Constructed Filters and Detention Ponds
for Metal Reduction in Storm Water

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Summary

Storm water runoff from roads often contains significant quantities of metals and other solids that should be removed before infiltrating the soil or being discharged to recipients. Many treatment methods based upon ecological-engineering principles, and utilising such features as detention ponds and wetlands, have been presented during the last number of years. Metals found in storm water from traffic areas are either dissolved or particulate bound. The use of detention ponds, where particles can settle, reduces particulate bound metals. Still, small particles and dissolved matter pass through detention ponds. Any treatment measures intended to immobilise the dissolved metals must be based on adsorption, ion exchange, and/or precipitation. Some of the dissolved metals can be removed by filtrating water through constructed filter systems. Increased demand for storm water treatment has resulted in further development of filtration technologies for storm water. Manufacturers are using different filtration facilities and different filter materials.

There is a need to compile current knowledge, to test different filter substrates in order to evaluate their efficiency in reducing metals and to clarify important aspects concerning constructed filter systems. There is also a need to increase the knowledge about detention ponds for storm water treatment regarding water and sediment quality. Therefore following research concerning constructed filters and detention ponds for metal separation from storm water has been conducted.

The thesis consists of three parts. The first part is a literature review of storm water quality and treatment and a mathematical background for filtration of contaminants through a porous media.

The second part of the thesis consists of investigations of the function of filtration systems for storm water and experimental studies of different filter materials, which have been carried out as laboratory studies and as field experiments. Different filter substrates were tested in order to evaluate their efficiency in removal heavy metals from water.

In the laboratory studies metal solutions were filtered through columns filled with substrates consisting of combinations of calcium silicate rock (opoka), zeolite and peat, and by conducting batch tests using pine bark.
In the field experiments, storm water was filtered through columns filled with natural and burned opoka and pine bark. Pine bark was found to be the most useful filter substrate with regard to parameters such as cost and handling of the used material. However, it had a lower sorption capacity than the other filter substrates. The pine bark was also tested as a filter substrate in gully-pots. 6 months of investigation showed very low metal removal efficiency. This depends most likely on the construction of the filters and insufficient water flow through the filter material.

The third part, presented in this thesis, consists of an investigation of a full-scale storm water treatment plant. The system consists of three treatment steps: a detention pond, a system of prefabricated filters installed in manholes and finally, a third step where the water enters a stream and pond system created in a golf course. Water quality and accumulation of sediments were investigated in the detention pond. Toxicity tests were conducted on the storm water and showed no toxicity. The pore water of the collected sediments was not toxic although the whole sediment, tested by the Microtox® Solid-phase test, showed toxicity.
Sammanfattning


Avhandlingen består av tre delar. En del i avhandlingen redovisar en litteraturstudie av dagvattenkvalitet och reningstekniker för dagvatten samt en matematisk bakgrund till filtrering av förorenat vatten genom ett poröst filtermaterial.

Den andra delen i avhandlingen är underökningar av filter system för dagvatten och experimentella studier av olika filtermaterial utförda genom laboratorie- och fältförsök. Olika filtermaterial testades med syfte att studera deras renings effekt av metaller i vatten.

I laboratorieförsöken filtrerades metalllösningar genom kolonner fyllda med olika substrat, bestående av kombinationer av kalciumsilikat (opoka), zeolit, torv, och genom skakförsök med furubarkflis.
Fältförsöken innebar filtrering av dagvatten genom kolonner fyllda med materialblandningar av naturlig och bränd opoka samt furubarkflis. Furubarkflis tycks vara det material som, vad gäller bland annat kostnader och kvittblivning av använt material, är det mest fördelaktiga. Däremot verkar furubarkflis ha lägre sorptionskapacitet än övriga testade material i fältförsöket. Furubarkflisen har även testats i brunnsfilterinsatser i dagvattenbrunnar under 6 månader för rening av metaller från dagvatten. Dessa resultat visade på mycket lågt metallupptag i materialen, vilket troligen beror på konstruktionen av brunnsfilterinsatserna och dålig vattengenomströmning i filtermaterialet.

Preface

This thesis is presented as a part of the requirements for the degree of Doctor of Philosophy (PhD). The research has been performed at the Department of Public Technology, Mälardalen University. The project has been financially supported by Mälarenergy – the Municipality of Västerås, the Swedish National Road Administration (Vägverket) and VA-forsk (the research committee associated with the Swedish Water and Wastewater Association), which are gratefully acknowledged.

I would like to express my gratitude to colleagues at the Department of Public Technology, especially Christina Ingwall-Johansson for her support in the laboratory, Prof. Erik Dahlquist, Dr Lena Johansson Westholm and Dr Sylvia Waara for their discussion, valuable advice and good collaboration; and to Anders Borg and Gert Bard for their assistance with the technical equipment. Dr Sylvia Waara is also a co-author in paper V, which is included in the thesis, and has conducted the toxicity tests and contributed with her knowledge as a specialist of eco-toxicology when evaluating the results. Thanks also to all colleagues who have given me comments on the manuscript.

I would like to thank Assoc. Prof. Gunno Renman at the Department of Land and Water Resources Engineering at the Royal Institute of Technology (KTH) who introduced the research concerning filter substrates into this project. I would also like to acknowledge the members of the group working with storm water management, (HAD-gruppen) at Mälarenergy and at the Municipality of Västerås, where I have had the privilege to participate during these years. Thanks also to the students at the environmental engineering programme who have helped me with monitoring and sampling.

Finally, I would like to thank my family, and especially my parents who have come from far in order to give me help and assistance during busy periods.

Västerås, February 2003

Carina Färn
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


1. Introduction

1.1 Background

Protection of freshwater resources such as rivers, lakes and groundwater is a big environmental challenge. Human activities are causing severe pollution of water resources in different ways. Due to anthropogenic pollution, rain and storm water contain different contaminants like metals, nutrients and bacteria. In urban areas, the majority of rain-, storm-, and melt water are collected, and discharged directly to the environment. In this way the contaminants found in urban runoff reach the surface and groundwater resources. It has become important to treat the urban runoff, in order to protect the water resources and the soil.

During the last 10-15 years open ponds have been used in Sweden for storm water treatment. Removal of pollutants and accumulation of sediments in these ponds need further investigation, especially with respect to dimension criteria and maintenance activities. Coarse particles will settle, while small particles and dissolved pollutants will leave the detention pond and be discharged to the recipient unless there is further treatment. Some of these pollutants can be removed by filtering water through natural or constructed filter systems. Constructed filter systems are a growing market, which require further investigation concerning specific filter materials, dimension criteria and operation.

1.2 Objectives

The aim of this research project has been to investigate and evaluate two different facilities for storm water treatment: constructed filter systems using selected natural filter substrates and a detention pond.

