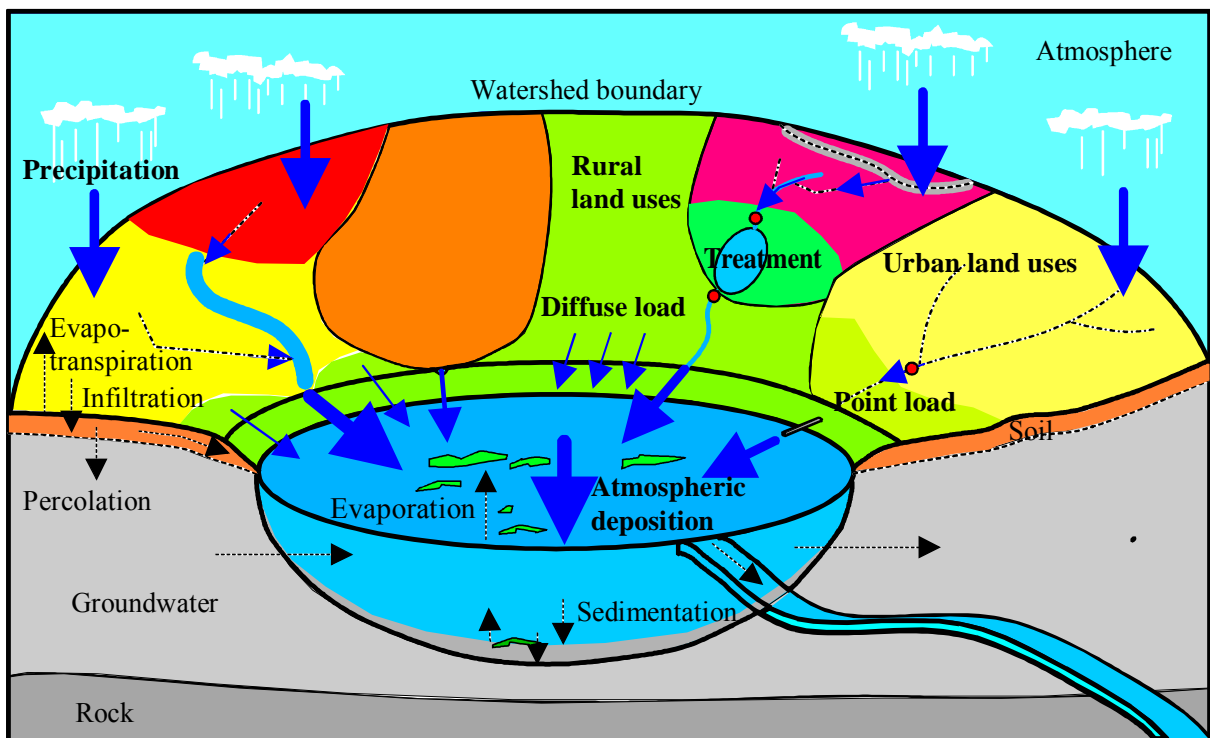# Watershed-based design of stormwater treatment facilities: model development and applications

Thomas Larm

Stockholm 2000

Corrections

to
"Watershed-based design of stormwater treatment facilities:
model development and applications"
by T. Larm

Correction No.	Current	Corrected	Pages
1	r_d=runoff depth	r_d=rain depth	*Summary:* vii,7,13,23, 36,51,52,60 *Paper I:* 1,9,10,11,20, Table 1
2	r_{da}=yearly average runoff depth	r_{da}=yearly average precipitation depth	*Summary:* 13,23,60 *Paper I:* 6,10,11,20, Table 1
3	Captured, capturing	Included, including	*Summary:* 36,53,60 *Paper I:* 10
4	85% 19 mm (18-20 mm) 16-17	90% 13-15 mm 9-10	*Paper I:* 10
5	15-20 mm 1.9-6.7	9-15 mm 1.1-5	*Paper I:* 11
6	18 (5-35) mm	9-15 (5-35) mm	*Paper I:* Table 1
7	$\varphi* = \dfrac{Q*}{p*A*}$	$\varphi* = \dfrac{Q*}{pA}$	*Paper I:* 5
8	137	1371	*Paper I:* Table 3
9	$Q_1=Q_{out}$x822x1217	$Q_1=Q_{out}$x822/1217	*Paper III:* 66
10	1 g/l	1 mg/l	*Paper IV:* 6

Watershed-based design of stormwater treatment facilities: model development and applications

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Acknowledgements

Preface

This thesis is based on the following papers, which are appended at the end of the thesis and referred to by their Roman numerals (I-IV):

I   Larm T., 2000. A comparative study of design methods for stormwater treatment in wet ponds. Water Environment Research. (Submitted).

II   Larm T. and Holmgren A., 1999. STORMWATER-GIS. A GIS planning tool for stormwater best management practices. Vatten No. 4, p. 291-297, Lund, Sweden.

III   Larm T., 2000. Stormwater quantity and quality in a multiple pond-wetland system: Flemingsbergsviken case study. Ecological Engineering, Vol. 15, Nos. 1-2, p. 57-75.

IV   Malmqvist P-A., Larm T., Bennerstedt K. and Wränghede A-K., 1999. Sources of pollutants discharging to Lake Trekanten, Stockholm. International Conference on Urban Storm Drainage (ICUSD), Sydney, Australia.

Other publications related to this research are not appended. An additional selected list is provided in the following:

Published in English:

A   Larm T. and Holmgren A., 1999. A GIS planning tool for stormwater best management practices. Paper in Stockholm Water Symposium 1999.

B   Larm T., 1997. A case study of the stormwater treatment facilities in Flemingsbergsviken, south of Stockholm. Paper for proceedings to "Stormwater Management-creating sustainable urban water resources for the 21st Century". Engineering Foundation Conference, Malmö, Sweden, 7-12 September 1997.

C   Larm T., 1996. Towards integrated watershed management. System identification, material transport and stormwater handling. Licentiate thesis, Water Resources Engineering, Royal Institute of Technology, Stockholm, Sweden.

Published in Swedish:

D   Larm T., 2000. Design of stormwater treatment facilities. VAV VA-FORSK report No. 2000-10.

E   Larm T., 1994. Stormwater characterization, impacts on recipients and treatment. VAV VA-FORSK report No. 1994-06.

F   Larm T., 1996. The use of constructed wetlands and wet ponds for treatment of stormwater. Paper in Stadsbyggnad No. 6.

G   Larm T., 1997. Standard concentrations of pollutants and nutrients in stormwater. VBB VIAK report, prepared for the Streets and Real Estate Administration in the City of Stockholm.

H   Larm T. and Holmgren A., 1999. Pollutant load on Lake Trekanten. Evaluation of a stormwater source model. VBB VIAK report. A cooperative study between the Streets and Real Estate Administration in the City of Stockholm, Stockholm Water Company, the Corrosion Institute and VBB VIAK, Stockholm.

I   Larm T. and Holmgren A., 2000. Stormwater investigation in Sätraån and Skärholmsbäcken during the one-year period 1999-06 to 2000-05. VBB VIAK report for the Streets and Real Estate Administration in the City of Stockholm.

J   Larm T., 1998. Classification of stormwater and recipients, and guidelines for treatment demands. Report, VBB VIAK in cooperation with Stockholm Water company, the Environment and Health Administration in Stockholm, the Streets and Real Estate Administration in Stockholm and Stockholm City Planning Administration.

Abstract

There is an increasing trend in constructing stormwater treatment facilities (STFs) in Sweden and in several other countries. Consequently, we require relatively simple and user-friendly tools for the design of such facilities that consider local conditions.

The contribution of this study is the development of a system framework which integrates runoff flow and pollutant characteristics with STF design routines. We present the operative model tool StormTac, developed to quantify pollutant transport with stormwater, base flow and atmospheric deposition and to design STFs such as wet ponds, filter strips, constructed wetlands, open ditches and swales. The model also includes routines for the design of detention facilities. StormTac is a spreadsheet Excel model employing programming in Visual Basic and including databases.

The planning-level tool can be used to identify the largest pollutant loads among sub watershed areas. It can also be used for estimating the required dimensions for implementing different types of STFs. By integrating selected parts of the model in a GIS (Geographical Information Systems) or an Internet environment we get a base for decision-making.

The watershed area is the system boundary for the model, which employs a land use approach with area per land use as the only obligatory input data. Both urban and rural land uses are considered. Model calculations may be performed by using default parameter values of e.g. precipitation intensity, land use specific runoff coefficients and standard concentrations for pollutant transport estimations and by employing e.g. rain depth, runoff coefficients and facility water depth for the design of STFs. We can improve the reliability and get more site-specific results by taking advantage of existing measured data (calibrating the model) or by changing parameter values of e.g. the facility water depth.

StormTac has been calibrated for several Swedish STF sites. The model parameters are continuously being calibrated to data from new case studies. Results from the pollutant transport calculations have shown good match for most of the pollutants studied, especially for nutrients and metals for which there are most data. Results from the design calculations have indicated the required areas for wet ponds to be around 160-300 (50-900) m^2 per reduced hectare (red ha). The corresponding values for filter strips are 700-1300 (150-2100) m^2/red ha and for constructed wetlands around 900-1200 (200-1300) m^2/red ha.

This study provides a framework for stormwater pollutant abatement strategies. Individual processes can (and should be) further studied and improved. Continued studies will focus on selecting among methods and parameter values, revisions of equations and on studying the uncertainty associated with the pollutant transport quantification.

Keywords: watershed, stormwater, runoff, pollutant transport, design criteria, constructed wetland, wet pond, filter strip, swale, reduction efficiency, monitoring program, StormTac

CONTENTS

x

1. INTRODUCTION

1.1 Background and state-of-the art

Stormwater is in this study defined as the part of the water from precipitation (rain, snow or melt water) or backwash-water that runs off open on impermeable surfaces, on open land or in ditches or that is collected and transported in separate stormwater sewers or in combined sewers together with sewage. The transport ends in surface waters, the subsurface or in wastewater treatment plants.

In recent international stormwater conferences (e.g. in the International Conferences of Urban Storm Drainage in Canada, Germany and Australia and in the Engineering Foundation Conference in Malmö), the general opinion was that pollutants in stormwater (e.g. nutrients, metals and organic compounds) may cause negative impacts on the recipients and that treatment and flow detention of stormwater are needed at many places (see also WEF and ASCE, 1998), especially when the share of urban land uses within the watershed is large and the recipient is sensitive.

Many different management strategies for stormwater can be considered. The so-called Best Management Practices (BMPs) may include the following type of measures:

- Measures aiming at reducing the pollutant sources (e.g. change of vehicle material and painting of galvanized objects). In Sweden, several studies (e.g. Malmqvist et al, 1999 (Paper IV) and Larm and Holmgren, 1999) are focused on the sources of pollutants, which end up in the receiving waters.

- Local disposal of stormwater (e.g. local infiltration practices).

- Detention facilities for compensating the runoff water flow; these measures can for instance be used when there is a risk for flooding.

- Stormwater Treatment Facilities (STFs) that employ natural reduction processes. Examples of STFs are wet ponds, filter strips, constructed wetlands, open ditches and swales; these facilities can be either "end-of-pipe" solutions or distributed measures for treating diffuse loads or point loads.

The applied type of measure will depend on site-specific conditions such as existing or desired use of the recipient, on the land uses in the watershed area and topography, groundwater level, soil characteristics etc.

The alternatives to the treatment and detention measures listed above are to transport the stormwater in combined sewers to wastewater treatment plants (there disturbing the reduction processes and enhancing the metal content of the sludge) or in duplicate sewers or separate ditches directly to the recipient (resulting in water quality problems).

In Sweden there is a rapid increasing trend in constructing STFs, but the knowledge concerning their pollutant reduction efficiency and design is limited (Paper I, Larm, 2000, Niemczynowicz, 1999, Persson, 1999 and Pettersson, 1999). Stormwater treatment, with consideration to recipient quality, is in focus and open STFs are

constructed where there is sufficient area available and where they are possible to implement with consideration to site specific conditions (Niemczynowicz, 1999).

At the Swedish conference VAV-dagen in June 1997 two out of three research topics were related to stormwater management. These were the following-up of existing STFs and recommendations for design and maintenance of STFs (Malmqvist, 1997 and Paper III). Examples of related Swedish research studies are currently carried out at Lund Institute of Technology ("Beneficial use of stormwater") and at Chalmers University of Technology ("Assessment of the sustainability of conventional and alternative stormwater systems"). The former study is planned to include analyses on the design of open stormwater systems in different urban environments and on recycling applications such as rainwater tanks for garden watering. The latter study is planned to include studies of future stormwater systems (intending to give recommendations on the planning and designing of stormwater systems) and to include the development of a watershed-based material flux model, which aims at tracking the materials from their sources to the receiving waters. The model is to include dynamic effects and temporal variations down to single rainfall events, and treatment. These two studies are within the Sustainable Urban Water Management MISTRA program (personal communication with the program coordinator Per-Arne Malmqvist), which e.g. aims at studying the design and operation of drinking water and wastewater systems in urban areas to be consistent with an ecological sustainable future in Sweden.

Examples of other related Swedish studies are focused on wet pond hydraulics (Persson, 1999) and reduction efficiency (Pettersson, 1999). The study of Pettersson (1999) included long-term measurements at 4 existing Swedish wet ponds. Pettersson showed that for these ponds a further increase in wet pond area per reduced hectare (red ha) watershed area above 250 m^2/red ha only marginally increased the pollutant removal efficiency. Internal flow patterns were also measured and modelled. Both these studies emphasized the role of designing pond geometry to avoid dead zones.

Continued research by T. Pettersson at MIT in Boston will focus on investigation and optimisation of pollution reduction through particle trapping in polluted urban and natural waters, where the impact of water vegetation characteristics (location, type and density) will be a main issue. The work will include modelling exercises, laboratory work and field measurements. The study will lead to guidelines regarding vegetation design promoting high particle settling and pollution reduction in polluted waters (personal communication with Thomas Pettersson).

Pond and wetland design is also studied within the Swedish Water Management Research Program (VASTRA) which aims at improving a model to simulate nitrogen removal in wetlands by adding a hydraulic parameter and by performing field experiments to investigate if flow effects short-circuiting and effective volume in wetlands (personal communication with Jesper Persson). Within VASTRA a joint project has been carried out with the University of Padua. In this work it was investigated how wetland vegetation affected the hydraulic performance in wetlands (Dal Cin and Persson, 2000).

In U.S.A., Canada and Germany there is currently much research on the design of STFs such as constructed wetlands, wet ponds and filter strips. In these countries, as in Scotland, design guidelines and operative models for STFs are used and are being developed (UDFCD, 1999, WEF and ASCE, 1998 and SEPA, 1997). The guidelines in

the first two of these references were developed by Larry Roesner and Ben Urbonas, among others. Examples of research studies regarding such design methods were performed by Urbonas, Guo and Tucker (1990), Guo and Urbonas (1996) and Urbonas, Roesner and Guo (1996).

Urbonas, Guo and Tucker (1990) described a simplified planning-level procedure utilizing hydrologic principles for optimizing the runoff capture volumes of the STFs. The employed design runoff events should not be too small nor too large.

Guo and Urbonas (1996) developed a design method to find a stormwater quality detention basin size where further increases in size produces diminishing returns in the number of storm events or runoff volume captured. They hypothesized that if the capture volume is too large and it´s emptying time is the same as is for a smaller volume, sediment removal rates will decrease. "This is because the predominant number of smaller storm events will not be detained for sufficient time to permit the settling of smaller sized sediments". The maximization techniques developed result in STFs that in the average will capture 82-88% of the total runoff volume from the tributary watershed.

Urbonas, Roesner and Guo (1996) updated and simplified the equations employed by Guo and Urbonas (1996). A maximized detention volume was calculated from a regression constant, the mean storm precipitation and the watershed runoff coefficient. The cost-effective method can help prevent oversizing of STFs located in the United States. It was emphasized that oversizing can result in poorer pollutant removal efficiency.

In Australia, various kinds of STFs are considered and studied. In Norway, Denmark and Japan many measures are based on infiltration. This kind of local disposal of stormwater is also in focus in Germany, France and in England where also permeable structures/asphalt and wetlands are studied. In the Netherlands, wet ponds, constructed wetlands and infiltration ditches are employed. Examples of other countries that employ STFs are Switzerland and Singapore (Niemczynowicz, 1999).

In Larm (1996) we suggested that treatment facilities should be located with consideration to the pathways of the largest sources of pollutants in the watershed. Which pollutants should be focused upon depends on the condition of the recipient, e.g., if eutrophication is the largest problem then phosphorus may be the most important pollutant to consider, assuming that phosphorus is the limiting nutrient.

