Best Management Practices to Reduce Phthalate and Nonylphenol Loads in Urban Runoff

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ABSTRACT
Phthalates and nonylphenols, organic substances of widespread use, are believed to be ubiquitous in Swedish stormwater and urban sediments. Due to their reported hazardous properties, it is of great interest to identify effective best management practices (BMPs) to reduce the release of these substances to recipient waters. The stormwater-quality model SEWSYS was used to identify sources and quantify loads of phthalates and nonylphenols in two urban catchment areas. Based on the modelling results, BMPs were proposed, and their efficiencies evaluated. The SEWSYS simulations showed that discharges of phthalates and nonylphenols depend on catchment area characteristics: pollutants in a residential area originate mainly from building materials, whereas vehicles are the dominant source in a high-density traffic area. By replacing traditional building materials by phthalate and nonylphenol-free alternatives and by implementing congestion taxes to reduce traffic, the simulated pollutant loads could be reduced by more than 20% in the high-density traffic area. However, discharges from many diffuse sources cannot entirely be stopped, and a structural BMP, e.g. a sedimentation pond, is essential to further decrease pollutant loads in urban runoff. This study shows that SEWSYS can be a useful tool for selecting and evaluating adequate BMPs to reduce stormwater contamination.

KEYWORDS
Diffuse pollution; non-structural/structural BMPs; organic pollutants; SEWSYS; stormwater-quality modelling

INTRODUCTION
Stormwater pollution reducing recipient water quality is a major problem in urban areas (Boller, 2004; Butler and Davies, 2004; Scholes *et al.*, 2008). Consequently, management of urban runoff pollution has become an increasingly important environmental concern. Studies have shown that by implementing measures to treat polluted runoff, often referred to as best management practices (BMPs), a significant improvement in stormwater quality can be achieved (see e.g. Hares and Ward, 2004; Pettersson *et al.*, 2005; Deletic and Fletcher, 2006). Non-structural BMPs, for example reduction of impervious surfaces and building-materials management, have been found effective for pollution prevention, and may reduce or even eliminate the need for expensive structural "end-of-pipe" solutions (Muthukrishnan *et al.*,

2004). In addition to source control, structural BMPs e.g. sedimentation ponds are nevertheless often required to further reduce pollutants in stormwater (Ahlman *et al.*, 2005).

Stormwater-quality models that simulate pollutant flows in urban catchments have proven to be valuable means for evaluating appropriate strategies to reduce adverse effects of runoff pollution (Zoppou, 2001; Ahlman, 2006). SEWSYS, developed in the Swedish Urban Water Programme, is a stormwater-quality model used for simulating urban nonpoint source pollution (Ahlman, 2006). The model has recently been expanded, from operating with nutrients, metals and polycyclic aromatic hydrocarbons (PAHs), to include phthalates and nonylphenols (NPs) for loading simulations in urban runoff.

Phthalates and NPs are organic substances that frequently occur in Swedish urban stormwater and sediments (Björklund *et al.*, 2007). These substances are used as additives in a wide range of products e.g. lubricants, sealing compounds, and plastics (Ying *et al.*, 2002; Rahman and Brazel, 2004). Nonylphenol and several of the phthalates, e.g. di-(2-ethylhexyl)-phthalate (DEHP), are classified as “very toxic to aquatic organisms” by the Swedish Chemicals Agency (KemI, 2005). It is therefore imperative to reduce the occurrence of these pollutants in runoff and receiving waters.

Despite the usefulness of stormwater-quality models, little work has been done on their utility in identifying urban sources of organic contaminants or for evaluating the impact of BMPs on organic pollutant loads. The objective of this study was threefold: (i) to use the SEWSYS model for identifying important phthalate and nonylphenol sources in two urban catchment areas: a residential area and a high traffic-density area, (ii) to propose relevant BMPs for each of the two study sites, based on the simulation results and findings from a literature study on best management practices, and (iii) to estimate the pollutant removal efficiencies of the selected practices. The outcome of the study should be a helpful tool for local authorities when planning effective abatement strategies to reduce contamination of organic substances in stormwater.

METHODS

The modelling of sources and the evaluation of BMP efficiencies were performed using DEHP as the representative phthalate. NP refers to the total nonylphenolic compounds, including ethoxylates of different length and 4-nonylphenols.