The objective with the research concerning the constructed filter systems was to investigate the function of the systems, and to evaluate different filter substrates regarding their metal sorption capacity from metal solution and storm water. Important aspects to consider are also the environmental impact of using the different filter systems such as the availability and the treatment of used filter substrates.
The objective with the investigation of the detention pond, that received road runoff, was to examine the water quality as well as the sediment accumulation in the pond.

1.3 Research Methods

A literature review of filter substrates (paper I), storm water quality and treatment (section 2) and mathematical background of filtration of contaminated water through porous media (section 3) has been carried out using databases and is based on books, research reports and articles from different scientific journals from 1990 until today.

Different filter substrates have been investigated in laboratory (paper II and IV) and pilot-scale experiments in the field (paper III). One of the filter substrates was also tested in gully-pot filters (paper I). The laboratory tests were made to enable control of the investigations regarding parameters such as metal concentration and the content of suspended solids in the water, compared to investigations using storm water in the field where these parameters varies with each site and the different storm events.

A full-scale storm water treatment plant has been investigated (paper V and VI) with regard to water quality, accumulated sediment in a detention pond and a constructed filter system. Paper V and VI are overlapping considering the chemical characterisation of the storm water and the sediment in the detention pond. Paper V also presents a study of the potential toxicity of the water and the sediment, as well as a more profound evaluation of the results.
2. Storm Water Quality and Treatment

Impervious areas such as highways, parking lots and roofs, cause runoff and lead to high peak flows, large runoff volumes, and accelerated transport of pollutants. The runoff contains significant loads of metal elements, particulate and dissolved solids and organic compounds. To avoid these problems, storm water management changed in the 1980s from using pipes, leading storm water directly to receiving waters, to storage of runoff with detention, retention and recharge. During the last 20 years there has been comprehensive research in solving urban storm drainage problems. The research has focused on local source control, flow treatment in natural or constructed systems, such as ponds and wetlands, plant filters, root-zone systems, soil infiltration, permeable asphalt, and many combinations of these. During the 1990s, hundreds of storm water treatment facilities have been constructed throughout the world (Niemczynowicz, 1999).

2.1 Storm Water Quality

The quality of storm water depends on the time between two rain events and the type of impervious area that causes the runoff. The quality of the precipitation is also important. Storm water quality varies with time and location. The most important sources of storm water pollution are atmospheric deposition, traffic, corrosion and debris from birds and dogs (Malmqvist et al. 1994). In Table 1 the content of pollutants in storm water are presented for different surfaces. The amount of pollutants varies within the given range depending on local conditions such as type of used material and traffic intensity.

Table 1. The content of different substances in storm water (Malmqvist et al. 1994).

<table>
<thead>
<tr>
<th>Substance</th>
<th>Roofs</th>
<th>Roads</th>
<th>Parking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>5-50 mg/L</td>
<td>100-600 mg/L</td>
<td>20-100 mg/L</td>
</tr>
<tr>
<td>COD</td>
<td>10-20 mg/L</td>
<td>150-250 mg/L</td>
<td>100-200 mg/L</td>
</tr>
<tr>
<td>Pb</td>
<td>5-50 μg/L</td>
<td>100-200 μg/L</td>
<td>30-150 μg/L</td>
</tr>
<tr>
<td>Zn</td>
<td>50-1000 μg/L</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>10-1000 μg/L</td>
<td>50-100 μg/L</td>
<td>50-100 μg/L</td>
</tr>
<tr>
<td>Cd</td>
<td>-</td>
<td>2-4 μg/L</td>
<td>2-4 μg/L</td>
</tr>
</tbody>
</table>
Long-term variations show that the amount of pollution per month is larger during autumn and winter and that the largest storm water flow happens during snowmelt and heavy rain. Results from investigations of the quality of snow and melt water in urban areas show that the majority of the dissolved substances were transported with the melt water while the particle bounded substances stayed in the sediment below the snow deposit (Viklander, 1997). Concentrations of chemical oxygen demand (COD) and lead can be doubled during the winter period compared to the summer because the pollution is accumulated in snow and ice (Larm, 1994). The amount of pollution is also augmented during winter because of the use of stud tyres and increased amounts of uncombusted exhaust due to cold engines.

Short-term variations in storm water quality, meaning within a rain event, are especially noticed after a long precedent dry period. The pollution accumulates on the catchment area during the dry period and is subsequently washed away. This effect is called the first flush effect and has been investigated by several researchers (e.g., Line et al., 1997; Sansalone & Buchberger, 1997; Deletic, 1998; Deletic & Maksimovic, 1998; Christina & Sansalone, 2002; Lau et al., 2002).

The composition of pollution in storm water can vary significantly within a catchment area. There are great differences between household areas, industrial areas and road runoff.

In road runoff the amount of suspended solids and particles, heavy metals and organic substances (from fuel and oil) is directly related to traffic intensity. Road construction materials as a source of pollutants have previously been studied (Lindgren, 1998), as well as street sediments (Viklander, 1997) and street sweeping as a pollutant control measure (German & Svensson, 2001).

The amount of pollution transported with highway runoff varies depending on the characteristics of the traffic, road construction material, maintenance activities, climate and surrounding area (Lundberg & Lindmark, 1994; Larm, 1997). Research has been carried out in order to characterize road runoff in general (Barrett et al., 1998a; Roger et al., 1998; Legret & Pagotto, 1999), particle size distribution (Sansalone & Buchberger, 1997), metal content (Morrison et al., 1990) and content of polycyclic aromatic hydrocarbons (PAH) (Mikkelsen et al., 1996a; Van Metre et al., 2000; Wachter & Herrmann, 2002) for example.
2.2 Storm Water Treatment

Pollutants that are attached to particles can be separated from the storm water by sedimentation or filtration. Filtration through reactive media is a possible treatment method to remove small particles and dissolved pollutants in the storm water leaving a detention pond. In this section a review of these treatment facilities is presented.

2.2.1 Filtration of Storm Water

There are a number of different types of infiltration facilities such as infiltration ponds, vegetated infiltration surfaces, open ditches, porous pavement, percolation basins and constructed filters with added filter material (Stenmark, 1992; Fujita, 1994; Barrett et al., 1998b; Bäckström, 2002). Rainfall infiltration was first used for reduction of runoff volume but was also important for maintenance of groundwater as a water resource.

With regard to water quality, infiltration reduces pollution in runoff before it reaches streams or groundwater. In the upper soil layer of an infiltration basin, metals, phosphorus, and other constituents accumulate, mostly in association with the soil’s clay portion (Ferguson, 1990). Infiltration of storm water through green surfaces is a technique where biological and chemical processes occur in the root zone and therefore protect the groundwater from contamination. In a review of infiltration of storm water, Mikkelsen et al. (1996b) points out the risk of contamination of groundwater and soil due to long-term infiltration of polluted storm water.