The diffuse character of stormwater pollutant sources makes it very difficult and expensive to carry out measurements for estimating the pollutant loads from a watershed or several sub watersheds to the recipients. It is more practical to use models. As noted in Paper II, Paper III and in Larm (1996), a number of models are available for quantifying material transport. The models differ in complexity and need different types and amounts of input data. We mention models such as STORM, SWMM, Mouse, XP-AQUALM and Walker´s model (P8), which provide more detailed descriptions of the watershed and consequently are relatively complex in relation to the often-limited amounts of data available. For example, P8 requires data on soils types and continuous hourly precipitation records. STORM is capable of generating hydrographs (flow versus time) and pollutographs (concentration versus time) at one or a few points in a watershed. SWMM may also be used for the design of STFs. STORM and SWMM may simulate the effects of several consecutive rain events. Examples of more simple models

available are SWMM Level I (Nix, 1994) and the Simple Method (Schueler, 1987). According to Schueler (1987), the Simple Method does not consider base flow runoff and associated pollutant loads, and is better used at small watersheds.

Generally, different watershed-based stormwater studies in Sweden and in other countries employ different parameter values and units, and also employ different designations for the specific types of STFs. Additionally, in many studies the applied design methods are only described by text and not by equations (Paper I). All together, this leads to a large risk for misinterpretations.

In Paper II we identified a need for user-friendly and simple design criteria that are applicable for Swedish climate conditions. There is also a need for simple planning-level models that require little input data and that both can be used for long-term material transport estimations and for the design of STFs. One example is that several Swedish municipalities now are working on the development of large-scale stormwater handling programs, covering almost the whole municipality area and including many (maybe 30-150) sub watershed areas. There is a need for planning-level analyses of the pollutant situation, identifying the largest pollutant emissions as a basis and a tool for studying where STFs or other measures may be implemented, which facilities can be used and for estimating the area requirements of the measures.

Most of the existing tools are too complex and expensive to implement, and do not include both pollutant transport and design calculations in one single model. Further-more, the input data of e.g. pollutant concentrations, precipitation data and runoff coefficients must consider site-specific conditions.

The employed system boundary in this study is the watershed area which is delimited by the water divider in natural areas and which coincides with the technical boundary (e.g. comprising stormwater sewers) in urban areas (Larm, 1996). Stormwater management/ planning is watershed-based which is in accordance with the European Union (EU) water directives. Urban stormwater guidelines in U.S.A., Canada and Australia are also watershed-based (Niemczynowicz, 1999).

1.2   Objectives and scope

The contribution of this study is the developed watershed-based system which integrates the quantification of runoff flow and pollutant transport with the design of stormwater treatment facilities and   which takes consideration to recipient and site-specific conditions. We have developed this integrated system in the form of an operative model tool. We identify what is required in the system and show how to implement the tool on case studies.

The objectives of this thesis are:

- To present a planning-level tool for quantification of pollutant transport and design of stormwater treatment facilities.
- To present equations and input data for the quantification of pollutant concentrations and pollutant transport.
- To present equations for the design of wet ponds, constructed wetlands and filter strips.
- To suggest parameter values for this design.

- To compare and prioritize these equations.
- To identify topics for continued studies.

This thesis is based on four studies. In Paper I, we compiled and compared design methods for stormwater wet ponds by using and developing a stormwater model (referred to as StormTac) and by implementing these methods on three Swedish case studies. Similar studies were reported in Larm (2000) with extension of compilation of methods for filter strips, constructed wetlands, open ditches and swales.

In Paper II, we introduced a planning tool for stormwater management, integrating GIS (Geographical Information Systems) with the spreadsheet pollutant transport sub model in StormTac, and the presentation of different stormwater measures. We implemented the tool for two Swedish municipalities.

In Paper III, we employed an early version of StormTac and presented the methodology of quantifying pollutant transport into and out from stormwater treatment facilities. We especially studied the constructed wetland facility at Flemingsbergsviken, Sweden. We presented the difficulties in calculating pollutant transport and estimating reduction efficiencies from instantaneous grab samples and discussed improved strategies concerning monitoring programs.

In Paper IV, we focused on quantification and identification of pollutant sources. We implemented and calibrated a source model on Trekanten case study, Sweden. We also simulated the effects of source control measures on the pollutant load on the lake recipient. Updated results from this study were later reported in Larm and Holmgren (1999).

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2. StormTac – MODEL DESCRIPTION

2.1 Conceptual model (flowchart)

In Larm (1996) the watershed as a system was characterized by identifying processes and parameters, and by quantifying pollutant loads on recipients from different land uses. A framework consisting of a conceptual model and a flowchart was proposed. Consideration was given to conditions in the recipients and the hypothesis was that the water quality criteria is not general but site specific regarding, for instance, the processes and conditions in the recipient and the pollutant pathways in the watershed. The conceptual model includes different urban areas, soil/rural areas, surface water, groundwater, atmosphere, STFs and wastewater treatment plants. The proposed flow-chart in Larm (1996) included a hypothetical case study and provided a methodology for optimization of the design of the treatment facilities by going through different steps for quantifying pollutant loads and identifying transport paths.

Based on the findings compiled in Larm (1996), the operational stormwater model StormTac was developed. The model employs relatively simple equations for quantification of pollutant transport with stormwater to be consistent with the generally very limited amount of input data available. The equations are considered accurate enough for planning-level analyses and considering that the focus is not on dynamic properties of the systems studied. The model system boundary is the watershed boundary. Land use specific input data are used, such as runoff coefficients, areas per land use and standard concentrations. Even if the focus is on stormwater, also base flow and atmospheric deposition may be considered in the quantification of pollutant transport. The intended wet and dry atmospheric deposition is falling directly on the recipient.

Furthermore, we developed the model to include design procedures for stormwater treatment facilities. The design methods included are integrated to the runoff and pollutant transport sub models. They were also implemented on three case studies (see Paper I). The design procedure takes into consideration site specific hydrological conditions and water quality criteria.

The spreadsheet stormwater model StormTac requires little input data to perform perspicuous calculations of long-term (yearly or monthly) runoff water fluxes, pollutant loads and design of stormwater treatment facilities. The only obligatory input data consists of land use specific areas. More detailed calculations can be made by changing the default input data, such as yearly and monthly data of precipitation, runoff coefficients and standard concentrations. It is possible to use calibrated data (i.e. justified to measured data). Regarding more detailed design calculations it is possible to change water depth, slope, design rain depth etc (see Paper I).

The flowchart in Fig. 1 is both the start and result screen of the model. By clicking on its boxes we for instance have direct links to the databases and the different sub models and we can change input data and substances to study.

GIS-stormwater model: Results from StormTac can be integrated with a GIS model to result in a GIS-stormwater model. The information about the sub watershed areas (e.g. land use distribution) and the recipients can be presented in an interactive GIS map,

which presents discharge points, sewer systems and suggested and existing stormwater treatment facilities. Different choices of presentation can be made from a designed menu (e.g. the choice of which pollutant to study). When pointing at a specific sub watershed area on the map presentation tables of flows, concentrations, loads etc. are opened (see Fig. 4, Paper II). These tables are interactive. By changing table values different scenarios can be simulated, e.g. changed land use results in changed loads. These scenarios are visualized on the map as well as in the tables. The concentration values can be updated. Photos of existing facilities (or areas where such facilities are planned) and a digital report with descriptions of areas and facilities can also be accessed from menus and maps. This stormwater management-planning tool has been implemented in two Swedish municipalities, Tyresö and Botkyrka, both outside Stockholm. The GIS-stormwater model is presented more detailed in Paper II.

2.2 Runoff model

Yearly (or monthly) runoff water flow is calculated by employing land use specific runoff coefficients, empirical precipitation data and estimated areas of each land use in the watershed. Eq. (1) has been used for quantification of runoff water flow. The equation was presented in Paper II.

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

Q   runoff water flow (m^3/year)
p   precipitation intensity (mm/year) corrected for systematical errors
φ_i yearly runoff coefficient for land use i
A_i size (ha) of land use i
i   land use i=1,2,…N
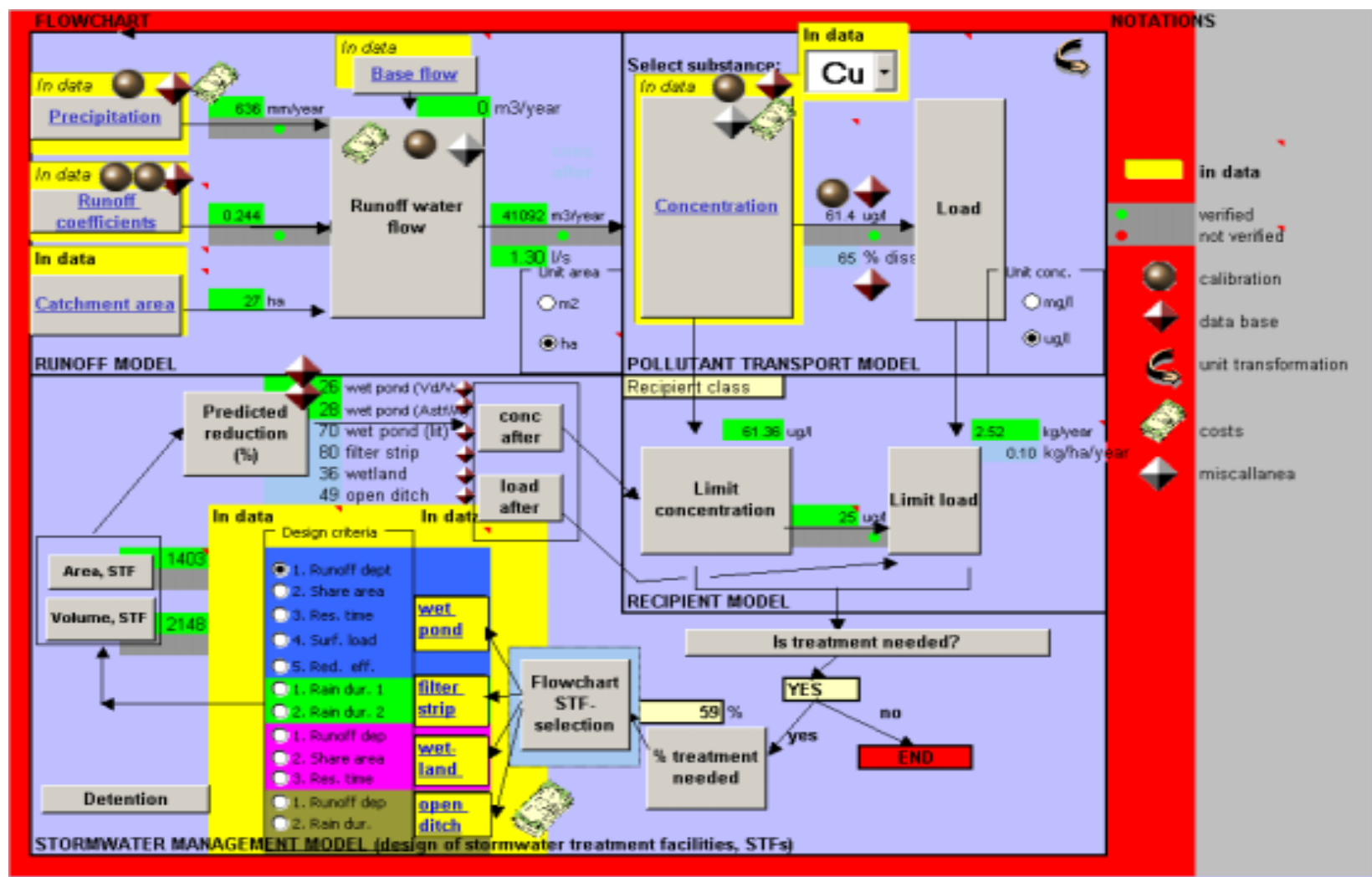
Figure 1   "Print screen" from the flowchart in StormTac, version 2000-11.

The employed precipitation intensity (p) is preferably taken from a local gauge and is adjusted for systematical errors (losses) by a correction factor (Chapter 3.1 and 3.6, Paper II, Paper III and Eriksson, 1983). This makes the runoff model "semi-empirical". According to Eriksson (1983) it is necessary to consider such systematical errors when calculating flow.

The runoff model has been calibrated to some case studies, employing precipitation and flow data. For better calibration, we need to study specific areas with one single land use and where there are measured flow (Q*) and local precipitation data (p). The runoff coefficient from measurements (φ*) can be estimated as (Paper II and Larm, 2000)

$$\varphi* = \frac{Q*}{10pA} \qquad (2)$$

The runoff coefficient (φ*) expresses the relation between runoff water volume and precipitation volume. Those runoff coefficients are referred to as "volume runoff coefficients" (VAV P31, 1976; Larm, 2000), which differ from the runoff coefficients that are used specifically for the design of stormwater sewers, i.e.

$$\varphi = \frac{\varphi_1 A_1 + \varphi_2 A_2 + ... + \varphi_N A_N}{A} \qquad (3)$$

Eq. (3) expresses that the total runoff coefficient (φ) of a watershed can be estimated from the runoff coefficient specific for each land use (φ_N) multiplied with the area of that land use (A_N) and by dividing these factors with the total area of the watershed ($A=A_1+A_2+...+A_N$), where N is the number of land uses.

The runoff coefficient can be estimated from the impermeable surface as (Urbonas, Roesner and Guo, 1996)

$$\varphi = 0.858(\frac{I}{100})^3 - 0.78(\frac{I}{100})^2 + 0.774(\frac{I}{100}) + 0.04 \qquad (4)$$

I   Percent (%) impermeable surface

Alternatively, the runoff coefficient can be estimated from the empirical equation (Akan, 1993)

$$\varphi = 0.05 + 0.009I \qquad (5)$$

Impermeability (I) can be estimated as a function of the runoff coefficient. The equation is derived from Eq. (4) ($R^2=0.98$) as

$$I = 44\ln\varphi + 102 \qquad (6)$$

Base flow: In this study we approximate the base flow from

$$Q_b = 10K_x K_{inf} pA \qquad (7)$$

$$K_{\text{inf}} = \frac{p - p\varphi - E}{p} \tag{8}$$

Q_b	Base flow (m³/year)
K_x	Share of K_{inf} that reaches the base flow
K_{inf}	Fraction of the yearly precipitation that is infiltrated (assuming that surface water storage is neglected or included in the parameter values φ and E).
E	(Potential) evaporation intensity (mm/year)

Alternatively, the base flow can be measured. The equations (7) and (8) are included in StormTac but are preliminary and further data are needed for estimating the parameters K_x and E.

The evaporation intensity from different land uses has been quantified using

$$E = 1000(0.50 - 0.55\varphi) \tag{9}$$

We obtained equation (9) by fitting the data compiled by Bucht et al (1977) and by Melanen (1978). Impermeability I was converted to φ following Eq. (4). The resulting evaporation values are e.g. 33 mm/year from road areas ($\varphi=0.85$) and 445 mm/year from forests ($\varphi=0.1$).

2.3 Pollutant transport model

Yearly mass transport (runoff load) has been quantified by multiplying an annual runoff volume with standard concentrations (Paper II).

$$L_j = \frac{\sum_{i=1}^{N} Q_i C_{ij}}{1000} \tag{10}$$

L	mass load rate (mass flux) (kg/year)
C	standard concentration (mg/l)
j	substance

Eqs. (1) and (10) consider base flow. However, the model is being updated to separate between base flow and stormwater flow. Appreciable base flow is especially generated from larger watershed areas (Paper III).

The quantification of pollutant loads was in Paper III suggested to include both point and diffuse loads. It is also possible to use or compare to measured concentrations and flows, and to calculate monthly mass transport.

Base flow pollutant load: In this study the base flow pollutant load (L_b) is estimated as

$$L_b = \frac{Q_b C_b *}{1000}$$

(11)

L_b Base flow pollutant load (kg/year)
C_b* Measured base flow pollutant concentration (mg/l)

Q_b in Eq. (11) can be estimated from Eq. (7) or be measured (Q_b*). The base flow pollutant concentration can preferably be measured (C_b*) in the watercourse or sewer during base flow conditions. It is more difficult and uncertain to calculate the concentration due to various site-specific characteristics. The denominator value 1000 is employed to get L_b in the unit kg/year.

2.4 Recipient model

The recipient model employs limit values of acceptable concentrations and loads for comparisons to corresponding stormwater values.

The limit recipient concentrations express which pollutant concentrations are considered acceptable for emission to different sensitive recipients. Such data can be used for a rough evaluation of which emissions that should be regarded for treatment. However, in Larm (1998) we emphasized that such studies must be complemented with estimations of acceptable pollutant loads (kg/year) on recipients, i.e. total load on a recipient and the relative importance of each emission should be investigated.

An equation quantifying acceptable recipient loads is under development and therefore not presented here. In its present version in StormTac it includes the parameters recipient water volume (V_{rec}), measured concentration in the receiving water phase (C_r*), recipient water quality criteria (C_{cr}), recipient detention time (t_{dr}), inflow concentration (C), total watershed area (A), total watershed runoff coefficient (φ) and yearly precipitation intensity (p). The following parameters are under consideration for being included in the equation; concentration in sediments ($C_{sed}*$), outflow (Q_{out}), water depth (h) and recipient water area (A_r).