The SEWSYS model

SEWSYS is used for simulating substance flows in urban stormwater, see Ahlman (2006) and Ahlman and Svensson (2002) for a detailed description. Stormwater pollution is modelled using buildup-washoff functions. Catchment-specific input data, including rain data and the total impervious area, determine the event mean concentrations (EMCs) in runoff and the pollutant load from different sources. The number of vehicle kilometres travelled per day as well as total impervious area, including roofs, roads and other impermeable surfaces, are the two main input data that affect resulting pollutant loads. Measures to reduce these loads can be simulated e.g. by disconnecting impervious surfaces or reducing traffic.

To include phthalates and nonylphenols in the model, potential sources of these substances were identified, and material emission factors were estimated based on results found in the literature. Calibration of the model generated simulation results comparable to measured pollutant concentrations (Björklund *et al.*, 2007).

Table 1. Characteristics of the studied catchment areas Nybohov and Gårda.

Study site	Characteristics	Total area / Impervious area (ha)	Land use (% of impervious area) Roads	Roofs	Other impervious[a]	ADT[b]
Nybohov (Stockholm)	Urban residential area (2000 residents) built in the 1960's.	3.9 / 2.6	5	30	65	960
Gårda (Göteborg)	Motorway E6	5.1 / 2.1	82	6	12	85700

[a] E.g. footpaths and parking spaces; [b] Average daily traffic (number of vehicles), including cars, motorbikes and heavy vehicles.

Study sites

SEWSYS simulations were carried out for DEHP and NP flows in the urban residential area Nybohov, Stockholm, and a motorway site in Gårda, Göteborg (both in Sweden). Nybohov is characterised by multi-family houses and a large outdoor parking facility (Table 1). Roof and road runoff from this area is directly discharged into the stormwater system, and conveyed without any pre-treatment to the recipient lake Trekanten. The Gårda area is dominated by the E6 motorway and a few smaller streets (Table 1). The road runoff from Gårda flows through a series of seven underground sedimentation chambers. After 40 hours of retention, stormwater is pumped from the facility into the nearby stream Mölndalsån. If precipitation continues when the sedimentation chambers are full, excess stormwater is directly discharged into Mölndalsån.

For this study, input data to drive the SEWSYS simulation were collected in Nybohov and Gårda during spring 2006. These data included rainfall measurements and occurrence of relevant phthalate and nonylphenol sources.

Study procedure

To start, SEWSYS was used for identifying the main sources of DEHP and NPs in the two study areas. The simulation results served as guidance for selecting relevant BMPs to reduce pollutant loads in each of the catchment areas. According to Muthukrishnan *et al.* (2004), an integrated approach to stormwater management, incorporating different types of BMPs that target pollutants with diverse properties, can be more effective in reducing pollution than any single BMP used on its own. For this reason, both non-structural and structural best management practices were considered in this study. The selection of suitable practices was based on the outcomes of a literature study, and site-specific criteria. An additional SEWSYS simulation was then executed, using new input data adjusted to the selected BMPs. The reduced phthalate and nonylphenol loads were thereafter compared with simulated initial loads, i.e. no measures applied, to evaluate the efficiency of each BMP.

Selection of best management practices

The following criteria were set for proposing appropriate practices to reduce DEHP and NP loads in the two study areas:

- Only BMPs with pollution removal outcomes that can be quantitatively tested were included in this study due to the difficulty in evaluating the results of some types of BMPs, such as education campaigns and legislative control.
- The chosen BMPs had to be applicable in cold climates, since the catchment areas are located in northern Europe. Recommendations found in e.g. Caraco and Claytor

(1997), Bäckström and Viklander (2000), or Muthukrishnan *et al.* (2004) were regarded.

- Space-demanding structural BMPs, including wetlands and detention ponds, were excluded in this study since both study sites are highly urbanised areas.

Summarised below are the conclusions of the literature study on suitable BMPs, and the conditions taken into consideration for the SEWSYS modelling of BMP implementation in Nybohov and Gårda.