There are also possibilities to construct filter systems for storm water filtration. These filter systems can be small and installed in gully-pots, or larger and situated as an end-of-pipe system. Sand filters are used to remove constituents from storm water runoff primarily through physical processes. There is also ongoing development to find filter materials other than sand, which may provide sorption processes and ionic adhesion or exchange for some dissolved constituents. A literature review presented in paper I, summarises important aspects concerning evaluation of adequate materials for metal sorption, involving criteria such as relevant hydraulic conductivity, high adsorption capacity and selectivity.
Natural materials that are available in large quantities, or certain waste products from industrial or agricultural operations, may have potential as sorbents. In a review of potentially low-cost sorbents for heavy metals Bailey et al. (1999) found that several inexpensive and effective materials, such as bark and other tannin-rich materials, lignin, dead biomass, zeolites, clay and peat moss, can be used to remove heavy metals from solution. Several researchers (Benjamin et al.; 1996; Smith, 1996; Sansalone, 1999; Møller et al., 2002) have tested iron-oxide-coated-sand as an adsorbent for dissolved metals and as a medium for filtration of particulate metals. These researchers found that this composite media could be useful for metal removal and possibly also metal recovery processes.

For all sorbents, there is a need for further knowledge concerning their lifetime, design criteria, pre-treatment, maintenance system etc. Also, an important question is what to do with used filter substrates, if they can be regenerated, used for another purpose or if they have to be deposited.

### 2.2.2 Detention Ponds

Detention ponds were initially used for temporary storage to reduce, or eliminate flow peaks, during heavy storm events. They were also constructed to trap sediments and decayed plant and animal debris in runoff water. Later it was recognized that these ponds could be useful for storm water treatment.

In a detention pond contaminants are removed mainly by sedimentation, since the majority of pollutants are attached to solids. Continued accumulation of sediments may lead to deterioration of water quality and migration of pollutants through the sediments, increasing the potential for ground water contamination beneath the ponds. Knowledge of sediment accumulation processes and metal accumulation in sediments is essential, to assess the removal efficiency of ponds, and to assess the time needed for maintenance activities.

German & Svensson (2002) have shown a correlation between storm water and sediment quality in detention ponds and concluded that analysing pond sediments is an appropriate method to characterise the pollutant load from a catchment area. Routine removal of accumulated sediments may be necessary to minimize the risk of contamination and maximize the operational efficiency of the pond. The sediment accumulation rate in ponds that have been in
operation for 5-15 years was found to be 10-40 mm per year (Yousef et al., 1990; Marsalek & Marsalek, 1997). Metal concentrations in core samples were found to decline rapidly with depth from the sediment surface and most highway runoff metals were detected in the top 20 cm (Yousef et al., 1990). Maldonato and Uchri (1994) found in their study of sediments in detention basins that petroleum hydrocarbons sorbed to particulates in the sediment.

Treatment efficiency in detention ponds has been found to vary widely between studies depending on construction and design of the pond as well as on variations in the catchment area connected to the pond. There are results showing a reduction of 80 % of some pollutants, while others have reported negative reduction rates (Bhaduri et al., 1995; Lundberg et al., 1999; Pettersson, 1999).
3. Mathematical Model of Filtration through a Porous Media

In sanitary engineering, filtration processes are often tested by practical laboratory experiments such as batch-tests and column experiments and sometimes by full-scale field experiments. Obtaining data in these ways is expensive and slow, as every change in the system needs a new set of experiments (Fetter, 1994). As a complement to these experiments sorption and mass transport processes can be described by mathematical equations.

Modelling of the processes for contaminant transport through a filter substrate (porous media) is important when designing a treatment plant. The reduction efficiency of pollutants in a filter material and the sensitivity in the system according to parameters such as the porosity, specific area, pH, flow rate etc can be examined in advance when using a model.

Practical experiments are still very important, not only to verify a model, but also to investigate a system in the reality where unexpected parameters will influence the results which are difficult to incorporate in a model.

Understanding of the processes for contaminant transport through a filter substrate is essential for comprehending the function of a filter system and the differences between different filter materials. The processes can be divided into mass transport, chemical and biological processes. The mass transport process can be divided into advection, dispersion and diffusion, where advection is the most important process.

Chemical processes include a number of different processes such as sorption processes, oxidation-reduction reactions, complexation reactions and precipitation. In a porous media for sorption of pollutants, adsorption is the most important process.

Biological processes in filter systems consist of biofilm on the solid surface of a filter material. These processes are summarised in paper 1 and are explained in detail in Domenico & Schwartz (1990), Fetter (1994; 1999), SEPA (1995), Andersson et al. (1997), Espeby & Gustafsson (1997), Altin et al. (1999) and Marsalek & Rochfort (2000).
The mathematical equation for contaminant concentration in a porous media is a mass transport equation with reactions. This equation in three dimensions becomes

\[
\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - u \frac{\partial C}{\partial x} - v \frac{\partial C}{\partial y} - w \frac{\partial C}{\partial z} - \frac{r}{n}
\]  

(1)

where

- \( C \) = concentration of solute in liquid phase (kg/m³)
- \( t \) = time (s)
- \( D_i \) = dispersion coefficient in x-, y- and z-direction respectively (m²/s)
- \( u, v, w \) = average water velocity in x-, y- and z-direction respectively (m/s)
- \( r \) = reaction rate (kg/m³·s)
- \( n \) = porosity

The first, second and third term, on the right hand side of the equation, describe mass transport by dispersion, the fourth, fifth and sixth term describe advection and the seventh term describes the mass reduced per unit volume per unit time, which can be sorption reactions, other chemical reactions or biological reactions.

In the mathematical model the filter is supposed to consist of a homogenous and isotropic porous media and the velocity is uniform in the filter, flowing in the x-direction. In field experiments it is difficult to avoid channelling and to achieve a perfectly homogenous and isotropic porous media. However, with the assumptions mentioned above, equation (1) simplifies to the following one-dimensional equation for the solute concentration in the filter:

\[
\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - \frac{r}{n}
\]  

(2)
3.1 Sorption Reactions

The reaction rate, \( r \), in equation (2), for sorption reactions is generally expressed as

\[
    r = \frac{\partial C^*}{\partial t}
\]  

(3)

where \( C^* \) is the concentration of the solute on the solid phase (kg/m\(^3\)).

Incorporating the bulk density, \( \rho_b \) (kg/m\(^3\)), the rate of mass sorption per unit volume of porous media is described as

\[
    \frac{\partial C^*}{\partial t} = \rho_s \frac{\partial S}{\partial t}
\]  

(4)

where \( S \) is the quantity of mass sorbed on the surface of the media (kg/kg).