2.5 Stormwater management model

Simple and at the same time reliable methods for estimating required areas and volumes for stormwater treatment facilities are needed. However, no simple method can replace more detailed and site specific investigations. The simplified methods presented in this study (and included in StormTac) can nevertheless be helpful for estimating the sizes of these facilities during planning stages or to make initial estimations of land space needed to be placed at disposal for the facilities in a planned site. Perspicuous design methods for stormwater treatment in wet ponds are compiled and compared by using the stormwater model StormTac. Areas per land use (A) are the only obligatory input data for estimating area and volume requirements of a wet pond.

The stormwater management model in StormTac includes design equations for wet ponds, filter strips, constructed wetlands, open ditches, swales and detention basins. It is possible to choose between several design methods for each facility and to change parameter values. Here only the method of highest priority for wet ponds, filter strips

and constructed wetlands respectively are presented. Literature studies have shown that there exist relatively few design methods for filter strips, constructed wetlands, open ditches and swales (Larm, 2000).

Generally, yearly average runoff volume is calculated from (Paper I)

$$V_r = 10 r_{da} \varphi A \qquad (12)$$

V_r Water volume of runoff at an average runoff event (m^3)
r_{da} Yearly average precipitation depth (mm)

Some of the parameters, e.g. V_p and V_d, are visualized in planes, profiles and sections of the STFs, see Fig. 10-13.

Wet ponds (”runoff depth”): The permanent volume of the pond (V_p) and its detention volume (V_d) should be calculated as (UDFCD, 1999)

$$V = V_p + V_d \qquad (13)$$

V Facility water volume (m^3)
V_p Facility permanent volume (m^3)
V_d Facility detention volume (m^3)

The methodology described in Vägverket (1998) expresses V_d as a function of rain depth as (see Paper I)

$$V_d = 10 \varphi A r_d \qquad (14)$$

r_d Rain depth (mm)

V_p can be expressed as a function of V_d as (see Paper I)

$$V_p = N_{d1} V_d = N_{d1} 10 \varphi A r_d \qquad (15)$$

N_{d1} Constant value of (number times) the detention volume (normally between 1.0-1.5)

A critical parameter to estimate is the value of the design rain depth r_d. If r_d is too small the reduction efficiency will be smaller since too many runoff events will exceed the capacity of the facility. If r_d is too large the smaller runoff events will be emptied quicker than desired in order to reach an acceptable sedimentation effect. Therefore, an optimized value of r_d should be estimated (see Chapter 5.4). The area of the facility (A_{STF}) is obtained according to

$$A_{STF} = \frac{V}{h} \qquad (16)$$

A_{STF} Facility area (m^2)
h Average water depth in the pond (m)

Other design methods (not presented here but included in StormTac) are "part of water-shed area", "residence time" and "surface load", see Paper I and Larm (2000).

Design flow from more intensive rain events is only used when the main objective is detention not treatment, and for the checking of maximum water levels and for design of overflow sewers from the stormwater treatment facility. In this study the maximum water level (h_r) is approximated for different intense flows and different rain durations (t_r), as

$$h_r = \frac{V_d}{A_{STF}} = \frac{3t_{r1}(Q_{dim} - Q_{out})}{50 A_{STF}}$$ (17)

h_r Maximal water depth for V_d (m)
t_{r1} Rain duration (h)
Q_{dim} Design flow to facility (l/s)
Q_{out} Outflow (l/s)

The design flow to facility Q_{dim} is calculated as (Larm, 2000)

$$Q_{dim} = i_N \varphi_s A_s$$ (18)

i_N Rain intensity with return time 1,2,3,..N years (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)

Calculations for estimating detention times at different flow conditions are also needed and included. Estimation of the detention time for ponds with large V_p in relation to V_d can be obtained using (Larm, 2000)

$$t_d = \frac{V_p}{3.6 Q_{in}}$$ (19)

t_d Detention time (h)
Q_{in} Inflow (l/s)

Different Q_{in} can be tested, e.g. at a yearly average flow, the flow during an average precipitation event and at a maximum precipitation day.

In Larm (2000) we proposed the following equation for roughly estimating detention time for ponds with relatively large V_d.

$$t_d = \frac{V_p}{3.6 Q_{in}} + \frac{V_d}{3.6 Q_{out}}$$ (20)

Q_{out} (in l/s) can be estimated from slope and dimension of the outlet sewer or from other functions if a v-weir is used.

The emptying time t_{out} (in hours) can be estimated using

$$t_{out} = \frac{V_d}{3.6Q_{out}} \quad (21)$$

t_{out} Time for outflow, emptying time (h)

It may be checked that t_{out}>6-12 h, preferably between 12-24 h (maximum 48 h).

Water balance calculations may also be performed for checking that base flow is larger than losses through evaporation, evapotranspiration and infiltration.

Filter strips: In StormTac the following equation set is used for the design of filter strips. The area of the filter strip is calculated as

$$A_{STF} = w_{tot}l \quad (22)$$

w_{tot} Total width of facility (m)
l Facility length (m)

The volume is not calculated for filter strips.

The smallest width required is estimated with the assumption that the flow is spread over the surface (i.e. not coming in as a point flow) as (UDFCD, 1999)

$$w_{tot} > 0.2l \quad (23)$$

If the equation results in a width smaller than 2.5-3 m then this width is used instead (UDFCD, 1999).

The following equation for l was presented in Larm (2000):

$$l > \frac{Q_{dim}}{r_d v} \quad (24)$$

v Water velocity (m/s)

r_d is around 25 mm and a value of v between 0.18-0.3 m/s may be used. Q_{dim} is calculated from Eq. (18), using N=5. The design flow for filter strips is based on a much more intensive rain intensity than what is the case for wet ponds. The design runoff area A_s, with the runoff coefficient φ_s, is estimated by calculating the flow distance s using (Larm, 2000)

$$t_f = \frac{s}{60v} \quad (25)$$

s   Distance (m)
t_f Time for runoff (min)

The value of v is different in stormwater sewers (around 1.5 m/s) and open ditches (around 0.5 m/s), see VAV P28 (1976).

It is assumed that $t_f=t_{r2}$. The rain intensity for Stockholm is calculated from (VAV P28, 1976)

$$i_5 = 5 + \frac{3921}{t_{r2} + 12.2} \tag{26}$$

t_{r2} Rain duration (min).

The value t_{r2}=10 minutes may be used.

Constructed wetlands ("runoff depth"): Constructed wetlands are principally calculated in a similar manner as wet ponds but employing a smaller water depth in Eq. (16). The following equation for V was obtained by fitting data compiled in SEPA (1997) (see Paper I):

$$V = V_p = N_{d2}V_d = \frac{N_{d2}Ap(110\varphi + 27.5)}{700} \tag{27}$$

N_{d2} Number times the detention volume V_d

According to Eq. (27) the wetland water volume is 3 times (N_{d2}=3) the detention volume for wet ponds. p=636 mm may be used for Stockholm (see Chapter 3.1). If Eq. (27) is employed then there will occur a biochemical removal of nutrients and dissolved biological degradable pollutants according to SEPA (1997). Other, not presented methods, included in StormTac are "share of the watershed area" and "design detention time", see Larm (2000).

Open ditches: The equations required for designing ditches are many and are therefore not presented here (see Larm, 2000). One method is based on runoff depth and the other is an iterative method in which design flow and water velocity are calculated and compared to limit (maximum acceptable) values. Bottom width, slope, length slope and water depth are changed until the design flow and the water velocity are below these limits (Larm, 2000; Vägverket, 1998).

3. INPUT DATA

Not all land uses included in StormTac are presented here. The land uses not presented here are "country roads", "highways", "traffic area", "petrol stations", "roofs", "domestic areas", "domestic areas and commercial areas", "urban", "golf courses" and "wetlands". The latter land uses have not been used for most of the implemented case studies.

3.1 Precipitation data

StormTac employs site specific precipitation data (p) that are transformed from sampled data. This "real" (true) precipitation for Stockholm is calculated to 636 mm for the SMHI (Swedish Meteorological and Hydrological Institute) reference normal year 1961-90. The sampling error is site specific and systematical. For Stockholm it corresponds to a correction factor of 1.18 for the transformation of sampled precipitation data p* (539 mm) to real precipitation (p) according to a methodology presented by SMHI (Eriksson, 1983). The type of errors is presented in Chapter 3.6 (Uncertainty). It is possible to use other values in the model, e.g. a value for a specific year or for another site. The correction factor 1.15 is an average value for Sweden (Pettersson, 1995).

3.2 Runoff coefficients

The yearly runoff coefficients employed in StormTac and presented in Table 1 are estimated from measured flow data (Q*) and "real" precipitation data (p) using Eq. (2). In order to choose a representative value in situ investigations of the prevailing land uses are needed. Standard values should be chosen for a typical area. Values closer to the maximum should be chosen for slanted areas and vice versa.

Table 1   Yearly runoff coefficients (φ) in StormTac, version 2000-11.

Land use	(φ_N)		
	Standard	Min	Max
Urban			
Roads	0.85	0.7	1.0
Parking	0.85	0.7	1.0
Houses	0.25	0.2	0.4
Row houses	0.32	0.3	0.5
Apartments	0.45	0.35	0.6
Leisure houses	0.2	0.05	0.5
Colony	0.2	0.1	0.5
Commercial	0.7	0.4	0.9
Industry	0.6	0.5	0.8
Park	0.18	0	0.3
Rural			
Forests	0.1	0.05	0.4
Agriculture, farmland	0.11	0.1	0.3
Pasture	0.08	0	0.3

The values in Table 1 are generally uncertain and continued calibration is required. One explanation of the large differences between minimum and maximum values (see Table 1) might be that maximum values include base flow. In StormTac monthly runoff

coefficients can be estimated from a sub model derived from empirical data using Eq. (2). The monthly values can exceed 1.0 and showed large variations between years, e.g. depending on snow melt. Such monthly data are not presented here but included in a database in the model.

3.3 Standard concentrations

In Paper III it was concluded that land use specific standard concentrations are more appropriate for use rather than instantaneous concentration data for the quantification of pollutant transport. Standard concentrations provide a relatively good estimation of the transport over longer time periods (yearly or monthly) and are based on continuous flow directed concentrations. The standard concentrations are assumed to be constant at all times for a specific pollutant.

In Larm (1997) we compiled standard concentrations from both urban and rural land uses. The ambition was to compile values that are valid for the conditions in Sweden with the focus on the Stockholm area. However, the uncertainty is large and many values have been taken from other sites. Therefore, the calculations using these values can also be used at other sites with about the same climate conditions as in Stockholm. In StormTac the original standard concentrations have been taken from this reference. However, the model is continuously being calibrated to site specific data from within the Stockholm region. In Table 2 the present standard concentrations are presented for the land uses most used (and for which there exist most data). The values that are written in bold format have been calibrated relatively accurately or accurately. Many of the values have been changed with regard to time trends and to be reasonable in relation to other land uses. It should be observed that the urban land uses "houses", "row houses", "apartments", "leisure houses", "colony", "commercial" and "industry" include local streets, smaller parking and green structures (e.g. gardens and smaller parks) within the land use area. Larger streets, highways, parking areas and parks are treated as specific land uses.

Table 2   Standard concentrations (mg/l and µg/l) for the land used most used in StormTac (version 2000-11).

Land use	P	N	Pb	Cu	Zn	Cd	Cr	Ni	Hg	SS	oil	PAH	BaP
	mg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	µg/l	µg/l
Urban													
Roads (ADT=20 000)	**0.13**	**1.3**	**33**	59	**275**	0.4	9.0	**6.5**	0.1	87	1.15	4.7	0.16
Parking	0.10	1.1	50	30	110	2.0	3.0	4.0	0.1	60	1	1.7	0.06
Houses	0.20	1.5	30	50	150	1.5	4.0	10	0.1	100	0.2	0.6	0.1
Row houses	**0.20**	1.5	**60**	**30**	**200**	**2.0**	4.0	**15**	0.1	100	0.4	0.6	0.1
Apartments	**0.40**	**2.0**	51	100	300	2.0	5.0	20	0.1	225	0.4	**0.6**	**0.1**
Leisure houses	1.0	5.0	10	20	100	1.0	2.0	5.0	0.05	50	0.1	0.3	0.05
Colony	0.15	8.5	10	15	50	0.2	0.2	1.0	0.01	38	0	0	0
Commercial	0.40	2.3	60	30	300	1.5	5.0	10	0.1	440	1	0.6	0.1
Industry	0.40	2.3	60	100	450	1.5	5.0	10	0.1	340	2	1	0.15
Park	0.08	7.0	20	15	18	0.3	0.7	2.0	0.02	340	0	0	0
Atmospheric dep.	0.003	2.5	10	20	35	0.2	0.2	0.5	0.01	0	0	6.8	0.01
Rural													
Forests	0.025	1.0	9	8	15	0.10	0.1	0.5	0.005	54	0	0	0
Farmland	0.30	8.0	9	8	15	0.10	0.1	0.5	0.005	190	0	0	0
Pasture	0.10	3.0	15	20	25	0.30	0.3	2.0	0.03	340	0	0	0

In Fig. 2 we show the standard, minimum and maximum values for some of the substances in the model for most common land uses. In order to choose a representative value in situ investigations of the prevailing land uses are needed. Standard values should be chosen for a typical area. Values closer to the maximum should be chosen for e.g. more densely populated areas and vice versa. In its present version (2000-11) StormTac includes linear functions for standard concentrations and runoff coefficients that make it possible to choose values closer to the maximum or the minimum. 1 represents the minimum value, 5 is the standard choice and 10 is the maximum. However, sensitivity studies showed that in some cases using for example the value 4 for values closer to the minimum resulted in very large differences in output concentrations and loads. Therefore, these functions are now under consideration for change, e.g. by using normal or lognormal distributions for the data of standard concentrations and runoff coefficients. Future calibration of the model will focus on narrowing these large intervals and to improve the statistical properties of the model.

In Larm (1997) we made an attempt to compile diagrams showing pollutant concentrations in relation to traffic intensity. There is a lack of similar studies, mainly because the uncertainty is so large. Examples of factors that influence the relation between traffic intensity and pollutant concentration are the road construction/design, climate conditions, the monitoring program (sampling method), type of traffic and road maintenance. The data also showed a large scattering. Nevertheless, the potential usefulness of such data is large. In StormTac, version 2000-11, linear functions have been developed and these are used for major roads in implemented case studies. The alternative would be to use a specific value for all roads. The assumption is that the functions represent "the best guess". Another assumption is that pollutant concentration increases with traffic intensity, which is indicated by the compiled data. This tendency was most evident for phosphorus, zinc and nickel. More data is needed to further study the relationships between traffic intensity and concentration and to present the correlations. Therefore, we do not present these data here. However, in Table 2 we choose to present the concentrations for the average daily traffic intensity (ADT) 20 000 vehicles/day. These presented concentrations follows from the proposed linear functions.

StormTac includes a database of the dissolved and particulate fractions of the pollutants. Generally, the data showed a large scattering. Median, minimum and maximum values of the dissolved fraction (% dissolved) from 10 case studies are presented in Table 3.

Table 3   % dissolved of different pollutants in stormwater. Median, minimum and maximum values from 10 case studies.