Source control. In this study, source control of stormwater pollution refers to measures that involve reducing the use, or preventing the generation of potential pollutants, at or near their source. As phthalates and nonylphenols have been found to reach the environment either by migration or by particle release from e.g. concrete, plastics and vehicles, (Vikelsøe *et al.*, 1998; Rahman and Brazel, 2004; Togerö, 2006), choosing appropriate building materials and reducing traffic may be effective measures to reduce the emission of these compounds.

The initial SEWSYS simulation indicated that the major source of DEHP and NPs included sealing compounds, plastic coating for wall cladding and roofing sheets, concrete and vehicular pollution. In the modelling scenarios, the above-mentioned building materials were all replaced by phthalate and NP-free alternatives in both Nybohov and Gårda (Table 2). In addition, traffic reduction was taken into consideration. An attempt to implement congestion taxes was in 2006 introduced to reduce the traffic density in central Stockholm (Bång and Moran, 2006). This led to a 19% decrease in traffic for larger traffic routes and a 10% decrease on city streets. These reported traffic reduction rates were used in the SEWSYS modelling of traffic control in Gårda (19%) and Nybohov (10%) (Table 2).

Structural BMPs. As a complement to source control, BMPs to reduce runoff volumes from impervious areas such as roads, roofs and parking areas were reviewed. Both phthalates and nonylphenols show high tendencies to sorb to particulate matter in water (Ying *et al.*, 2002; Cousins *et al.*, 2003). Infiltration and sedimentation measures were therefore considered suitable for reducing the discharge of DEHP and NP into the stormwater system. To the authors' knowledge, the reduction of phthalates and NPs has not been studied for any structural BMP, but the removal of these compounds by different BMPs is believed to be similar to that of suspended solids (SS) (Staples *et al.*, 1997; ECB, 2002). Studies have shown that SS concentrations may be reduced by 38–99% by grassed swales (Legret *et al.*, 1996; Bäckström, 2003; DayWater, 2003); bioretention facilities may reduce SS by 29–99% (Muthukrishnan *et al.*, 2004; Hsieh and Davis, 2005; Muthanna *et al.*, 2007); whereas reported reductions of SS for permeable pavements vary between 50 and 95% (DayWater, 2003); and a 91% SS-reduction has been shown for permeable pavement with swales (Rushton, 2001).

Based on the outcomes of the literature study and the set criteria, the measures suggested for implementation in the residential area Nybohov included: using permeable pavement and grassed swales for car park and road runoff; treating roof runoff in bioretention areas; and reducing roof runoff by installing green roofs (Table 2). When estimating the removal of DEHP and NP during the simulated storm event in Nybohov, a best-case-scenario was assumed where: pollutant concentrations were comparably high; no bypass of excess stormwater occurred at the BMPs; and 50% of the runoff volume could be reduced. Based on the reported reduction of suspended matter, it was concluded that around 30 to 90% of the DEHP and NP loads could be reduced in the mentioned BMPs, and that an average reduction

Table 2. Hypothetical control program for reducing phthalate and nonylphenol loads in a residential area and a high-density traffic area.

Nybohov residential area	**Comment**
Building-material management	Replacing coated metal sheets, sealing compounds and concrete with phthalate and nonylphenol-free alternatives
Reduction of traffic density	10% reduction
50% reduction of runoff volumes from car park and road	E.g. grassed swales and permeable pavement
50% reduction of roof runoff volumes	E.g. green roofs, bioretention
Gårda high-density traffic area	
Building-material management	Replacing coated metal sheets, sealing compounds and concrete with phthalate and nonylphenol-free alternatives
Reduction of traffic density	19% reduction
Sedimentation facility	20% reduction of incoming phthalate and nonylphenol loads

of 50% of the loads was likely to occur. The reduction of DEHP and NP loads was therefore set to 50% for the suggested BMPs.

A study on pollutant removal efficiencies in a sedimentation system for treatment of road runoff in Gårda has been presented by Pettersson *et al.* (2005). Concentrations of total suspended solids (TSS) and PAHs were, when excess water volumes were included, reduced by 25% and 20%, respectively. The removal efficiencies for phthalates and NPs have not been examined for the Gårda system, but these substances are supposed to behave similarly to TSS and PAHs due to common environmental properties (Staples *et al.*, 1997; Mackay and Callcott, 1998; ECB, 2002). In Gårda, no other structural BMP than the existing sedimentation facility was used for the BMP-simulation in SEWSYS. The reduction of DEHP and NP loads in the facility was set to 20%, close to that of TSS and PAHs.