The bulk density can also be defined as

\[
    \rho_s = \rho_s (1 - n)
\]  

(5)

where \( \rho_s \) is the mass density of the material (kg/m\(^3\)) and the quantity \( \rho_s (1 - n) \) is the total mass of solids per unit volume of porous media.

The sorption reactions can be described with an expression for an equilibrium sorption isotherm. For linear adsorption, the following equation provides a relationship between the liquid phase concentration and the surface concentration. The most used isotherm is the linear Freundlich isotherm.

\[
    S = K_d C
\]  

(6)

where \( K_d \) is the distribution coefficient (m\(^3\)/kg). By taking this isotherm and differentiating with respect to time, the following equation is obtained

\[
    \frac{\partial S}{\partial t} = K_d \frac{\partial C}{\partial t}
\]  

(7)
3.2 Other Chemical or Biological Reactions

Biological and chemical reactions other than sorption can be described as a reaction, \( r \), where \( r \) is a function of several parameters

\[
r = f(C, t, T, n, O_2, \ldots, pH)
\]  

(8)

\( T \) is temperature and \( O_2 \) is the availability of oxygen.

The reactions can be described simply by indicating that there may be a change in concentration of the solute with time due to these reactions by using subscripts

\[
r = \left( \frac{\partial C}{\partial t} \right)_{\text{react}}
\]  

(9)

One example of a chemical reaction is a kinetic reaction of the first order of a constituent

\[
r = \frac{d(nC)}{dt} = -\lambda nC
\]  

(10)

where \( \lambda \) is the decay constant or a reaction rate coefficient.

3.3 Equation for Solute Concentration in a Porous Media Including Reactions

By including sorption reactions (equations 3 and 4) and a simplified term for other chemical and biological reactions (equation 9) in equation (2), the one-dimensional solute concentration equation through a porous media including reactions becomes

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - \frac{\rho_k}{n \partial t} \left( \frac{\partial C}{\partial t} \right)_{\text{react}}
\]  

(11)

This equation describes dispersion and advection together with sorption processes and other chemical and/or biological reactions, according to the
cited references. The coefficient $D_s$ can also be justified to incorporate both dispersion and diffusion coefficients according to Domenico & Schwartz (1990), then

$$D_s = D + D'_d$$  \hspace{1cm} (12)

where $D_s$ is the coefficient of hydrodynamic dispersion, $D'$ is the coefficient of mechanical dispersion and $D'_d$ is the bulk diffusion coefficient.

### 3.4 Boundary and Initial Conditions

In order to obtain a solution to the differential equation (11) above, the boundary and initial conditions must be defined. The conditions applied to a filter bed with an inlet concentration $C_0$ (e.g. the storm water concentration) becomes

$$C(0,t) = C_0 \hspace{1cm} t \geq 0$$  \hspace{1cm} (13)

$$C(x,0) = 0 \hspace{1cm} x > 0$$  \hspace{1cm} (14)

The boundary condition (13) means that at all time $t$, at $x = 0$ the concentration is maintained of $C_0$. The initial condition (14) means that the concentration is 0 everywhere in the filter bed at time $t = 0$.

### 3.5 Experimental Work to Obtain Parameters for the Mathematical Model

Experimental investigations must be performed to determine sorption isotherms for the actual filter media. There are two different ways to carry out these tests, batch tests and column experiments.

In batch tests substrates samples are shaken with a solution containing known concentrations of different substances. The concentration of each of the substances in the solution is then measured at equilibrium, and the amount of sorbed substance can be calculated.
In column experiments a solution with known concentration of different substances is filtered through a column with the selected filter substrate. The concentration in the filtered water is registered as a function of time and plotted to achieve a so-called break through curve, BTC. From this curve the sorption isotherm can be calculated.

The laboratory experiments of different filter materials presented in this thesis were conducted in order to determine the quantity of mass sorbed in the media (S), and to investigate the dispersion coefficient (D). Paper IV presents batch tests, using pine bark, which were carried out to assess the sorption capacity and the sorption isotherms. These results will be used in further studies for mathematical modelling of the filtration through pine bark.
4. Filter Materials

In the present investigation natural materials were tested as filter substrates for metal sorption. The filter substrates used were calcium silicate rock (opoka), zeolite and pine bark. Details concerning the composition and other parameters of opoka and zeolite are presented in Paper II and III, and for pine bark in paper I and IV.

4.1 Calcium Silicate – Opoka

The material opoka was chosen because it has shown good reduction efficiency of phosphorus when the P-sorption capacity was tested in batch and column experiments (Johansson, 1998). Opoka is supposed to have good sorption capacity even for metals regarding its chemical composition. The calcium silicate (opoka) is excavated from deposits in Poland and Russia. The opoka used in this investigation derive from Poland and was used in two variants, natural (OpN) and burned opoka (OpB). Burned opoka was produced by heating the opoka to over 900 °C. This material was tested in combination with zeolite and peat. The chemical composition of opoka is presented in Table 2.

4.2 Zeolite

Zeolite has been chosen because it has been tested for metal reduction in effluents and has also shown good results (Kesraou-Ouki et al., 1994). Zeolites are complex hydrated aluminium silicates, which can occur as a natural mineral or may be artificially synthesised. Zeolites have open frameworks characterised by networks of channels or pores. This gives the mineral a very large surface area. The structure with its large surface area has a high cation exchange capacity (CEC). This high CEC enables zeolite to absorb and freely exchange positively charged cations.

The zeolite used in this research project is natural clinoptilolite imported from Hungary. This substrate is used as a sorbent for pollution control and recovery of metals (Kesraou-Ouki et al., 1994). The chemical composition of clinoptilolite is: SiO₂ (70 %), Al₂O₃ (13 %), Fe₂O₃ (1 %), K₂O + Na₂O (5%), CaO (2 %), TiO₂ (0.2 %), MnO (0.2%) and other constituents (8.6 %).
Table 2. Physical and chemical characteristics of opoka (Johansson, 1998).

<table>
<thead>
<tr>
<th>Components</th>
<th>Natural opoka (OpN)</th>
<th>Burned opoka (OpB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO (%)</td>
<td>-</td>
<td>23</td>
</tr>
<tr>
<td>CaCO₃ (%)</td>
<td>51</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂ (%)</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Other constituents (%)</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td>8.3</td>
<td>12.6</td>
</tr>
<tr>
<td>Density (g cm⁻³)</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Spec. surface (m² g⁻¹)</td>
<td>64</td>
<td>0.7</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>47</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3 Pine Bark

The pine bark was chosen to investigate the possibility of using a residual product from the cellulose and paper industry as a sorbent material. The pine bark used in the pilot-scale column experiments consists of 85-90% dried and granulated pine bark and 10-15% wood fibre, a product called Zugo™. The pine bark used in the gully-pot filters, shown in Figure 1, was analysed with regard to its metal content, and is presented in Table 3.