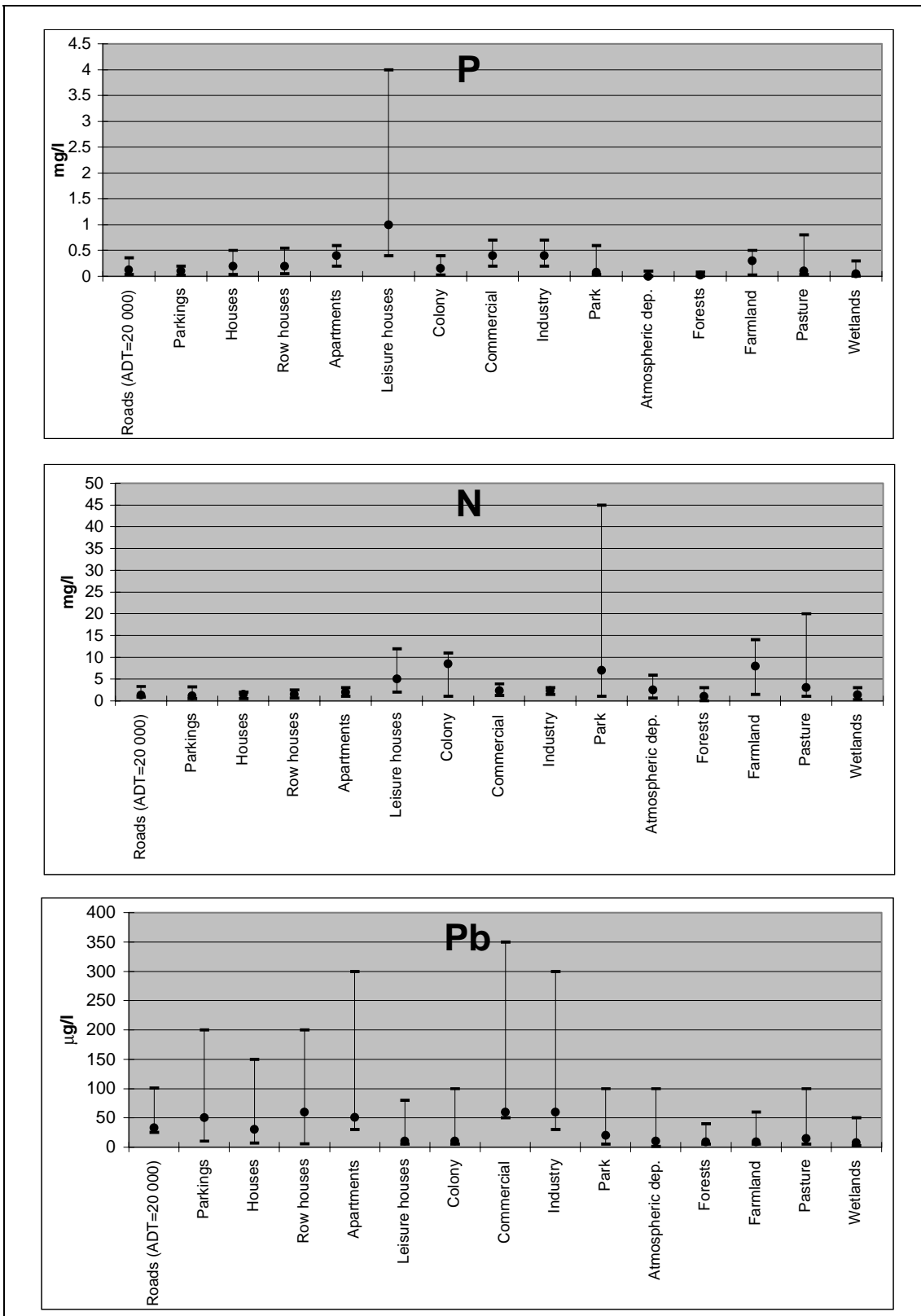|	P	N	Pb	Cu	Zn	Cd	Cr	Ni	Hg	SS	oil	PAH	BaP
median	32	34	21	65	63	68	45	76	64	-	-	12	-
min	25	-	3	23	30	50	10	30	-	-	-	10	-
max	43	-	27	71	95	95	65	78	-	-	-	14	-

Figure 2   Land use specific standard concentrations, minimum and maximum concentrations of P, N and Pb used in StormTac, version 2000-11.
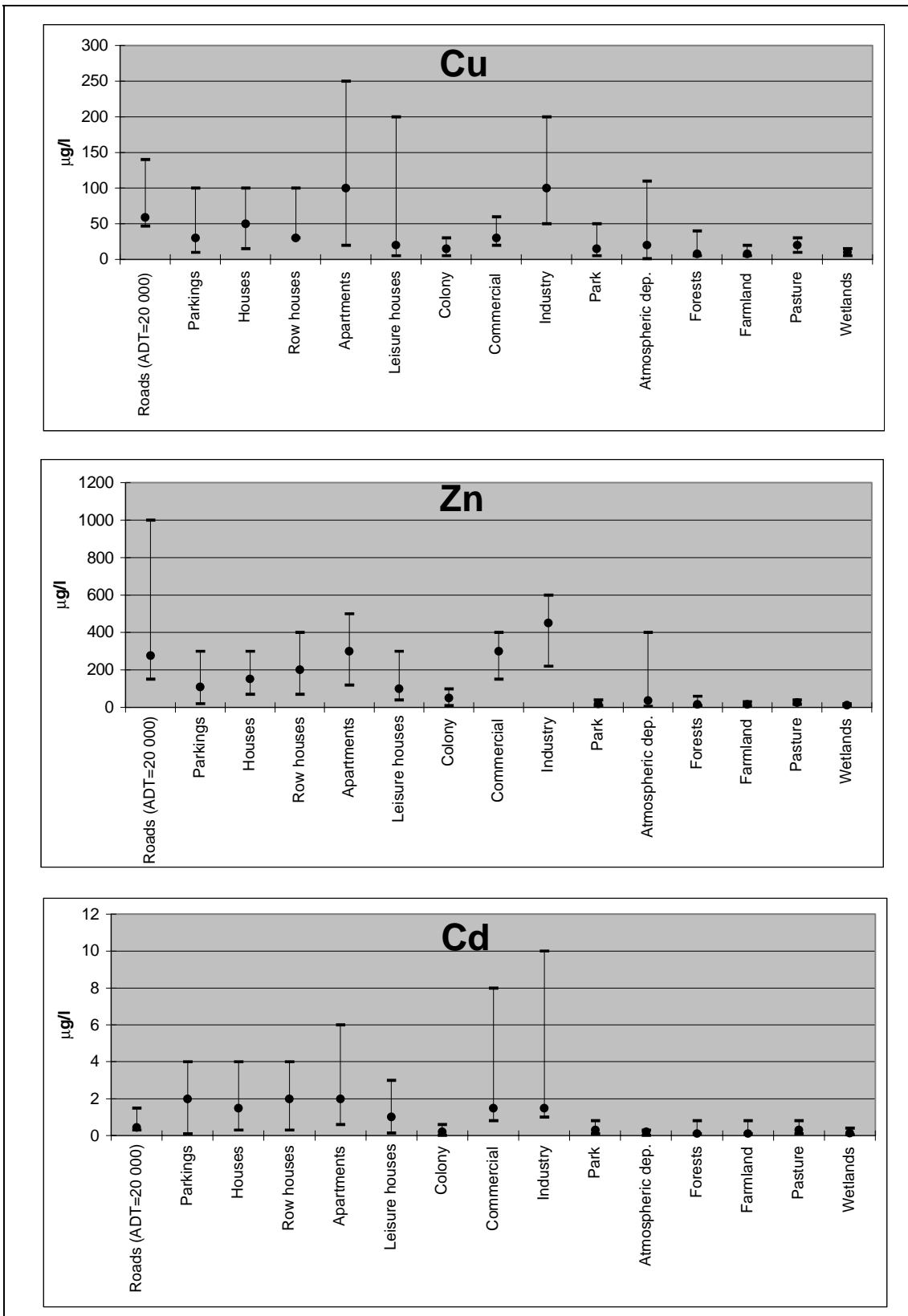
Figure 3   Land use specific standard concentrations, minimum and maximum concentrations of Cu, Zn and Cd used in StormTac, version 2000-11.

3.4 Preliminary stormwater quality criteria

The concentration rather than the annual load is in some cases needed to assess a water quality problem. This is the case with trace metals and toxicants, which primarily impact the environment when their concentration exceeds a critical limit (Schueler, 1987).

In Larm (1998) we compiled preliminary limit pollutant concentrations, i.e. stormwater quality criteria. The values were obtained from cooperation with Stockholm Water Company, the Environment and Health Administration in Stockholm, the Streets and Real Estate Administration in Stockholm and Stockholm City Planning Administration. There is a lack of similar studies both in Sweden and in other countries.

In Table 4 we present these preliminary limit concentration values for stormwater, where exceedence of the lower values indicate a need for treatment, especially at sensitive recipients. These values are the most important. Exceedence of the higher values indicate that more sophisticated treatment is required, see Larm (1998).

Table 4   Preliminary limit concentrations values for acceptable emission to surface water recipients (Larm, 1998). Comparisons to U.S. EPA criteria from 1983 for water hardness 50 mg/l CACO3 (Schueler, 1987).

	P	N	Pb	Cu	Zn	Cd	Cr	Ni	Hg	SS	oil	PAH	BaP
	mg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	µg/l	µg/l
low	**0.125**	**1.7**	**20**	**25**	**175**	**0. 4**	**15**	**20**	**0.04**	**80**	**1**	**1**	**-**
high	0.300	3	60	75	250	2	20	40	0.2	250	3	3	-
EPA1			150	20	380	3							
EPA2			50			10		13					

In Table 4 "EPA1" is U.S. EPAs ambient life intermittent threshold effect concentration from 1983 causing mortality to the most sensitive individuals of the most sensitive species. "EPA2" is U.S. EPAs drinking water criteria from 1983 (Schueler, 1987).

The values "high" and "low" in Table 4 have been estimated with consideration to background concentration, groundwater concentration, standard concentrations for stormwater and limit concentration values for recipients. We classified stormwater concentrations by designating the class "low concentrations" for values lower than the lower limit values in Table 4. The concentrations between the lower and higher values in Table 4 were considered as "relatively high" and higher values as "high".

3.5 Design parameter values for stormwater treatment facilities

The design parameter values in Table 5 are used for the design of the treatment facilities in the case study Sätra, see Chapter 5.4.

*Table 5   Design parameter values for stormwater treatment facilities. Values marked
            "*" are specific for the case study Sätra.*

Notation	Description	Unit	Input data
φ	Runoff coefficient		0.24*
φ_s	Specific runoff coefficient for A_s		0.24*
A	Watershed area	ha	26.5*
A_s	Specific watershed area that contributes to runoff during the design rain duration	ha	26.5*
h	Average water depth for the whole facility	m	1.25 (1-2) wet pond 0.5 (0.5-0.75) wetland
N_{d1}	Constant value of (number times) the detention volume	-	1.25 (1.0-1.5)
N_{d2}	Constant value of (number times) the detention volume	-	3
p	Precipitation intensity (rain+snow)	mm/year	636 (400-900)
r_d	Rain depth	mm	15 (5-35) wet pond 25 filter strip
t_{r2}	Rain duration	min	10
v	Water velocity	m/s	0.3 (0.18-0.3)

In Paper I and in Larm (2000) we identified some other important design parameters, for instance yearly average precipitation depth (r_{da}) and rain duration (t_{r1}). This indicates that precipitation statistics are important parameters for continued studies. The values of these parameters are site specific and play an important role regarding which areas and volumes of the facilities that are needed. Research results have shown that it is the smaller and more frequent rain events that contribute to the largest part of yearly pollutant loads. Therefore, stormwater treatment facilities should be designed for these rain events. This is especially the case for ponds and wetlands, but is partly also the case for filter strips and ditches (Larm, 2000). In contrast, for facilities where detention of stormwater flows is the main objective, it is more convenient to design after less frequent and larger rain events. The latter methodology is partly applied also for filter strips and open ditches.

3.6   Uncertainty

The uncertainty of the model is only briefly discussed below. Continued studies will focus on analyzing the uncertainty of the model results in StormTac. Results from 4 case studies indicate that monthly runoff coefficients and (standard) pollutant concentrations are the most uncertain parameters for the quantification of pollutant transport. The errors of these parameters are probably much larger than the errors concerning sampling and analyses.

Runoff coefficients: The uncertainty regarding the estimation of land use specific yearly runoff coefficients is yet to be estimated. The minimum and maximum values in Table 1 show that the uncertainty is large. Data from a couple of case studies indicate an even larger variation of runoff coefficients for specific months.

Standard concentrations: As for runoff coefficients we have not estimated the uncertainty of the standard concentration values, but the minimum and maximum values of the data are presented in Fig. 2-3, indicating a large uncertainty. Statistical studies of the American NURP (National Urban Runoff Program) data from 1983 have indicated that urban runoff and pollutant concentrations follow a lognormal distribution (Schueler, 1987).

Sampling: The analyzed grab samples from Sätra case study indicate as expected that grab samples taken during rain events generally give higher concentrations than during base flow conditions. This is especially evident for P, Pb, Cu, Zn, Cd and Cr. N, Ni and SS gave more varied results. A diagram presenting the error (%) of grab sample in relation to monthly flow proportional sample is under development. More data are required since the present data show a large scattering with both positive (concentration grab sample during rain > monthly flow proportional sample) and negative values. However, if the complementary analyses give the same indications, we have shown that grab sampling during precipitation events can not be used for calculating monthly pollutant loads. For example, the values for P were 0.11 mg/l for one grab sample from Sätra and 0.012 mg/l for the flow proportional sample during the same month, resulting in a positive error of 89%. During another month the corresponding values were 0.15 mg/l and 0.12 mg/l (20% error). The largest errors were indicated regarding Cd, SS and Ni.

Flow measurements: In Paper III we discussed that even automatic flow measurements may provide uncertain data due to water leakage bypassing the equipment, backflows from the recipient, low altitude differences and freezing problems wintertime.

Precipitation: The sampling errors regarding precipitation are in this case divided into wind field deformation, evaporation and adhesion. The wind losses for Stockholm are estimated to 7 (2-10)% for rain and 15 (10-50)% for snow. These losses sum up to around 9% or 48 mm/year. Evaporation is especially occurring during spring and summer in Stockholm. The evaporation losses are estimated to 2.4 (0-4)% equal to an underestimation of about 13 (8-15) mm on a yearly basis. Adhesion means that precipitation is left on the surface of the sampling pot when emptied. The adhesion loss is 7 (2-10)%, 0.2-0.25 mm/sample or about 38 mm/year (Eriksson, 1983; Alexandersson and Andersson, 1995). These sampling errors give an underestimation of the precipitation of about 18% or 100 mm/year in Stockholm.

Number of rain gauges: a case study within the FIFE catchment (a multi-disciplinary field experiment over a 15 km grid in the Konza Prairie) concluded that up to 8 rain gauges covering the whole catchment would be needed for valuable precipitation measurements. The results from analysis of 21 rain gauges (collected at 30-minute intervals) showed that the sampling error is reduced by adding more rain gauges, but the improvements in error performance is less as the number of gauges increases. It was assumed that the average rainfall information over the area represents the "true" rainfall. The sampling RMS (root mean square) error $\varepsilon = \sum(OBS-TRUE)^{1/2}$ between the observed rainfall (OBS) at one point in the catchment area and the "true" rainfall (TRUE) for that area was calculated at each time of observation, i.e., every 30 minutes. An estimation of the least number of gauges required to observe the rainfall event (a short rainfall event selected for spatial sampling analysis) to a required accuracy was provided in a diagram (Larm, 1996 and Andersson et al, 1995). One curve relates the total rainfall recorded at each gauge over an event to the sampling error, indicating that

approximately 4 gauges are necessary to observe precipitation to within 10% of the mean. The other curve showed rainfall sampling at each time (30 minute interval) within the storm event integrated over the duration of the storm, accounting for the temporal variability within the event. The latter curve indicated greater sampling errors, as well as that 6-8 gauges are required for achieving a 10% error (Andersson et al, 1995).

4. STORMWATER POLLUTANT SOURCES: TREKANTEN AND SÄTRA CASE STUDIES

During stormwater runoff from roads, roofs, parking areas, green areas etc, particles and pollutants are flushed with it. Therefore, stormwater runoff contains, e.g. nutrients (nitrogen and phosphorus), oil, persistent organic compounds and heavy metals such as zinc, lead, copper and cadmium. The origin of these substances is for example tearing of car breaks and road surface and erosion of tin roofs, copper sewers and lampposts, but also natural soil. The substances are naturally discharged in the environment, but in stormwater the concentrations can be so high that the pollutants cause negative impacts on plants and animals. Furthermore, in many watersheds, stormwater contributes to the largest pollutant load on lake recipients relative to other sources. The relative share of stormwater of this total load on a lake will probably continue to increase, e.g. depending on the increasing development of wastewater treatment plants and the decrease in industrial emissions (Stenström et al., 1984).

Generally, the largest pollutant sources of stormwater are traffic areas, atmospheric deposition, corrosion of copper roofs, surfaces coated with zinc and animal excretions (Svensson and Malmqvist, 1995). Analyses of the land use specific pollutant standard concentrations used in StormTac (see Table 2) and the standard concentrations compiled in Larm (1997) indicate that traffic areas generally are the most polluted land uses, especially concerning oil, Cd, Ni, Fe and COD. Among the traffic land uses, parking areas are generally the least polluted. Stormwater from areas with houses contains lower concentrations of nitrogen and oil compared to other urban land uses. Nutrient (P and N) concentrations generally increase with more densely urban land uses. Stormwater from areas with apartments contains higher concentrations of nutrients and pollutants than stormwater from areas with houses. Stormwater from roofs generally contains low pollutant concentrations, with the exception of e.g. copper roofs, which contribute to large stormwater copper concentrations (see Paper IV). The contribution of zinc from roofs to stormwater can locally be substantial due to corrosion effects. Storm-water from commercial areas contains about equal high nutrient concentrations as domestic and traffic areas. Animal excretions may be a large source of phosphorus. Stormwater from industrial areas is generally very polluted and contain especially high concentrations of SS, Pb, Zn and Cu. Runoff water from forests contains low concentrations of P, BOD and metals, and relatively low concentrations of N and SS. Runoff from agriculture land (farmland) contains high nitrogen concentrations (Larm, 1997).