RESULTS AND DISCUSSION

DEHP and nonylphenol source distributions

Simulating the source distribution using SEWSYS showed that plastic-coated roofing sheets were the main phthalate source in the residential area (Figure 1). Pollution from vehicles in the car park contributed largely to the total DEHP and NPs pollution. Vehicular pollution on roads and migration from concrete, PVC and other plastics were minor sources of DEHP and NPs because of their limited areal distribution in Nybohov. Since building materials largely contributed to the pollutant loads in this catchment area, material management (Table 2) or infiltration of roof runoff could be effective measures to abate pollutant discharges. Moreover, infiltration of runoff from the car park could significantly help reduce NP loads.

At the high-density traffic site Gårda, vehicular pollution, tyre wear, and migration from coated roofing sheets proved to be the major DEHP sources (Figure 1). The principal NP sources included tyre wear, vehicular pollution and migration from concrete. The simulation results showed that a reduction in traffic would lead to reduced discharges of stormwater pollution in this area. In addition, material management (Table 2) and a complementary structural BMP could further improve water quality.

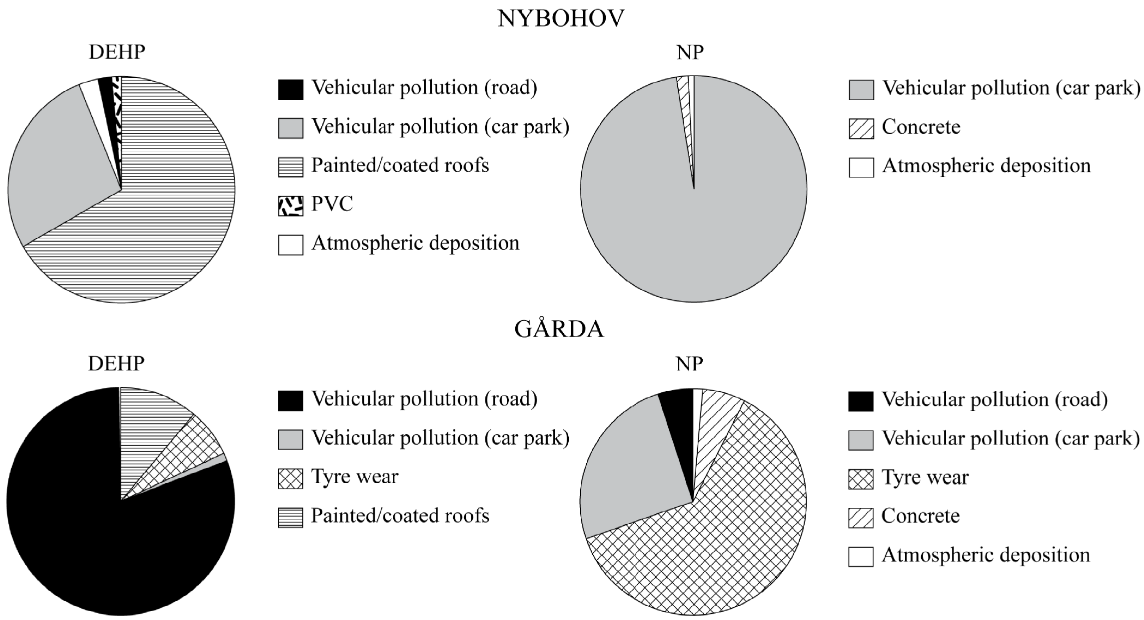

Figure 1. Source distributions of DEHP and NP in the residential area Nybohov and the high-density traffic area Gårda.