![Photo of pine bark used in the gully-pot filters.](image)

Table 3. Metal content in unused pine bark, used in the gully-pot filters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>As</th>
<th>Pb</th>
<th>Cd</th>
<th>Co</th>
<th>Cu</th>
<th>Cr</th>
<th>Ni</th>
<th>V</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg/kg dw</td>
<td>0.11</td>
<td>2.5</td>
<td>0.6</td>
<td>0.25</td>
<td>6.0</td>
<td>1.8</td>
<td>0.8</td>
<td>0.54</td>
<td>83</td>
</tr>
</tbody>
</table>
5. Methods

The research methods consist of experiments in both the laboratory and in the field. It is important to combine these experiments to be able to compare controlled investigations in the laboratory with experiments in the field, using storm water, which are not possible to control to the same extent. Experimental studies give the opportunity to make a theoretical estimation of some parameters such as sorption capacity in the filter substrate. Field studies give the possibility to implement the technique and to focus on questions on a practical basis concerning operation and maintenance. Table 4 presents a matrix for the different investigations.

Table 4. A matrix for the investigations presented in this thesis.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of investigation</th>
<th>What was investigated?</th>
<th>Presented in paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab.</td>
<td>Batch tests</td>
<td>Pine bark</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>Column tests</td>
<td>Opoka, zeolite, peat</td>
<td>II</td>
</tr>
<tr>
<td>Field</td>
<td>Pilot-scale column tests</td>
<td>Opoka, zeolite, pine bark</td>
<td>III</td>
</tr>
<tr>
<td></td>
<td>Gully-pot filters</td>
<td>Pine bark</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>Storm water treatment plant, Vallby</td>
<td>Water quality, Sediment</td>
<td>V, VI</td>
</tr>
</tbody>
</table>

Different filter substrates have been investigated using batch tests (paper IV) and column experiments (paper II) in the laboratory. The laboratory experiments were carried out to control parameters such as concentrations of metals in the solution, temperature and particles in the water to be filtered. The batch tests were also made to investigate the parameters for the sorption capacity in the mathematical model presented in section 3.

In the field, a pilot-scale column experiment has been carried out to investigate the filter material when filtrating storm water from a detention pond through the material (paper III). One of the filter substrates was also tested in gully-pot filters (paper I), which is one possible method of using a filter material for storm water treatment. The hydraulic function of the filter systems is necessary to investigate. A good water flow through the filter system is a requirement to attain a functioning filter system.

A full-scale storm water treatment plant has been investigated. The storm water treatment plant includes a detention pond, a constructed filter system
and a constructed wetland. The treatment plant was studied with regard to water quality and accumulated sediment in the detention pond (paper V and IV). Both chemical analyses and toxicity tests were carried out in the investigation.

5.1 Laboratory Experiments

Column experiments on a laboratory scale were carried out. The selected filter substrates were tested in order to evaluate the sorption capacity and the efficiency in removal of heavy metals from water. These parameters were tested with regard to the load, to obtain information about design aspects of a constructed filter.

The columns were filled with different compositions and mixtures of the filter substrates. Solutions containing zinc (Zn), cadmium (Cd), chromium (Cr), copper (Cu) and lead (Pb) were filtered through the columns. A mesh was placed at the bottom of each column to prevent losses of the filter material. Details concerning the set up for the column experiments using calcium silicate (opoka) and zeolite as filter substrates are presented in Paper II.

Batch tests were performed using pine bark to determine the metal removal by the material from metal solutions containing Cu, Zn and Pb. This investigation was also carried out as a consequence of the results of the experiment with pine bark installed in gully-pot filters (see paper I and section 6.3). A matrix was set-up for investigating the pine bark, using metal solutions with different metal concentrations and different contact time with the material. A rinse procedure using de-ionised water was made to examine how much of the metals that were easily removed from the pine bark and which had not been sorbed to the material. The aim of the batch tests was to evaluate the sorption capacity and the sorption isotherms of the pine bark according to the mathematical model presented in section 3.1.

In order to examine the influence of road salt in storm water during winter periods on the removal efficiency of the filter material, NaCl was added to a metal solution. The solution was used in batch tests with the pine bark and the metal uptake in the material was determined.

More information about the batch tests is found in paper IV.
5.2 Pilot-Scale Experiment

In the pilot-scale experiment, presented in paper III, storm water from a section of a highway and its surrounding roads was filtered through different columns filled with calcium silicate rock (opoka), zeolite and pine bark. Results from the laboratory column experiments (paper II) showed that opoka and zeolite were interesting for further investigations with storm water. Pine bark was chosen because it is used in gully-pot filters and its purification efficiency needs to be investigated. Storm water from a detention pond was pumped to an array of columns filled with the filter materials. The hydraulic load was 4.8 m³/m²h.

Water samples taken before and after filtration through the columns were analysed for pH and concentrations of the heavy metals — Pb, Zn, Cu, Cr and Cd — as the total amount of each metal present in each sample.

Figure 2 shows the detention pond and the set up of the columns. Filtration was performed in a downward direction under unsaturated conditions. A pump and valves regulated the flow through the filter material in each column.

![Figure 2](image_url)  
*Figure 2. a) Storm-water detention pond and shed housing the columns,  
b) Column set-up viewed from inside the shed.*
5.3 Gully-Pot Filters

Results from the pilot-scale experiments (see section 6.2) showed that pine bark was interesting for further investigations. Therefore storm water runoff from two small urban catchment areas was filtered through pine bark installed in gully-pots. The storm water came from a parking lot and a residential quarter. The gully-pot filters were made of stainless steel, in which the pine bark was placed in tubes made of geotextile, as shown in Figure 3.

![Pine bark in a filter tube made of geotextile.](image)

Figure 3. Pine bark in a filter tube made of geotextile.

The gully-pot filters were tested during 6 months, from November 2000 to April 2001. The filter material was analysed to determine the amount of heavy metals before and after use. The load of metal from the storm water connected to the gully-pots was calculated using statistical data of metal content in storm water from these types of impervious areas together with precipitation data recorded close to the site. The metal uptake in the filters was then calculated. Details concerning this investigation are found in paper III.

5.4 Investigation of a Detention Pond and a Constructed Filter in Full-Scale

A storm water treatment plant was constructed at Vallby, in Västerås, Sweden in 1998 to deal with large volumes of storm water from a section of highway E18 and surrounding roads. On average, 20 000 vehicles per day are recorded passing this site. Storm water treated in the plant enters a detention pond first, and then flows through a specially constructed filter system and into an
artificial wetland. A general outline of the treatment system is shown in Figure 4.