In Larm (1997) there are some indications of time trends in concentrations presented, with the help of indications made by Malmqvist et al (1994). The resulted indications were that phosphorus, nitrogen and oil concentrations do not show any change in values in time. From 1980 to around 1994 the concentration of suspended solids decreased with around 25%. The lead concentration has decreased heavily, approximately around 60-80% for larger Swedish cities, during the same period. For smaller cities the decrease in lead concentration was around 50-60%. No clear trend regarding copper and zinc was indicated by the data compiled in Larm (1997), but according to Malmqvist (1994) copper concentrations have decreased with 65-90% from 1980 to around 1994 and zinc concentrations have decreased with around 25%. The indicated decrease in concentrations is due to harder emission limits. The continued decrease in lead

concentrations after 1994, as indicated by data from Sätra (Larm and Holmgren, 2000) and Trekanten (Paper IV and Larm and Holmgren, 1999), is also due to lead free petrol.

The land use of highest pollutant concentrations is not necessarily the most important regarding measures for pollutant reduction. We need to get an overview of the pollutant loads on the recipients in order to choose proper measures.

4.1   Trekanten case study

In Paper IV, we employed and calibrated a source model in order to study different pollutant sources of the loads on Lake Trekanten in Stockholm. We performed flow proportional sampling during one year including deposition and corrosion measurements and a detailed material inventory of the area. Furthermore, the source model simulated the effects of assumed pollution abatement measures. The study has been updated with complementary data (Larm and Holmgren, 1999).

In the updated study, the source model has been adjusted concerning precipitation data (mm/year), deposition data (mg/m^2/year) and material emission coefficients (mg/m^2/year). After this calibration of the model, calculations of water flow, concentrations and load for the domestic area Nybohov show good agreement with measured data. Based on the experiences from Nybohov, the model seems to be able to estimate the pollutant loads from residential areas, at least for the specific metals studied. However, the source model did not make reliable estimations of phosphorous. The explanation is either unidentified phosphorus sources, especially from traffic, or wrongly estimated phosphorus emission coefficients. The model results concerning PAH are not verified, which render a complete evaluation. It is also uncertain if the model is trustworthy for quantification of pollutant loads from traffic areas. However, the agreement between measurements and model results were improved also for "Essingeleden" (a highway passing through the watershed) after the adjustments. The model applicability is limited by the extensive amount of site-specific data and assumptions needed. However, it is not unique for this specific model that the model results improves with more and better data, since this applies to most models. Provided that some input data adjustments are done, the source model may be used to identify the major metal sources polluting stormwater.

The updated source model results indicate that building materials are the largest source of copper in areas with copper roofs and an important source of zinc. Generally, traffic is also estimated to be an important copper source. Additionally, traffic is an important source of PAH, lead and zinc. Large amounts of cadmium and PAH also come from atmospheric deposition.

4.2   Sätra case study

The dominant urban land use in Sätra is row houses, see Table 6. Copper loads were identified as the largest problem in respect to acceptable loads and concentrations on the planned (today the stormwater is lead directly to Lake Mälaren) receiving watercourse Sätraån. In the study (Larm and Holmgren, 2000) we employed two different methods for identification of the major copper sources. One method was to use StormTac for quantification of the copper loads (kg/year) from prevailing land uses. The other method was to employ used emission coefficients from Trekanten case study, using Eq. (28).

Fig. 4 indicates that the land use consisting of row houses contributes to the largest copper load (47% of totally 2.0 kg copper from the total catchment area). The concentration of copper from row houses are estimated to be less than from apartments and the road area, but the dominating area of the row houses explains the larger load from this land use. It should be observed that the land uses houses, row houses and apartments include local traffic and traffic surfaces, gardens etc. 26% (0.5 kg/year) of the copper load comes from the apartments.
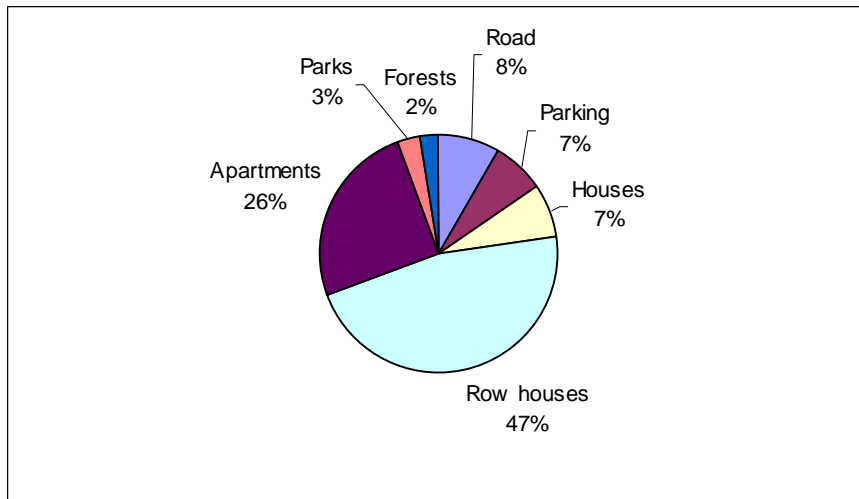

Figure 4   Copper sources in the form of different land uses. Percentages of the total load coming from the studied catchment.

By using data from Trekanten case study (Paper IV and Larm and Holmgren, 1999) we identified the dominant specific copper sources. From in-situ investigations we estimated that the contributing copper surfaces in direct contact with stormwater was only 95 m^2, all coming from the building installations gutters, drainpipes and metal window sills attached to the apartments. Employing the copper emission coefficient 2600 mg/m^2/year (calibrated value from Trekanten case study) we estimated these buildings contribution to 0.25 kg copper per year (see Fig. 5), i.e. 13% of the total load. The following equation was used for this application:

$$L_{jm} = \frac{K_{jm} A_m}{10^6}$$
(28)

L_{jm} load from a material surface (kg/year)
j   substance
m   material surface
K_{jm} emission coefficient for a specific material surface m and a specific substance j
         (mg/m^2/year)
A_m area of a material surface (m^2)

We compared this copper value (0.25 kg/year) to the value 0.5 kg/year from the land use apartments and estimated that 0.25 kg/year within the area with apartments comes from traffic and atmospheric deposition.

In Larm and Holmgren (2000) we concluded that the largest specific copper sources for the total watershed of Sätraån were traffic and atmospheric deposition. Fig. 5 shows the

specific copper sources from this watershed, in terms of kg copper per year. The estimated uncertainty is indicated by the interval values. To get these intervals we employed minimum and maximum data from Trekanten case study. More specifically, these data consisted of e.g. measured emissions of copper from copper roofs, deposition data and measured concentrations from the highway Essingeleden. The points indicate the most probable values.
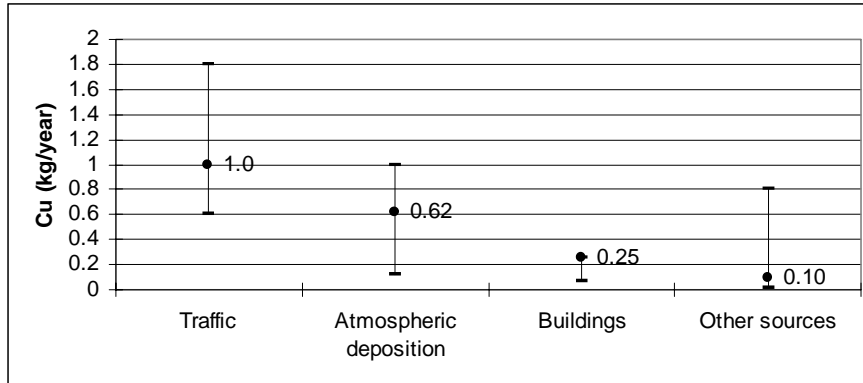

Figure 5   The contribution of copper loads (kg/year) from different specific sources within the watershed of Sätraån. Most probable, minimum and maximum values

In the following chapter, we summarize in more detail the results of the Sätra case study.

5.   SUMMARY OF RESULTS: SÄTRA CASE STUDY

The following two sections include presentation of the calibrated model parameters runoff coefficients (for calculation of runoff flow) and standard concentrations (for calculation of pollutant loads) as results from model application to the Sätra case study.

5.1   Calibration of stormwater flow and runoff coefficients

In Sätra case study, the objective was to investigate the possibilities to increase the water flow in the watercourses of Sätraån and Skärholmsbäcken by the addition of stormwater. This stormwater is today conducted in sewers directly to the lake recipient Mälaren. The watershed areas were identified concerning land use distribution and the areas of each land use were quantified, see Table 6.

Table 6   Land use distribution in Sätra.

Land use	Area
	ha
Roads	0.7
Parking	1.0
Houses	2.1
Row houses	6.5
Apartments	1.3
Parks	4.2
Forests	10.7
Total	**26.5**

Stormwater flow was measured automatically and pollutant concentrations were measured by performing flow proportional sampling during a period of one year (June 1999 to May 2000) in a stormwater well at Sätraån. The collected samples were mixed proportional to the flow and composite samples each representing a period of one month were analyzed. These data were compared to model calculation with StormTac, using standard values. Complementary grab samples during precipitation events and during base flow were also taken. An automatic precipitation gauge was placed within the catchment to register the precipitation, known to have local variations.

The precipitation during the 12 months is presented in Fig. 6 The match between local measured precipitation and measured precipitation from the gauge in Stockholm (placed at a distance of around 10 km from the local gauge) was very good, in spite of the generally large local variations.
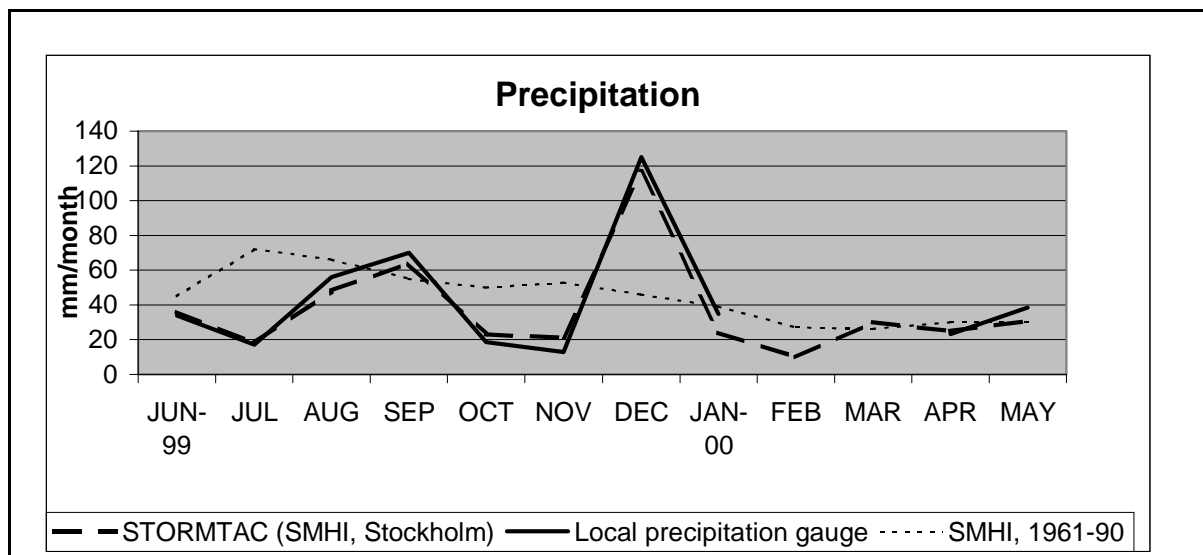
Figure 6   Precipitation data from the SMHI gauge Stockholm compared to local data.

Monthly values of runoff coefficients have been estimated from existing flow data, precipitation data and estimated watershed area, see Eq. (2). The runoff coefficients are typically largest during snowmelt, see Paper III. One example is the high runoff coefficient during December 1999, see Table 7.

The intention was to calibrate yearly runoff coefficients for each land use. However, due to problems related to the flow logger there were only monthly flow data for the period June to December 1999, why such yearly runoff coefficients could not be calibrated. Furthermore, monthly values have not been calculated for so many case studies as yearly values. In Table 7, we therefore only compare monthly runoff coefficients estimated from measured flow data with the corresponding model computed values. The computed monthly runoff coefficients (φ) are estimated from empirical data and are depending on their estimated yearly total runoff coefficient for the case study. The uncertainty is large regarding monthly values since the empirical data from other case studies showed large variations between years.

Table 7   Comparison of monthly estimated runoff coefficients in Sätra 1999. φ^* is estimated from measured flow data and φ is computed by StormTac.

Month	φ^* Sätra	φ StormTac
June	0.16	0.19
July	0.13	0.16
August	0.13	0.29
September	0.17	0.17
October	0.17	0.24
November	0.19	0.27
December	0.93	0.33

The results also show that flow and runoff coefficients vary significantly between different land uses.

Base flow: The base flow has been calculated to 0.45 l/s, using Eq. (7) and assuming $K_x=1$. The performed flow measurements were uncertain at such low flows, but they indicate that the base flow is less than 1 l/s even if estimations of up to 3-4 l/s have been made during the period of measurements.

5.2 Calibration of pollutant concentrations and loads.

Model calibration or comparison to measured data regarding runoff flow and pollutant concentrations has earlier been performed for the following case studies: Nybohov, Stockholm (residential), Essingeleden, Stockholm (road) and Flemingsbergsviken, Huddinge (mixed). Very good match between estimated concentrations from the model and the measurements in Sätra case study were achieved for P, Cu, Cr and Ni, see Fig. 7-8.
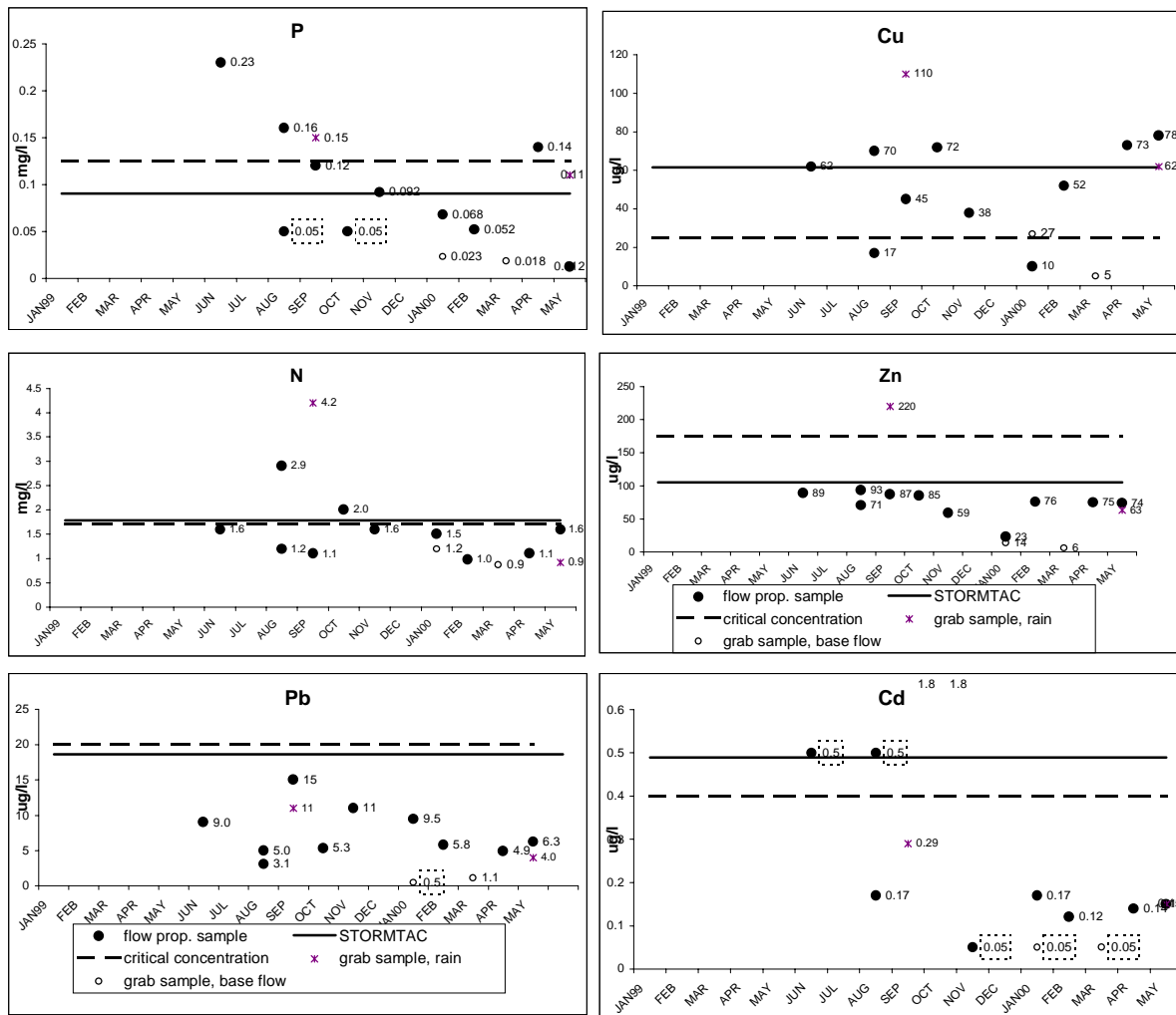