Estimated reduction of DEHP and nonylphenol loads

As seen in Figure 2, material management was shown to be very effective in reducing phthalate loads in the residential area whereas other measures were of minor significance. NPs were not as effectively reduced as DEHP through source control, whereas implementing e.g. permeable pavements and grassed swales resulted in a 24% decrease of NP loads. To increase the removal of NPs in Nybohov, a larger part of the runoff volume from the major source, vehicular pollution in the car park, would need to be infiltrated. Infiltration of polluted stormwater has raised concern because of the potential for groundwater contamination (Mikkelsen *et al.*, 1997; Pitt *et al.*, 1999). However, if runoff from buildings and areas with low traffic-density is infiltrated, the groundwater contamination potential is considered to be low to moderate (Dietz, 2007). The responsible public authorities of Stockholm are in fact discussing infiltration devices as one of the feasible measures for use in Nybohov because of the limited area available and the current acute pollutant stress on the receiving water.

In Gårda, the implementation of material management and congestion taxes reduced DEHP and NP loads by 28% and 20%, respectively. Because the reduction of average daily traffic is limited, a complementary structural BMP, such as a sedimentation facility, is indispensable to further reduce phthalate and nonylphenol loads in stormwater. Pettersson *et al*. (2005) showed that the operation of the Gårda sedimentation facility is crucial for the overall removal of pollutants. When the water retention time was reduced from 40 to around two hours, overflows during large storm events were decreased and larger runoff volumes passed through the sedimentation tanks. The removal efficiencies of TSS and PAHs were then increased from 25% and 20%, to 51% and 72%, respectively. Shortening the water residence time to increase pollution removal would help reduce DEHP and NP loads to less than 40% of the incoming load. Optimising the facility's control program could therefore be an effective practice to further decrease pollutant discharges into the recipient stream.

