reflecting time trends in e.g. concentration and precipitation data. However, the aim 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. In the paper and in www.stormtac.com the methodology and the equations are presented in a transparent way. 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] |
| $\varphi$ | 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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## REFERENCES

Larm T. (2000). Watershed-based design of storm water treatment facilities: model development and applications. Ph.D. Dissertation, Royal Institute of Technology, Stockholm, Sweden.

Larm T. (2003): 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. Proc. International conference on urban drainage and highway runoff in cold climate, pp. 235-245, 2003. Riksgränsen, Sweden.

Stenvall B. (2004). Sensitivity and uncertainty analyses of parameters and input data in the storm water and recipient model StormTac. MSc thesis, UPTEC W 04036, in Swedish, Uppsala University, Sweden.

Vollenweider R.A. (1976). Advances in defining critical loading levels for phosphorus in lake eutrophication. Men. 1st. Ital. Idrobiol. 33:53-83.

Vollenweider R.A. and Kerekes J. (1982). Eutrophication of waters: monitoring, assessment and control. Organization for Economic Co-operation and Development (OECD), Paris. 156p.

WEF and ASCE (1998). Urban runoff quality management. WEF manual of practice No. 23. ASCE manual and report on engineering practice No. 87. WEF, Water environment Federation and ASCE, American Society of Civil Engineers. USA.