Figure 7   Concentrations of P, N, Pb, Cu, Zn and Cd during 1999-2000. Monthly flow proportional samples (●), grab samples during rain (x) and during base flow (o). Yearly calculated concentrations with StormTac (—) before calibration and preliminary limit acceptable concentrations (---) are also included. The framed values are below the detection limits.
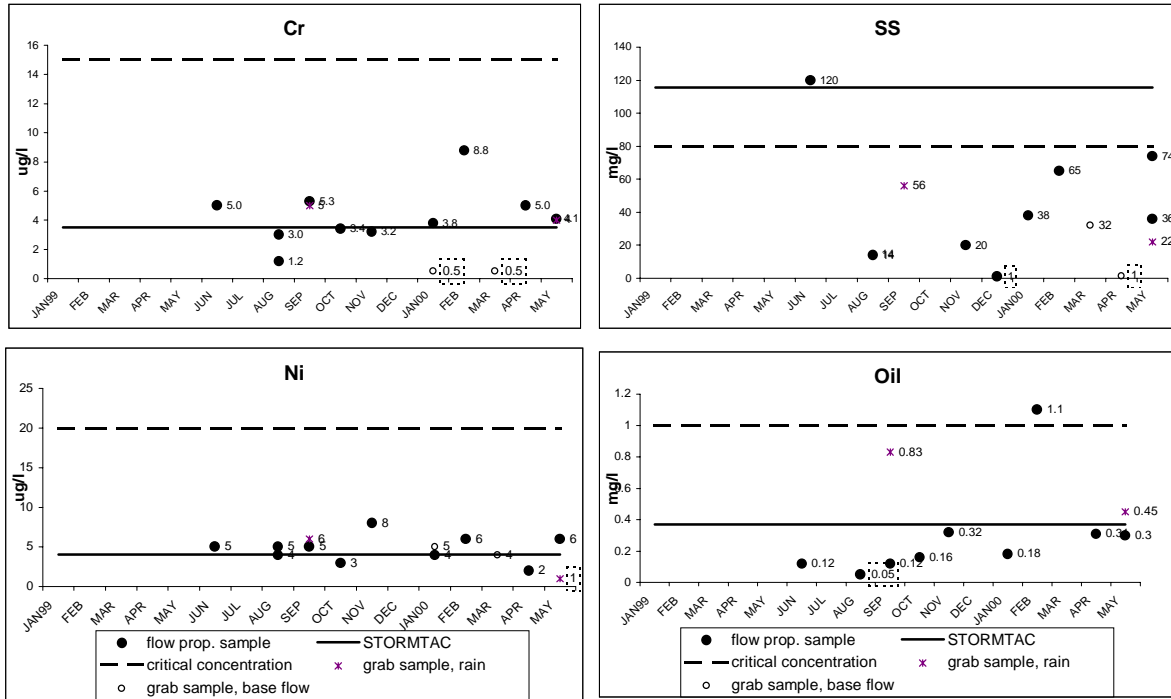
Figure 8   Concentrations of Cr, Ni, SS and oil during 1999-2000. Monthly flow proportional samples (●), grab samples during rain (x) and during base flow (o). Yearly calculated concentrations with StormTac (—) before calibration and preliminary limit acceptable concentrations (---) are also included. The framed values are below the detection limits.

Reasonable agreement was estimated for N, Zn, Cd and oil with somewhat high model values. Pb and SS showed a relatively good match. The higher Pb-values are explained by the strong decreasing trend in Pb-concentrations since the introduction of lead-free petrol around 1994. The measured SS-concentrations are low compared to similar case studies. The framed values in Fig. 7-8 are assumed to be half of the detection limits.

The yearly concentrations proportional to flow are compiled in the bottom row of Table 8. We justified/calibrated some of the parameters for the prevailing land uses. Empty cells in the table indicate that the original value is assumed/estimated to be representative. The largest changes of parameter values were performed for Pb and SS.

After having justified the standard concentrations in StormTac, the calibrated model was applied on Skärholmsbäcken. Since we have data from "only" a yearly period and from a mixture of land uses, we employ only the calibrated model parameters for this specific case study, i.e. for Sätraån and Skärholmsbäcken. Complementary data are needed however before it is justified to change any of the standard values in the model.

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Table 8   *Standard concentrations (mg/l and μg/l) from original and calibrated values. Comparisons to yearly flow proportional measured values (bottom row).*

Land use		P	N	Pb	Cu	Zn	Cd	Cr	Ni	SS	Oil
		mg/l	mg/l	μg/l	μg/l	μg/l	μg/l	μg/l	μg/l	mg/l	mg/l
Road	origin	0.05	1.0	26	49	169	0.3	2	2	56	0.6
	calibrated			20		150	0.5	4			0.4
Parking	origin	0.1	1.1	50	30	110	2.0	3	4	60	1
	calibrated			14							0.6
Houses	origin	0.1	1.4	10	50	100	0.3	4	4	100	0.2
	calibrated	0.15	1.3	6		50	0.5		5	45	
Row houses	origin	0.1	1.5	15	100	150	0.3	4	4	100	0.4
	calibrated	0.16	1.4	10	80	90	0.7	6	7	45	0.25
Apartments	origin	0.2	1.6	20	150	150	0.5	13	16	150	0.4
	calibrated			17		120	1.0		12	60	0.25
Park	origin	0.08	5.55	5	15	18	0.1	1	2	340	0
	calibrated		4.3	1.0			0.2			70	
Forest	origin	0.025	1	9	8	15	0.1	0.1	0.5	54	0
	calibrated		0.9	1.0						30	
total	origin	0.09	1.8	19	62	100	0.5	3.5	4.0	116	0.37
	calibrated	0.11	1.6	9	55	77	0.7	4.4	4.7	50	0.24
	measured	0.11	1.6	9	56	75	0.7	4.4	4.6	46	0.24

Calculated stormwater loads from measured (flow-proportional) concentrations and from standard concentrations are shown in Table 9. It is difficult to calculate base flow concentrations and loads. The measured base flow concentrations at Sätra showed to be much larger than measured groundwater concentrations in Stockholm. We used measured base flow values even if only grab samples were carried out. The assumption is that the time variations in base flow concentrations are small. Table 9 shows the yearly load from base flow based on only two grab samples. Further sampling is planned.

Table 9   *Calculated pollutant loads in stormwater resulting from standard values (original model) and from measured concentrations and flow (calibrated model). Base flow loads from measured concentrations and the share of base flow to stormwater are also presented.*

	P	N	Pb	Cu	Zn	Cd	Cr	Ni	SS	Oil
	kg/year	kg/year	kg/year	kg/year	kg/year	g/year	kg/year	kg/year	kg/year	kg/year
Stormwater; original model	3.2	64	0.67	2.2	3.8	18	0.13	0.15	4200	13
Stormwater; calibrated model	4.1	57	0.33	2.0	2.8	25	0.16	0.17	1800	8.5
Base flow; measured concentrations	0.29	15	0.01	0.23	0.14	0.7	0.007	0.064	198	-
Base flow / stormwater calibrated model (%)	7	26	3	12	5	3	4	38	11	-

The match between loads from the original and the calibrated model is relatively good for all substances studies, with the exception of SS. According to Schueler (1987) SS concentrations in urban runoff cannot be predicted from simple models based on standard values. Data from the American NURP study indicated that SS concentrations are better estimated by relating them to watershed size. Lower SS concentrations were e.g. reported for very small watersheds. However, the relationship between mean storm sediment levels and drainage areas has a large variability.

5.3   Comparisons to stormwater quality criteria.

Stormwater in which the yearly average pollutant concentrations do not exceed critical or limit concentrations may be discharged to recipients without treatment. The critical concentrations that measured data and model data have been compared to in Fig. 7 through 8 correspond to preliminary values valid for Stockholm (Larm, 1998), see Table 4 in the row marked "low". This comparison can provide an indication whether treatment is needed or not.

Even if the comparisons to the preliminary values are uncertain, there were relatively strong indications that the copper concentrations are high enough for considering treatment or reduction of copper sources. The other pollutant concentrations, possibly with the exception of cadmium, are below the limit concentrations.

5.4   Design of stormwater treatment facilities.

The design methods compiled in Chapter 2.5 have been applied on three Swedish case studies with different land uses, see Paper I. This chapter shows the results for the additional case study Sätra. We only present the results in required area per "reduced" hectare (red ha) watershed, but in contrast to Paper I we also show the needed area for filter strips and constructed wetlands. By a reduced area we refer to an area that has been multiplied with the runoff coefficient of this area. We also show here the required areas for minimum and maximum values of each parameter, assuming fixed and constant values of runoff coefficients (φ and φ_s), areas (A and A_s), yearly precipitation (p) and rain duration (t_{r2}). The parameter values used are presented in Chapter 3.5.

Employed "standard" values of rain depths r_d=13-15 mm result in around 90% of the yearly precipitation is included, assuming that the initial rain loss r_s is 0.5-2.5 mm. If r_d=9-10 mm for the same r_s then around 80% of the precipitation is included. In Paper I and in Larm (2000) we estimated that 80% of the precipitation in a watershed in Stockholm is included at r_d=16-17 mm. Updated analyses of the precipitation data have shown that events with maximum r_d=16-17 mm comprise 80% of the total precipitation. However, for larger rain depths the first 16-17 mm are also captured, resulting in a total of over 90% of the precipitation being included at these depths. This also results in that wet ponds only need to be designed for a rain depth between 9-10 mm, and not 16-17 mm, to include 80% of the precipitation. In the case study Sätra we employed a rain depth between 5-35 mm and 15 mm being the standard value. This results in including 90% of the yearly precipitation.

The results presented in Fig. 9, which are to be considered as preliminary, show large differences in required dimensions of the facilities depending on which values of the design parameters are used. The results indicate that wet ponds require an area of around 270 (50-875) m^2/red ha, filter strips around 1235 (1235-2060) m^2/red ha and constructed wetlands around 1215 (810-1215) m^2/red ha.
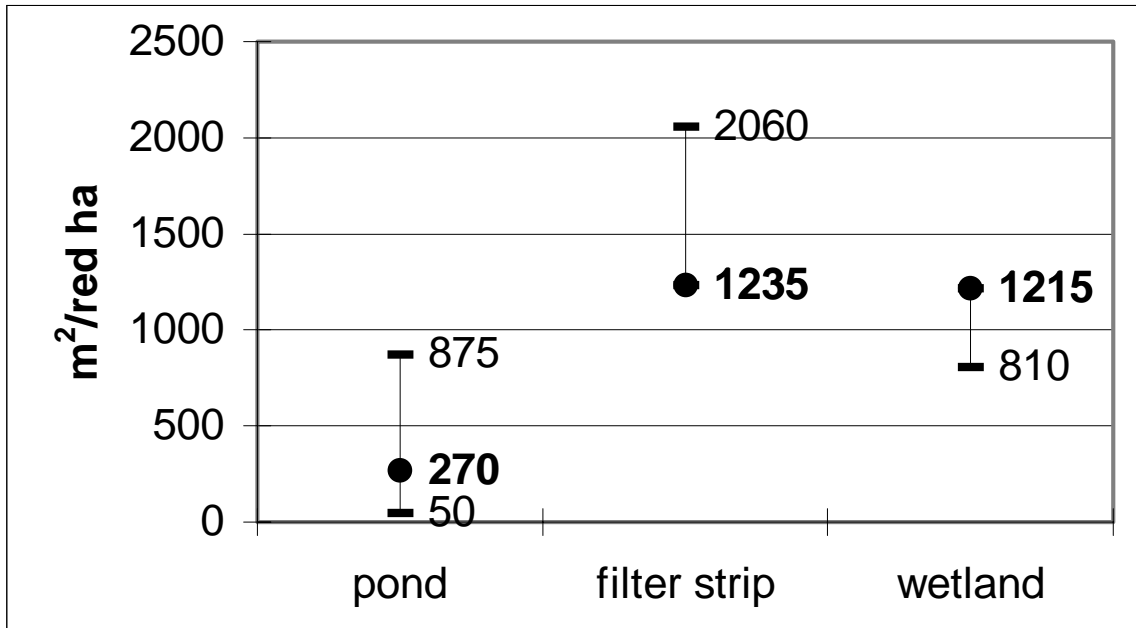
Figure 9   Required areas per reduced hectare watershed area (m²/red ha) for wet ponds, filter strips and constructed wetlands. Standard, minimum and maximum values for the presented methods (by using maximum and minimum values of parameters).

Below, we show results from literature studies and consultant experiences from several case studies regarding the general design of wet ponds, filter strips, constructed wetlands, open ditches and swales. These general design "guidelines" are presented in more detail in Larm (2000).

Wet ponds: Wet ponds are ponds with a permanent water surface, which are receiving, compensating and treating stormwater, see Fig. 10. For wet ponds the optimal water depth appears to be around 1.5-2 meter. A side slope flatter than or equal to 1:3 and a length:width ratio larger than 3:1 is also preferable. It is advantageous with a shallow vegetation zone around the pond (see section A-A in Fig. 10). The inlet ought to be constructed to spread the water into the pond. Stones, which also have an airing effect on the water, can for example be used. A v-shaped weir or sewer at the outlet provides a flow compensation effect (UDFCD, 1999; Persson, 1999; WEF and ASCE, 1998; Vägverket, 1998; SEPA, 1997; Larm, 1994). This flow compensation is performed in the detention volume (V_d) above the permanent volume (V_p), see Fig. 10. Furthermore, multiple outlets at two or more levels can be used, with the outlet of the smallest dimension at the level of the permanent pond surface. This may result in letting out flows from smaller runoff events during a design emptying time (t_{out}). These flows contain the largest pollutant load on a yearly basis.
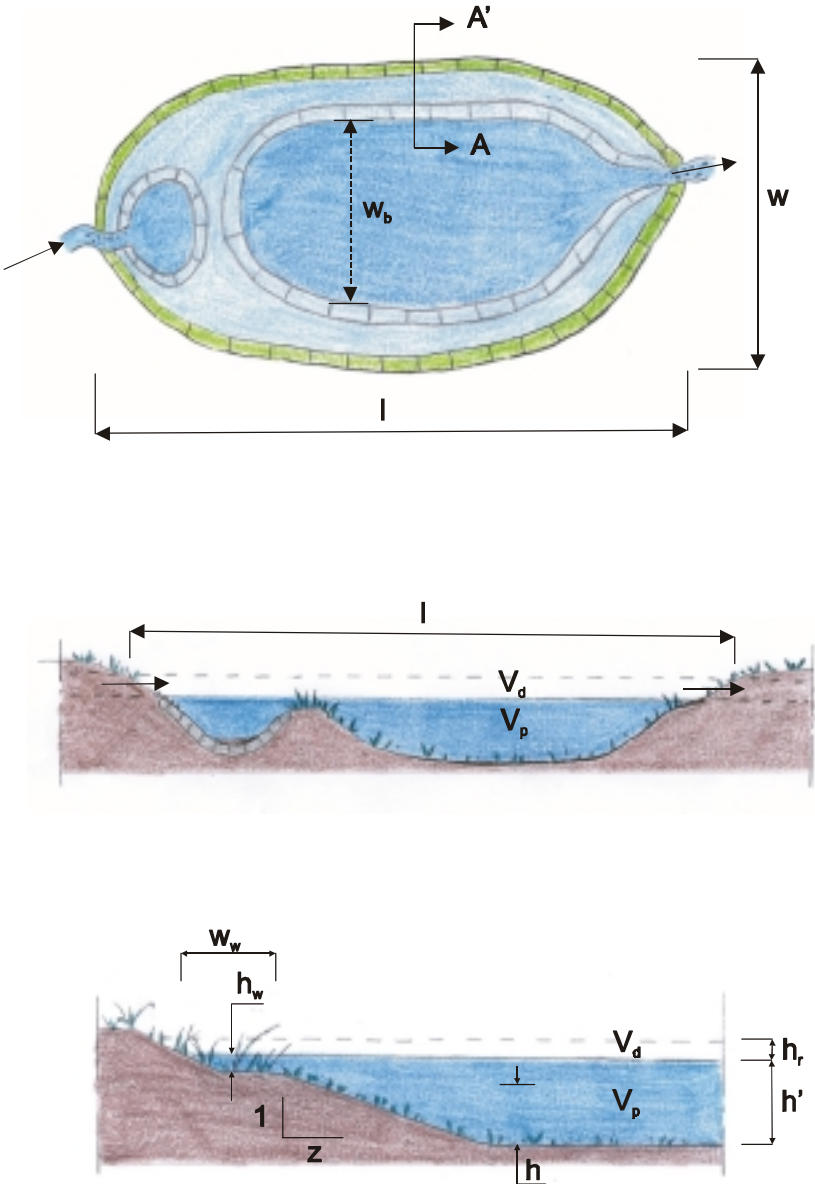
Figure 10 Plane, profile and section (A'-A) of a wet pond (not made to scale) (Paper I and Larm, 2000).