The detention pond deals with the first flush from the catchment area. The constructed filter system consists of two steps. The first step is filtration through a high-density polyethylene (HDPE) filter to remove particles and oil. The second step is filtration through filter substrates, burned opoka and zeolite in two layers. Zeolite was chosen to achieve ion exchange because it has cations that can be changed with positively charged metal ions. Zeolite has also good adsorption effect due to the high porosity. In the opoka the immobilisation process primarily involves precipitation and adsorption.

In Figure 5 the filter system appears in the front of the photo and the detention pond in the background. Figure 6 presents the cross-section of the filter wells.

![Figure 4](image_url)

Figure 4. The storm water treatment plant in Västerås. Number 1 shows the detention pond, number 2 the filter system and number 3 the system of open ditches and a pond.

A constructed wetland system with open ditches and a pond is located downstream of the filter system. The wetland system is designed for the reduction of nitrogen by nitrification in the open stream followed by denitrification in the pond.

The efficiency of the storm water treatment plant has been monitored during 18 months, paying attention to the reduction of pollution in the treated storm water, sediment accumulation, and the operating and maintenance facilities at
the pond. Precipitation data was supplied from a meteorological station located close to the site.

Figure 5. The filter wells with the detention pond in the background.

Figure 6. Cross-section of the filter wells (1) HDPE-filter, (2) two layers of filter substrates.

Samples for water-quality analysis were obtained from both the inlet and the outlet points of the detention pond. Water samples were analysed for concentrations of Pb, Zn, Cu, Cr, and Cd. The metals were analysed in both particulate bound and filtered (0.45 μm) forms. Nutrient content using total
phosphorous (total P), total nitrogen (total N) and chemical oxygen demand (COD) were analysed. Water samples taken at the inlet point during the year 2000 were also analysed for suspended solids (TSS) and pH.

Sediment samples collected from the inlet and the outlet of the pond were analysed for the heavy metals Cd, Cr, Cu, nickel (Ni), Pb and Zn, dry matter content (DMC) and volatile organic compound content (VOC).

Toxicity tests were conducted on water samples from the detention pond. The potential toxicity of runoff was evaluated using the following bioassays; the Microtox® comparison test, duckweed (Lemma minor), a green algae (Raphidocelis subcapitata), the crustaceans Daphnia magna, and Thamnocephalus platyurus using the microbiotests Daptoxkit™magna and Thamnotoxkit™. The toxkits are based upon larvae obtained from cysts. A runoff sample or pore water was regarded as toxic if EC30 could be determined at the highest tested sample concentration (80-100 % depending upon toxicity test).

To evaluate potential toxicity of sediments, toxicity tests with both pore water and the whole sediments were conducted. The toxicity of 2 sediment samples collected from the inflow and the outflow was analysed. The toxicity of the pore water was assessed with the Microtox® comparison test and the Thamnotoxkit™ and whole sediment toxicity was assessed with Microtox®SPT using both intact and dewatered sediment.

The function of the constructed filter system was investigated. The reduction efficiency in the constructed wetland was not investigated because of the number of parameters affecting the water quality at the golf course, such as drainage and irrigation, as well as the spreading of pesticides and fertilisers. Therefore no field measurements were carried out in the constructed wetland.

A more detailed description of the treatment plant in Vallby and of the chemical analyses and toxicity tests can be found in papers V and VI.
6. Results and Discussion

6.1 Laboratory Experiments

The column experiments resulted in further knowledge of the selected filter substrates and their removal efficiency with regard to load to the filtered metal solutions. Information about the hydraulic efficiency of the filter substrates was also obtained. The results from the laboratory column experiments are described in Paper II.

An important parameter is the removal capacity of the filter material in relation to filtration time; in other words the removal capacity per cubic meter of filter substrate. One of the column experiments showed a metal sorption capacity that varied from 0.6 - 1.8 kg/m³ filter substrate depending on the metal, choice of filter substrate and the volume of filtered metal solution. The most efficient materials with regard to this parameter were natural opoka and a mixture of burned opoka and zeolite.

The metal uptake was correlated to load and showed that the reduction efficiency decreased with increased load. Statistical results of the uptake for Cr, Cu and Zn mixtures of opoka and zeolites are presented in Table 5. The statistical results are presented for the load <2 m³/m²-h and for the load 3-6 m³/m²-h. The results presented in paper II, Table 4, include even the reduction efficiency for loads between 2-3 m³/m²-h, which are low or even negative. The removal efficiency dropped at 2-3 m³/m²-h, which may be explained by channelling of the water in the columns. When the load exceeded 5-6 m³/m²-h the metal sorption efficiency showed a distinct decrease. This indicates that the contact time between the metal solution and the filter material is essential. It is important to establish as long retention time as possible in order to get high removal of metals.

The hydraulic efficiency was good for the mixtures of opoka and zeolite. When solely opoka was used the material clogged. This is proposed to be caused by chemical reactions between sulphur in the metal solution and calcium oxide in the material, causing cementation in the substrate (formation of gypsum). Burned opoka mixed with peat also clogged because the peat was
mobilized and transported with filtered water. This blocked the mesh in the bottom of the column.

Table 5. Results for the reduction efficiency (%) of metals in mixtures of opoka and zeolite for the loads < 2 and 3-6 m$^3$/m$^2$h.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Cr</td>
<td>Cu</td>
<td>Zn</td>
</tr>
<tr>
<td>Min</td>
<td>76.2</td>
<td>81.6</td>
<td>73.5</td>
</tr>
<tr>
<td>Max</td>
<td>85.7</td>
<td>89.5</td>
<td>93.6</td>
</tr>
<tr>
<td>Median</td>
<td>80.9</td>
<td>86.9</td>
<td>85.7</td>
</tr>
<tr>
<td>Mean</td>
<td>80.9</td>
<td>86.2</td>
<td>84.7</td>
</tr>
<tr>
<td>S.D.</td>
<td>3.9</td>
<td>4.0</td>
<td>9.8</td>
</tr>
<tr>
<td>No</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Load 3-6 m$^3$/m$^2$h

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Cr</td>
<td>Cu</td>
<td>Zn</td>
</tr>
<tr>
<td>Min</td>
<td>22.7</td>
<td>42.1</td>
<td>66.7</td>
</tr>
<tr>
<td>Max</td>
<td>45.5</td>
<td>93.7</td>
<td>94.7</td>
</tr>
<tr>
<td>Median</td>
<td>40.9</td>
<td>68.7</td>
<td>78.9</td>
</tr>
<tr>
<td>Mean</td>
<td>37.7</td>
<td>68.4</td>
<td>80.7</td>
</tr>
<tr>
<td>S.D.</td>
<td>9.0</td>
<td>22.6</td>
<td>11.4</td>
</tr>
<tr>
<td>No</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

The results from the investigation of pine bark in batch tests (paper IV) showed that a high metal sorption was achieved after a short contact time, which means that the reactions are very fast, and that a longer contact time does not have a big influence on the removal efficiency. The results also showed that the metal sorption to the material is similar for the tests whether the batches were shaken or not. This implies that the diffusion is the most important process. In Figure 7 the sorption of Cu to the pine bark is presented.