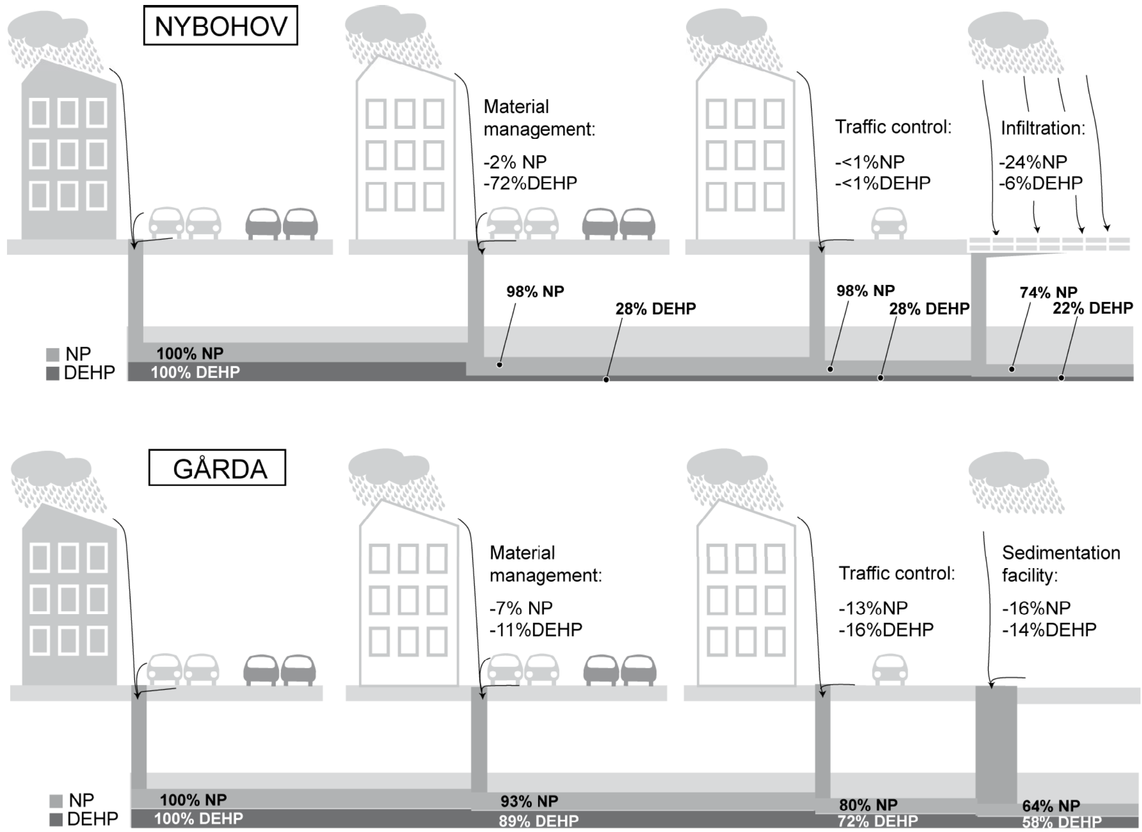

Figure 2. Estimated reduction of DEHP and NP loads after BMP implementation in Nybohov (residential area) and Gårda (high-density traffic site). Illustrated in the sewers are the stormwater loads: 100% represents the initial load of pollutants when no measures are applied, whereas the following percentages represent the remaining load after implementing the BMPs.

Ahlman *et al.* (2005) have earlier used SEWSYS for evaluating the efficiency of non-structural BMPs, e.g. replacing or painting metal roofs and changing driving patterns, to reduce metal and PAH loads in stormwater. The study showed that relatively high reductions of copper and PAHs could be achieved. Similarly, the results of this study indicate that source control, in this case material management and traffic regulation through taxes, can be effective measures to prevent pollution discharges with urban runoff. By carefully choosing materials that have less impact on the environment, future problems with pollutant emissions and disposal of harmful products can be avoided. Moreover, controlling traffic not only helps reduce the environmental load of e.g. DEHP, NPs and particulate matter, but also the emission of green-house gases. New ideas on stormwater management will, however, be slow to implement, and replacing hazardous materials will take many years to accomplish, as already pointed out by Boller (2004). Hence, the discharge of pollutants from nonpoint sources may not be fully prevented and structural BMPs are therefore necessary barriers to help reduce the contamination of urban watercourses.

A recent study (Björklund *et al.*, 2007) confirms the occurrence of nonylphenols, nonylphenol ethoxylates and eight phthalates in urban stormwater and sediments in Göteborg and Stockholm. Phthalates and nonylphenols are, however, only two of the organic substances reported to be found in urban runoff. According to an extensive literature review, up to almost 600 substances, of which nearly 400 were xenobiotic organic compounds, have been detected in stormwater (Eriksson, 2002). Most of these substances are believed to originate from nonpoint sources that may be difficult to trace and prevent. BMPs that are efficient in reducing a battery of substances with different physicochemical properties need to be identified in order to reduce the stress of these pollutants on receiving waters. Further evaluations of the removal efficiencies of structural BMPs are therefore needed.

As in all models, the quality of the input data is very important for the reliability of the simulation outputs. The phthalate and nonylphenol release factors from materials have been calibrated in SEWSYS, but further investigations to validate these factors, and other parameters influencing pollution transport to stormwater, need to be done to enhance the predictive power of the model. Furthermore, the reduction capacities presented for the infiltration and sedimentation BMPs were based on an estimated removal of suspended solids and organic pollutants, due to the lack of data derived from experimental studies. As stressed by many authors, removal efficiencies for different BMPs are pollutant, site, year and even storm-event specific (Bäckström, 2003; Muthukrishnan *et al.*, 2004). In addition, it is often unclear if reported efficiencies concern reduction of concentration or of load, and if bypass volumes are included. The suggested source distributions and calculated removal of loads are therefore not definitive, but present an approximation of the major sources of DEHP and NP, and indicate effective measures for reducing the discharges of these pollutants into stormwater.

CONCLUSIONS

From the result found in this study it is concluded that:

- In the two studied areas, major DEHP sources include plastic-coated roofing sheets and vehicular pollution, whereas tyre wear, migration from concrete and vehicular emissions are the most relevant NP sources.
- Source control is important for reducing the emission of pollutants into urban watercourses, and may in the case for DEHP and NPs include building-material management and reduction of traffic density. In the studied catchment areas, these measures may reduce DEHP loads up to over 70%, and NPs loads up to 20%. However, to further decrease pollutant loads in stormwater, structural BMPs such as sedimentation facilities, permeable pavements and bioretention areas need to be implemented.
- SEWSYS can be a helpful tool for finding nonpoint sources and evaluating the effectiveness of measures to reduce stormwater loads of phthalates and nonylphenols. The approach and methodology used in this study could be applied by e.g. local authorities when planning strategies to reduce the loads of pollutants in urban catchment areas.

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