Filter strips: Filter strips are constructed or existing green surfaces, which preferably are receiving stormwater over their total width, see Fig. 11. Part of the water is runoff and part is infiltrated through the soil. Filter strips require a spreading construction at the inlet, e.g. a ditch followed by a macadam layer, to evenly spread the water to the green surface (see Fig. 11). The surface should be even and have a length slope of around 2-5%.
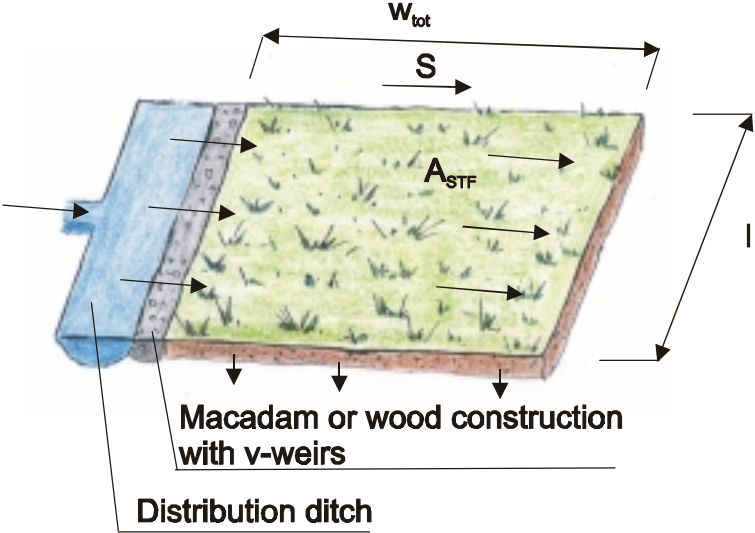
Figure 11   A filter strip (Larm, 2000).

Constructed wetlands: Constructed wetlands consist of mainly a shallow wetland part but also of a deeper wet pond at the inlet and often an outlet pond, see Fig. 12. Constructed wetlands are preferably performed oval with inlets and outlets at opposite short ends. The inlet construction for filter strips (see Fig. 11) may also be used for constructed wetlands in order to avoid channeling of the wetland. A wet pond at the inlet may reduce the sediment load on the wetland part. The wetland part may be constructed with various depths (see Fig. 12).
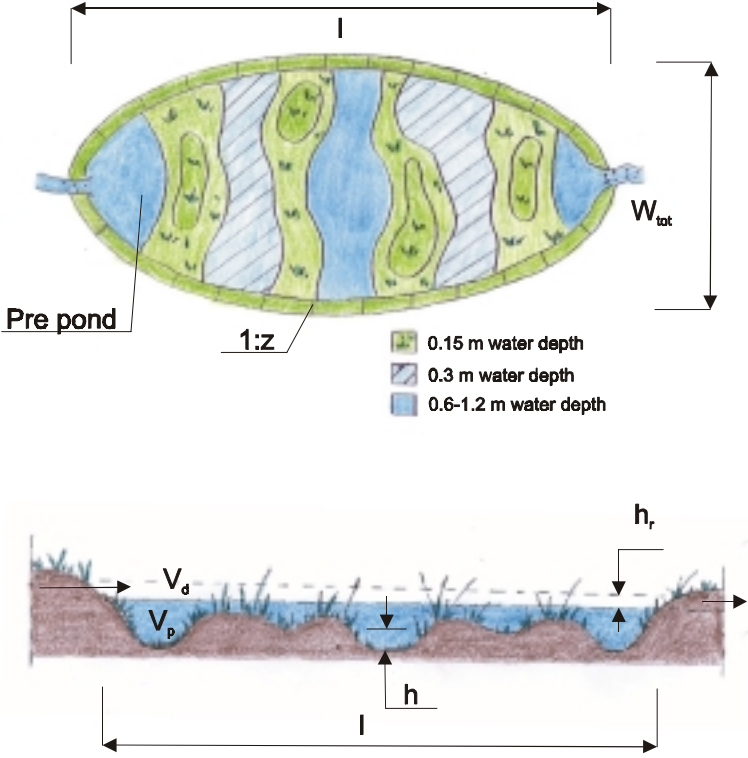
Figure 12   Plane (with example of different water depths) and profile of a constructed wetland (not made to scale) (Larm, 2000).

Open ditches and swales: Open ditches are stormwater ditches with relatively large slope, see Fig. 13, and swales are ditches that have smaller slope. For open ditches the slope is preferably less than 1:3. The flatter slope <1:4-5 is preferable for swales. The length slope can be around 2%. See Fig. 13.
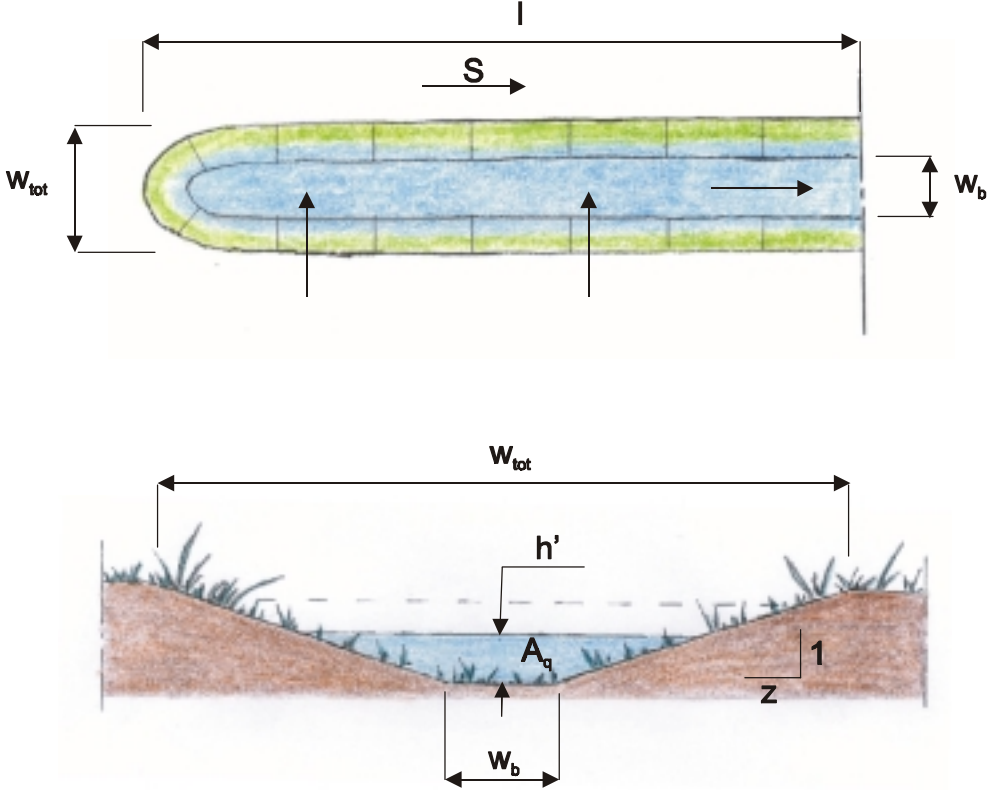
Figure 13 Plane and section of an open ditch (not made to scale) (Larm, 2000).

6. MONITORING PROGRAMS

In this chapter we summarize experiences from performing stormwater monitoring at, e.g., Sätra case study and Flemingsbergsviken case study (see Paper III). This chapter has no direct connection to our model development. However, a monitoring program has an important role for estimation of the reduction efficiency (see next chapter) of a stormwater treatment facility and for estimation of the quantity and quality of stormwater fluxes.

The optimal program may require flow proportional sampling during several successive years. Consideration should be made to that the efficiency is expected to be lower during the first years of operation, see Paper III. However, it is practical due to economical reasons to optimize the program to site-specific objectives, e.g. recipient's conditions, and to the economical situation of the project. If the only acceptable method would be to perform long term flow proportional sampling then there is a large risk that the constructed stormwater treatment facilities will not be evaluated at all. Therefore, it is necessary to have some ideas of the uncertainties and limitations of different sampling methods. Also, it is not always advisable to carry out flow sampling due to turbulent situations in the sewers, the risk for stealing the equipment etc.

To decrease the cost, one method is to perform the analyses on flow proportional collected composite samples, i.e. several frozen samples can be collected and analyzed as one sample. This sample can for example represent a period of one month. In order to include seasonal variations and to estimate yearly loads either a period of at least one year sampling with monthly values can be chosen or certain "campaign" periods can be selected. Such campaign periods can be divided into seasons, as for Sweden can e.g. a composite sample from samples taken during December to February represent winter, Mars to May represent spring, June to August represent summer and September to November represent autumn. During each period, samples from at least three precipitation events should be taken.

It is desirable, but can be difficult, to sample the same water mass at the inlet and outlet of a facility. In the long term, when we have a large set of relatively reliable monitoring data for each type of facility during different conditions; it is possible that we can estimate the reduction efficiencies from developed empirical models based on this data set. Until then it is important to monitor the facilities constructed. Here follows a short compilation of examples of monitoring methods, their possibilities and problems.

Pre studies: StormTac can be used for establishing the monitoring program by calculating expected pollutant concentrations and expected flows. This can help in choosing the proper analysis method (e.g. for avoiding values below the detection limit) and in adjusting the flow intake to the sampler when taking flow proportional samples. After some time of the sampling, the model can be calibrated to the data and the model may replace some of the sampling. The calibrated model can then also be used to estimate the other external pollutant loads on the recipient in a more reliable and site-specific manner, which is of relevance for quantification of acceptable loads on the recipient. It is advantageous to estimate if the facility is good enough for reducing enough of the total external load on the recipient or if added measures are needed for reaching a more sustainable recipient situation.

If possible, it is advantageous to perform sampling in the recipient before construction of the facility. Such monitoring should be performed both in the water phase and in the sediment near the planned outlet from the facility. The same parameters as are chosen for the facility should be monitored. This sampling should continue during the monitoring phase of the facilities and will provide a base for estimating the improving recipient effects.

The choice of parameters: Selected parameters to be included in the monitoring program are depended on recipient conditions. For instance, if a lake is eutrophied it is important to include phosphorus. Total concentrations should be included, but it is advantageous also to perform analyses on the dissolved fractions of the metals and the nutrients. It is difficult to estimate the dissolved fraction from literature data or from models since the dissolved fraction generally can differ from maybe in the order of 20 to 80 percent, see Table 3. The samples should be collected shortly after the precipitation event.

The following parameters are generally prioritized in a monitoring program: total concentrations of SS, P, N, Pb, Cu, Zn and Cd, and also pH and conductivity (both measured the same day as sampled), sediment depth (once per year) and continuously measured water level (to register possible overflow volumes). Furthermore, at least one precipitation gauge should be placed near the site to automatically register the precipitation. Precipitation data can be used for estimating flow during periods with lacking flow data and to be able to model the flow and loads for future calculations. Such calculated flow can also be used to collect samples proportional to calculated flow for analyses if not flow proportional sampling is used.

Examples of other parameters that at least can be analyzed for some of the samples are oil, Cr, Ni, bacteria (to identify possible leakage of sewage water into the stormwater system), phosphate (PO_4-P), nitrate (NO_3-N), ammonia (NH_4-N), chloride, water and air temperature, PAH, Hg, platinum and palladium. SS is an important parameter because other substances such as nutrients and metals can be estimated as a function of SS concentration (i.e. they have a certain correlation to SS). Such correlations are included in StormTac, developed from empirical data.

Sampling sites: Samples should preferably be taken at all major inlets and outlets of the facility and in the recipient. It is advantageous to complement with yearly taken sediment samples from within the facility.

Flow proportional sampling (Method 1): The sampler is connected to the flow measuring equipment and takes flow proportional samples (i.e. a large water flow gives a large sample volume). The method may require an installation of a weir to be able to measure the flow. The water level over the weir is measured whereas the flow can be calculated automatically. A water level difference is needed. The latter can be difficult at flat sites. The amount of sample to be taken for a predefined water volume is calculated to get enough large volume of water for the analyses.

Sampling proportional to the precipitation intensity (Method 2): The precipitation gauge is connected to the automatic sampler, which takes predefined sample amount proportional to the precipitation intensity, e.g. a certain sample volume is taken every half millimeter of rain. One problem is that the flow reaches the point of sampling at a certain time that is varying for different precipitation intensities. No reference studies using this method have been found in the literature.

Water level registration and time interval (Method 3): A collected sample of a predefined volume, e.g. 25 ml, is taken when the water level reaches a predefined value and then takes samples of this volume at a certain time interval, e.g. 5 minutes, until the water level reaches its start level. The result is a sample that is more representative than a grab sample but less representative than a flow proportional sample.

Time interval (Method 4): The sampler can be connected to a telephone to begin taking samples when a telephone signal reaches the sampler. Samples are taken at a predefined time interval until another telephone signal stops the samples or until there is no more water to sample. Either the sample can be taken when a precipitation is occurring off site, assuming that the precipitation at the site occurs at the same time as at the place where the telephone is placed (Method 4a), or preferably the local precipitation gauge can be connected to the telephone (Method 4b).

Grab sampling (Method 5): If sampling is performed during predestinated days or after a precipitation event has started, the effects may be too low concentration values since often the highest concentrations occurring during first flush are missed. If samples are taken at the same time at the inlet and the outlet of a facility, different water will be analyzed and consideration is not taken to the water residence time in the facility. If the first flush effect with high concentrations is missed for the inlet sample but not for the outlet sample, the resulted estimation of reduction efficiency will indicate a too low value and vice versa. The case study of the constructed wetland facility at Flemingsbergsviken in Paper III showed that grab samples taken at predestinated times do not provide a reliable basis for the estimation of reduction efficiencies. Sätra case study showed preliminary indications that grab samples during rain events generally result in higher concentrations than flow proportional composite samples but that grab sampling of the base flow may be used due to smaller flow variations. At base flow sampling the flow may be estimated either manually (by collecting a volume of water while measuring the time or alternatively by measuring the flow area and the water velocity of a floating object) or by a flow measuring equipment.

7. REDUCTION EFFICIENCY

7.1 Quantification of reduction efficiency

The reduction efficiency over the total facility can be estimated more trustworthy for time periods when both flow and concentration measurements exist, especially when there is more than one inflow. For quantification of reduction efficiency (RE), the following general formula is suggested in this study

$$RE = \frac{100 K_y \sum\limits_{i=1}^{N} (L_{in} - L_{out})}{\sum\limits_{i=1}^{N} L_{in}} \tag{29}$$

RE   Reduction efficiency (%)
K_y Share (0-1) of the yearly flow that is captured by the facility
L_{in} Inflow load on facility (kg/year)
L_{out} Outflow load from facility (kg/year)

L_{in} preferably includes diffuse mass fluxes from the ground surrounding the facility and atmospheric deposition directly on the facility. This diffuse load has often been neglected.

We approximate K_y by fitting precipitation data (average data from 1984-1993, showing precipitation in mm/h):

$$K_y = 0.16 \ln(\frac{3.6 Q_{in}}{10 A \varphi}) + 0.47 \tag{30}$$

This data was compiled by Stockholm Water Company (personal communication with Knut Bennerstedt) from road Torsgatan in Stockholm, assuming an initial rain loss (r_s) of 0.5 mm. Equation (30) can be used in many other cases when the objective is to estimate K_y for a certain stormwater flow.

The reduction efficiency is also dependent on inflow concentrations, with generally lower efficiency at low concentrations (see Paper III). An empirical equation of RE as a function of REs from Flemingsbergsviken case study is included in StormTac. The function is not presented here due to large uncertainties and the quality of the data (Paper III). The equation will be further developed when there is access to more data, e.g. to come from Kolardammen constructed wetland, south of Stockholm. In StormTac there is another sub model under development where RE for SS is expressed as a function of sedimentation time.

The following equations are developed in StormTac for estimating the reduction efficiencies of SS and P.

By fitting empirical data compiled in Hvitved-Jacobsen et al (1994), we get

$$RE_{SS} = 15.2 \ln(\frac{V_d}{V_r}) + 45.5 \qquad\qquad (31)$$

$$RE_P = 14.0 \ln(\frac{V_d}{V_r}) + 25.3 \qquad\qquad (32)$$

The regression coefficients are respectively R^2=0.44 and 0.57, implying that the fit is moderate.