Low metal concentrations (0.1 mg/L) resulted in lower or even negative metal sorption in the pine bark, than compared to the sorption with the initial metal concentrations of 1 and 10 mg/L. This is proposed to be caused by the metal content in the pine bark itself. The reduction efficiency of metals was similar for 1 and 10 mg/L, which may imply that the diffusion in the liquid is not limited but the diffusion into the particles. Negative sorption was detected for Zn and Pb which is a result of diffusion of the substances from the pine bark to the metal solution to achieve equilibrium.
Figure 7. Comparison of the uptake of Cu in the pine bark depending on concentration and contact time.

The results from the rinse procedure with de-ionised water, presented in Figure 8, show that the metals are easily removed from the material when there were low metal concentrations (0.1 mg/L) in the initial metal solution. For higher concentrations the metals were sorbed to the pine bark to a larger extent.

Figure 8. Presentation of the relationships between the content of Cu in the filtered water (out), the rinse-water and the sorbed amount of metals according to the metal content in the initial solutions (mg/L) in run A.

According to the results of the low metal sorption for metal concentrations of 0.1 mg/L in the solution, a filter system using pine bark would therefore only be useful for storm water and other effluents with higher metal concentrations.

The results of the metal sorption in the pine bark for metal concentrations 1 and 10 mg/L averaged 67 % for Cu, 76 % for Zn and 69.5 % for Pb. The
sorption capacities of the metals were found to be 2.6 g Cu, 1.3 g Zn and 3.8 g Pb per kg pine bark. In paper IV the sorption isotherms are presented which may be used to describe the sorption reactions in pine bark as described in the mathematical model of filtration through a porous media (see section 3.1).

The investigation of metal chloride solution in contact with pine bark resulted in a decrease of metal reduction by 15-23 %, compared to the studies without chloride in the solution. Consequently, the metal removal by the pine bark is not as effective for storm water containing road salt used for de-icing the roads as for storm water with no chloride ions. However, the metal reduction was 60 % or more for the investigated metals even when the chloride was present.

This investigation shows that the pine bark is useful for metal reduction and that further development must focus on the technical equipment and its hydraulic function. This is important to achieve an adequate contact between the material and the storm water, to avoid insufficient function as shown in the test with the gully-pot filters (see paper I and section 6.3).

To avoid channelling and to improve the hydraulic function in a filter system for storm water, the filter material could be arranged in layers using different particle sizes. The upper layer could be designed to separate particles as a mechanical filter, in order to increase the sorption efficiency in the subsequent layers.

6.2 Pilot-Scale Experiments

The mean concentrations in unfiltered storm water were 40.8 µg/L Cu and 27.1 µg/L Zn. The removal of Cu from storm water by the different filter substrates showed small variations. The median value for the reduction efficiency of Cu was nearly 80% for all the filter materials.

These results show that there are high metal reductions even though the metal concentrations in the storm water are low compared to the metal solutions in the batch tests (see discussion of results from batch tests in section 6.1). This is assumed to be caused by mechanical separation in the filter of particulate bound metals in the storm water, and not only by sorption processes. In the storm water the metals are both particulate bound and dissolved compared to the batch tests where the metals were dissolved.
The concentration of Zn in the filtered storm waters showed high variation. In two samples filtered through natural opoka, and in three samples filtered through the mixture of burned opoka and zeolite, the amount of Zn was much higher than in the unfiltered storm water. These amounts are questionable in comparison with other water samples taken both before and after these particular samples. The concentration of Zn is a difficult parameter to determine because samples can easily become contaminated during sampling or laboratory analysis. Because of these extreme values for Zn in natural opoka and the mixture of burned opoka and zeolite, the statistical results presented in Table 2 in paper III show mean reduction values which are low compared to the median value, and the standard deviations are very large. Results from the pilot-scale experiments presented, with these extreme values removed are shown in Table 6. However, these negative values should be considered because they may also depend on small colloid particles transported out from the column.

Table 6. Results of the metal concentration in filtered water (mg/L) and sorption of metals in the different filter substrates (%), when the negative removal values are excluded.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Natural opoka</th>
<th>Pine bark (Zugol)</th>
<th>Burned opoka and zeolite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu (mg/L) %</td>
<td>Zn (mg/L) %</td>
<td>Cu (mg/L) %</td>
</tr>
<tr>
<td>Min.</td>
<td>3.2 92.2</td>
<td>1.1 95.9</td>
<td>3.4 91.7</td>
</tr>
<tr>
<td>Max.</td>
<td>15.2 62.8</td>
<td>19.4 28.4</td>
<td>30.0 26.4</td>
</tr>
<tr>
<td>Median</td>
<td>7.7 81.1</td>
<td>6.6 75.6</td>
<td>8.4 79.4</td>
</tr>
<tr>
<td>Mean</td>
<td>8.1 80.2</td>
<td>8.2 69.9</td>
<td>10.1 75.2</td>
</tr>
<tr>
<td>SD</td>
<td>3.7 9.0</td>
<td>4.9 18.3</td>
<td>7.0 17.3</td>
</tr>
<tr>
<td>No.</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

The natural opoka and the mixture of burned opoka and zeolite had nearly the same removal efficiencies for Cu and Zn. The pine bark showed decreasing metal-removal efficiency in the last two samples. This tendency is supposedly caused by saturation of the material.

Details concerning results from these column experiments are described in Paper III.

Regarding cost, availability and the treatment of the substrates used, pine bark is interesting, because it is available in large quantities as a low-cost sorbent, being a residual product from local cellulose and paper industries. Having
these industries within a country does not require long-distance transportation. After being used as filter substrate, it can be burned as biomass, reducing the disposal volume, and the metals remain in the ashes. Pine bark is also compostable, however the metal content in the material must be taken into consideration in relation to how the compost will be used after treatment.

6.3 Gully-Pot Filters

In the gully-pot filter tests, presented in paper I, precipitation information for the 6-month period together with statistical data of the metal content in storm water was used to calculate the amount of metal, which theoretically passed the gully-pot filters during the test period. This calculated amount of metal has been compared with the actual accumulated metals in the filter material during the 6-month period.

The amount of metal accumulated in the pine bark during the experiment was very low in comparison to the calculated metal content in the filtered storm water. The Cd and Zn content were lower in the used filter material than before the investigation, which implies that these metals had leached from the pine bark. The reduction of Pb, Cu and Cr is very low, under 1%. Similar results using gully-pot filters have been found by Lundin (1999).