By fitting empirical data compiled in Pettersson (1999), we get an alternative estimation of RE for SS:

$$RE_{SS} = 17.5 \ln(\frac{A_{STF}}{A\varphi}) - 19.5 \qquad\qquad (33)$$

with R^2=0.91; the data only represent 4 case studies.

In StormTac, preliminary functions have been developed for estimating REs for other pollutants. These functions are based on estimated dissolved fractions and also include a constant factor for representing the part of the dissolved fraction that is treated.

Both automatic flow and concentration data are required for reliable estimations of the reduction efficiency of a stormwater treatment facility. Reliable values of reduction efficiencies (REs) of the different facilities at Flemingsbergsviken cannot be estimated since no flow proportional sampling has been carried out. However, the sediment content of nutrients and metals has decreased in the lake bay after the facility, see Paper III.

The relatively large number of instantaneous samples during three years can nevertheless provide some indications of the relative importance of different types of facilities. The results indicate the most effective nutrient reduction to occur in the wet ponds. The oil separator and the open ditch seams to have no substantial nutrient reduction effect. One wetland indicates a small positive phosphorus reduction. The second wetland showed negative nutrient effects.

The positive trend in increasing REs of nutrients in the total facility is promising. Furthermore, the analyzed data indicate an effective reduction of bacteria during at least the first two periods (Huononen, 1996, 1997).

It should also be observed that these kinds of facilities often exhibit low reduction efficiency during the first couple of years. When conditions are more stabilized regarding soil and vegetation, an increased RE is probable, see Paper III.

The use of the site before construction of the facility can also influence the efficiency. If the site at Flemingsbergsviken was flooded by polluted stormwater the sediments of the facility will consist of accumulated pollutants even directly after the construction. The construction works may increase the risk of pollutant leakage from such sediments. This may lead to lower estimated reduction efficiencies.

Regarding seasonal variations of the total constructed wetland area at Flemingsbergsviken there are indications that phosphorus is removed most efficiently during winter. The common

wisdom is that the removal of phosphorus is lowest during winter and greatest during summer, since biological activity is greatest summertime and lowest wintertime. However, although plant growth and microbial uptake may be "operating in high gear" during the summer period, so are the processes of leaching and decomposition. This means that high P returns from, e.g., the sediments may counterbalance high uptake rates. During winter, the low temperature slows both uptake and return transfers, but the net transfer may remain high according to Kadlec and Knight (1996).

The fraction phosphate phosphorus (PO_4-P) to total phosphorus (P) was around 43% in the inflow water to the facility at Flemingsbergsviken. The reduction efficiency was lower for PO_4-P than for total P. Around 32% of the total nitrogen (N) was nitrate (NO_3-N) and nitrite (NO_2-N) nitrogen. The reduction efficiency was higher for NO_3-N and NO_2-N than for total N. It is especially the PO_4-P but also the NO_3-N (in more eutrophic lakes) that are most available for plant uptake; these nutrients are limiting for growth and have largest importance for the lake eutrophication processes.

7.2 Data base in StormTac

Table 10 is compiled from a database in StormTac. It shows literature values of reduction efficiency (%). The data should be used only for comparison to reduction efficiencies estimated from Eq. (29)-(33). The use of the data is limited since the references of the data generally do not present the design methods used and it is not clear if e.g. a constructed wetland includes a wet pond or not.

Table 10   Reduction efficiencies for some of the stormwater treatment facilities compiled from the database in StormTac, version 2000-11.

	P			N			Pb			Cu		
	median	min	max	median	min	max	median	min	max	median	min	max
Wet pond	55	15	85	35	7	50	75	47	93	70	18	90
Filter strip	40	30	50	25	7	50	80	70	90	80	70	90
Constructed wetland	54	10	60	21	12	25	75	65	80	36		
Open ditch	31	30	38	18			30	25	35	49		
Grassed swale	30	10	40	30	10	40	75			50		

	Zn			Cd			SS			Oil		
	median	min	max	median	min	max	median	min	max	median	min	max
Wet pond	45	20	90	80	70	90	80	56	91	80		
Filter strip	80	70	90	80	70	90	80	70	90			
Constructed wetland	62.5	50	75				77.5	73	90	96		
Open ditch	62.5	51	74	54	50	70	74					
Grassed swale	30			65			30	30	80			

8. SUMMARY AND CONCLUSIONS

Treatment and detention of larger pollutant loads or fluxes are needed for improvement of the quality of sensible receiving waters and for decreasing the risks for flooding. There are many different best management practices (BMPs) and the choice of measure (e.g. wet ponds, filter strips, constructed wetlands, open ditches, swales, infiltration facilities, filter facilities, source control and detention basins) is dependent on site-specific conditions. There is no solution that is suitable at all sites and combinations of facilities are often advantageous.

In Sweden and in some other countries there is an increasing trend in constructing stormwater treatment facilities (STFs), such as wet ponds, filter strips and constructed wetlands. There is a need for watershed-based tools for the design of these STFs, including quantification of pollutants on the stormwater recipients. We need a simpler, more user-friendly, more cost effective and site-specific tool than is available to be used at e.g. Swedish municipalities. Furthermore, more unitary designations of the included parameters and of different STFs are required.

The contribution of this thesis is to summarize the development of a system framework which integrates runoff flow and pollutant characteristics with design routines for STFs. The system takes consideration to conditions of receiving waters and to site specific conditions such as local climate and soil properties. We present a planning-level tool for quantification of pollutant transport and design of the stormwater treatment facilities wet ponds, constructed wetlands and filter strips.

The model system boundary is the watershed boundary. The developed spreadsheet stormwater model StormTac requires little input data to perform perspicuous calculations of long-term runoff water fluxes, pollutant loads and design of stormwater treatment facilities. The only obligatory input data consists of land use specific areas. However, the model employs a relatively detailed division of the (sub) watersheds into different land uses in order to more accurately estimate the pollutant transport. We present unique notations and to simplify the calculations, we employ generally applied units in the equations.

The developed model employs relatively simple equations for quantification of pollutant transport with stormwater to be consistent with the generally very limited amount of input data available. Runoff water flow (Q) is estimated from local precipitation intensity data (p) and land use specific runoff coefficients (φ) and areas (A). Stormwater pollutant load (L) is calculated from Q and land use specific standard concentrations (C). There are default parameter values for p, φ and C. We implemented the model on several case studies. The equations were considered accurate enough for planning-level analyses and considering that the focus is not on dynamic properties of the systems studies. In Paper IV and in Larm and Holmgren (1999), we presented an alternative method for calculation of pollutant loads. This "source model" can be used for the identification of specific pollutant sources. For instance, the source model may simulate the contribution of copper loads from copper roofs. A simplified source sub model is planned to be included in StormTac and the thesis provides some results from Sätra case study.

For simple design calculations of wet pond dimensions (area and volume) we employ the model default parameter values of rain depth (r_d), a constant value of the detention volume (N_{d1}) and average water depth (h). The corresponding parameters for filter strips are rain

intensity (i_N), specific watershed area (A_s), specific runoff coefficient (φ_s), rain depth (r_d), water velocity (v), distance (s) and rain duration (t_{r2}). For constructed wetlands, the default parameter values of importance are a constant value of the detention volume (N_{d2}) and precipitation intensity (p). StormTac includes a relatively large number of equations that employ many other parameters, see e.g. Larm (2000).

Before the final design of wet ponds, StormTac also employs e.g. the parameters rain intensity (i_N), specific watershed area (A_s), specific runoff coefficient (φ_s), inflow (Q_{in}) and outflow (Q_{out}) for estimating detention times and water levels. Regarding ponds, it has been shown that there exists an optimal size to be estimated and that larger size than the optimal in fact can result in decreased reduction efficiencies, in opposite to common wisdom. This is due to the fact that water from smaller runoff events tends to be emptied quicker than desired for reaching acceptable sedimentation effects. A large outlet dimension can explain the latter. Too large ponds do not provide therefore the required residence time for the dominant number of smaller runoff events.

By changing the default input data one can make more detailed calculations with StormTac. One can easily compare the results of using different parameter values and test different design methods. We may also study different estimations of reduction efficiencies (REs) as results of the design. The reduction efficiency (RE) of different STFs are difficult to estimate trustworthy without accurate monitoring programs that preferably include flow proportional sampling. Different values of RE are expected with different runoff coefficients and pollutant concentrations, i.e. the hypothesis is that RE is dependent on the land use properties within the watershed. For instance, for the same watershed area and runoff coefficient we get higher values of RE for a wet pond with pollutant loads coming from a highway with large traffic intensity than for a wet pond (with the same dimension) getting loads from a road with little traffic. One explanation is that we have higher concentrations of particles (SS) from the highway. A relatively large share of other pollutants is bound to these particles and sedimentation is probably the most important process for the removal of pollutants in wet ponds.

In the model, the calculated loads are also compared with specific concentration and load criteria on the recipient, in order to estimate the magnitude of loads that need to be reduced by STFs.

By integrating StormTac to GIS (Geographical Information Systems) the implementations in the two case studies Tyresö and Botkyrka have shown that we have created a useful tool for testing different scenarios, e.g. the effects of changed land use. The GIS format can also be used as basis for decision-making. The pollutant fluxes from different diffuse and point sources are compared with each other and the largest sources of the considered pollutant(s) are identified in order to optimize the location of STFs.

Procedures for the selection of facility type are also included in the model. The selection is based on existing or desired use of the recipient, on the land uses in the entire watershed area and topography, groundwater level, soil characteristics etc.

Results from the design of STFs from three case studies (φ=0.22-0.85), using different design methods and assuming fixed parameter values, indicated required areas per reduced hectare (red ha), see Paper I and Larm (2000). These areas were 230 (60-450) m^2/red ha for wet ponds, 700 (150-1300) m^2/red ha for filter strips and 930 (180-1300) m^2/red ha for

constructed wetlands. By using the "runoff depth" method (Eq. (13)-(16)) for wet ponds, 200 m^2/red ha was required for the case study Flemingsbergsviken (φ=0.22), 230 m^2/red ha for Nybohov (φ=0.45) and 250 m^2/red ha for Essingeleden (φ=0.85). These values show that the required area increases with an increased runoff coefficient.

Updated studies in Sätra case study (φ=0.24) by instead selecting a specific design method for each type of facility and by considering varied parameter values resulted in 270 (50-875) m^2/red ha for wet ponds, 1235 (1235-2060) m^2/red ha for filter strips and around 1215 (810-1215) m^2/red ha for constructed wetlands. The values 230 m^2/red ha and 270 m^2/red ha for wet ponds employ r_d=15 mm and result in approximately 90% of the precipitation (after initial rain losses) being included. The corresponding values to include 80% (using r_d=10 mm) are 160-180 m^2/red ha.

These gathered results show large variations in resulted dimensions both if choosing different design methods and if selecting different parameter values for a specific method. The design methods for filter strips are probably the most unreliable.

Since there generally exist limited amounts of measured data it is not certain that the reliability of the model results will improve by increasing the model complexity. Regarding material transport calculations, the focus is to get an overview of the relative importance of prevailing emissions as basis for location and design of STFs. The included design methods are also simple but believed to be complex enough considering the large uncertainty of included parameter values. The importance of site specific conditions (soil conditions, topography etc.) and detailed design of inlet and outlet structures and checking of emptying times and maximum and minimum water levels at different precipitation events is probably greater than the issue of changing model complexity.

In this study, we have provided a system framework for a number of relevant processes and scenarios. Each individual process considered was described in a relatively simple manner, with a simple parameterization. Clearly, the description of all considered processes and events can be improved, with more comprehensive parameterizations. Such improvements, however, must be consistent with the parameters that actually can be estimated for typical applications. We summarize below a few specific suggestions for continued studies which are likely to improve the accuracy and reliability of the system model.

Generally, we need to improve the values of runoff coefficients and standard concentrations in StormTac. Complementary measurements are needed in order to get more accurate estimations of yearly and monthly runoff coefficients, and standard concentrations representative for each land use in the studied watersheds, especially from rural land uses.

We also need to understand the groundwater impacts on the developed system. Examples of questions that could be studied are: In what way does the composition of the water in the stream/sewer vary regarding its origin (the share of superficial groundwater compared to the share of stormwater from different types of impermeable surfaces)? Which part of the water comes during the base flow in dry periods compared to during periods with high precipitation and how large are the seasonal variations?

Other specific studies that are needed are:

- Further development of the pollutant transport model to include load reductions due to

overland transport and transport in open ditches as a function of transport distance.

- Further development of the equations used for the quantification of flow and load from base flow.
- Presentation of model scenarios for minimum and maximum values of the studied parameters.
- Development of a simple source model applying material emission coefficients ($mg/m^2/year$) for comparison to loads that are quantified based on land uses.
- Identification of important pollutant sources of e.g. phosphorus and copper.
- Further development of the equations for acceptable loads on recipients.
- Development of statistical properties to present uncertainties (probable minimum and maximum values) for standard concentrations, runoff coefficients and pollutant loads.

Continued studies of precipitation statistics and design parameters are needed and can result in changed parameter values used for the design of stormwater treatment facilities. It is for example important to carry out more reliable estimations of the site-specific initial rain loss (r_s) to be used. Longer periods of hourly precipitation data are needed both at more sites in Stockholm and at other sites in Sweden. Continued evaluations and applications of the design methods are needed. An effective method can be to carry out multivariate sensitivity analyses to study which parameters that have the strongest effects on the dimensions of the stormwater treatment facility. Such analyses can result in large differences in required pond area and volume. The results of such continued studies can lead to a selection among methods and more user-friendly design criteria can eventually be compiled.

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NOTATIONS

Table 11   Notations used.

Notation	Description	Unit	Comments
φ	Runoff coefficient		
φ^*	Runoff coefficient estimated from measurements data		
φ_s	Specific runoff coefficient for A_s		
A	Watershed area	ha	1 ha=10 000 m^2
A_m	Area of material surface	m^2	
A_s	Specific watershed area that contributes to runoff during the design rain duration	ha	
A_{STF}	Required facility area	m^2	STF=Stormwater Treatment Facility
C	Standard concentration	mg/l	
C_b	Base flow pollutant concentration	mg/l	
E	(Potential) evaporation intensity	mm/year	
h	Average water depth for the whole facility	m	1-2 m for wet ponds 0.5-0.75 m for wetlands
h_r	Maximal water depth for the detention volume in a pond	m	0.9-1.5 m
I	Percentage of impermeable area	%	0-100
i_N	Rain intensity with return time 1,2,3,..N years	l/s/ha	
i	Land use		
j	Substance		
K_{jm}	Emission coefficient for a specific material surface m and a specific substance j	mg/m^2/year	
K_{inf}	Fraction of the yearly precipitation that is infiltrated		
K_x	Share of K_{inf} that reaches the base flow		
K_y	Share (0-1) of the yearly flow that is captured by the facility		
l	Facility length	m	
L	Mass load rate (mass flux)	kg/year	
L_b	Base flow pollutant load	kg/year	
L_{in}	Inflow load on facility	kg/year	
L_{jm}	Load from a material surface	kg/year	
L_{out}	Outflow load from a facility	kg/year	
m	Material surface		
N_{d1}	Constant value of (number times) the detention volume	-	1.0-1.5
N_{d2}	Constant value of (number times)	-	3

	the detention volume		
N_r	Yearly number of runoff events	$year^{-1}$	90 (60-110)
p	Precipitation intensity data (rain+snow) corrected for systematic errors	mm/year	636 (400-900) mm/year for Stockholm p=precipitation
p^*	Measured precipitation intensity (rain+snow)	mm/year	539 (300-800) mm/year for Stockholm
Q	Runoff water flow	m^3/year	
Q^*	Measured water flow	m^3/year	
Q_b	Base flow	m^3/year	
Q_{dim}	Design flow to facility	l/s	
Q_{in}	Inflow	l/s	
Q_{out}	Outflow	l/s	
R^2	Correlation coefficient		R^2 is closer to 1 when the correlation (between x and y) is strong
r_d	Rain depth	mm	5-35 mm pond 9-10 mm: 80% of p in Stockholm included. 13-15 mm: 90% of p in Stockholm included. 25 mm filter strip
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	Reduction efficiency	%	
r_s	Initial rain loss	mm	0.6-1.5 (0-2.5) mm
s	Distance	m	
t_d	Hydraulic residence time (detention time)	h	24 h is required to treat smaller rain events. 12-24 h normal
t_f	Time for runoff	min	
t_{out}	Time for outflow, emptying time	h	12-24 (6-48) h
t_{r1}	Rain duration	h	
t_{r2}	Rain duration	min	
v	Water velocity	m/s	0.18-0.3 m/s
V	Facility water volume	m^3	
V_d	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	
w_{tot}	Total width of facility	m	