The low metal reduction capacity in the gully-pot filters may depend on an inadequate removal capacity of the filter material or on the construction of the filter system. The pilot-scale study, where the storm water passed through the material, showed high metal removal by the pine bark. In the gully-pot filters storm water can pass through channels outside the filter tubes and in the geotextile, which results in little or no water passing through the filter material. Therefore the hydraulic function of the gully-pot filters needs to be improved and the technical equipment must be developed. These results are important since there are several communities in Sweden, which have installed gully-pot filters with pine bark, due to new environmental regulations for the treatment of storm water.
6.4 Investigation of a Detention Pond and a Constructed Filter in Full-Scale

6.4.1 Storm Water Quality and Removal Efficiency in the Detention Pond

The concentrations of heavy metals in the storm water were investigated with respect to dissolved and particulate bound metals. Figure 9 compares the concentrations of dissolved only (filtered sample) and total heavy metals.

![Graph showing metal concentrations in water samples.](image)

Figure 9. Concentrations of dissolved (filtered sample) and total heavy metals in the storm water flowing into the detention pond, where filt means filtered and tot means total; a) presents the results for Cr and Pb, and b) results for Cu and Zn.
The amount of particulate bound heavy metals has been calculated from the results and the median values for the particulate bound fractions of Pb (58%) and Zn (77%) show that these metals are mainly particulate bound while Cr and Cu (48% and 43% respectively) are mainly dissolved in water. These results are not consistent with those found by Petterson, 1999, who reported that lead was mostly associated with sediments, while zinc remained in dissolved or colloidal form. This discrepancy may be explained by the fact that some of the runoff to the Vallby detention pond passes vegetated areas before entering the pond, which strain the particles in the storm water, by filtration through the grass.

These results show the importance of designing the entire pathway for storm water, from the impervious area to the recipient. Vegetated areas may be an efficient way to separate particles from the storm water before entering a filter system, where it is not possible to construct a detention pond for sedimentation of particles.

A comparison made between the total metal content in the storm water entering the Vallby treatment plant, and the metal content in the receiving water, the river Svartån shows that the metals were 5-8 times higher in the runoff, Table 7.

Some of these discrepancies may depend on the differences in analysis method between the metal content in the storm water and in the river Svartån. The analysis method used for assessing the total amount of metals in the storm water, even measure the metals that are strongly bound to the particles.

The mean levels of the total heavy metals in the storm water, shown in Table 7, were compared to the Swedish guideline values used for assessing if metal levels implicate an increased risk of biological effects in surface water (SEPA, 1999a). The comparison showed that the levels of Cd, Cr and Zn are all below probable biological effect levels while the levels of Pb and Cu both exceed the values expected to give an increased biological effect. If the storm water is not treated the maximum metal levels might cause a biological effect in the recipient river Svartån.

The monitoring of the storm water has not been conducted during winter periods. The melting away of snow and periods when salt for de-icing the roads are used would be interesting to investigate. The purpose would be to
study if there is a leakage of metals from the roadsides, and how these circumstances influence the storm water quality, both regarding the chemical characterisation as well as the toxicity of the storm water.

Table 7. Metal content in the recipient river Svartån (Mälarenergi, 2000) compared to metal content in storm water entering the Vallby detention pond during year 2000.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Min (µg/L)</th>
<th>Mean (µg/L)</th>
<th>Max (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Svartån¹</td>
<td>Storm water</td>
<td>Svartån¹</td>
</tr>
<tr>
<td></td>
<td>Diss.²</td>
<td>Tot.²</td>
<td>Diss.²</td>
</tr>
<tr>
<td>Cr</td>
<td>0.5</td>
<td>2.7³ 3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Cu</td>
<td>1.6</td>
<td>2.2 4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Zn</td>
<td>1</td>
<td>1.0 6</td>
<td>10</td>
</tr>
<tr>
<td>Pb</td>
<td>0.1</td>
<td>2.6 1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Cd</td>
<td>0.02</td>
<td>0.37³ 0.3³</td>
<td>0.04</td>
</tr>
</tbody>
</table>

¹ First acid preserved and then filtrated samples
² Dissolved metals (filtrated and then acid preserved samples)
³ Total amounts of metals
⁴ Lowest determinable content

The reduction efficiency of the detention pond was calculated by relating the median value of each parameter analysed in the samples collected from storm water flowing into the pond to the corresponding parameter in the samples collected from storm water flowing out of the detention pond. The detention pond was found to have the following reduction efficiencies: 67 % for total N, 78 % for total P, 92 % for COD, 52 % for Cr, 51 % for Cu, 26 % for Pb and 84 % for Zn.

The accuracy of the calculated reduction efficiencies in the detention pond could be improved and guaranteed by more frequent flow weighted sampling of the outflow.

6.4.2 Sediment in the Detention Pond

The sediment samples showed that the thickness of the accumulated, unconsolidated sediment during 18 months was 5-8 cm at the pond inlet and 1.5 cm at the pond outlet. These results are similar to other investigations of the accumulation of sediments (Yousef et al., 1990; Marsalek & Marsalek, 1997 and Buren et al., 1996). The mean metal concentrations of the sediment
samples are presented in Table 8. They are compared to values from the Swedish Environmental Protection Agency in order to relate the metal concentrations in the pond sediments with other types of polluted substrates. The comparison shows that only the content of Ni and Cd exceeded the values for polluted soil and/or the values for sewage sludge on fields.

Table 8. Results from sediment analyses in the detention pond and the limit values for metals in different media according to the Swedish Environmental Protection Agency (metal per kg dry weight).

<table>
<thead>
<tr>
<th></th>
<th>Cd (µg/kg)</th>
<th>Cr (mg/kg)</th>
<th>Cu (mg/kg)</th>
<th>Ni (mg/kg)</th>
<th>Pb (mg/kg)</th>
<th>Zn (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>561</td>
<td>38</td>
<td>52</td>
<td>43</td>
<td>33</td>
<td>204</td>
</tr>
<tr>
<td>Outlet</td>
<td>172</td>
<td>49</td>
<td>29</td>
<td>31</td>
<td>21</td>
<td>115</td>
</tr>
<tr>
<td>No of samples</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Polluted soil</td>
<td>400</td>
<td>120</td>
<td>100</td>
<td>35</td>
<td>80</td>
<td>350</td>
</tr>
<tr>
<td>Lake sediment</td>
<td>32000</td>
<td>160</td>
<td>140</td>
<td>80</td>
<td>6400</td>
<td>2400</td>
</tr>
<tr>
<td>Sewage sludge on fields</td>
<td>200</td>
<td>100</td>
<td>600</td>
<td>50</td>
<td>100</td>
<td>800</td>
</tr>
</tbody>
</table>

1 Swedish guideline values for metal levels in polluted soils (SEPA, 1996)
2 Background levels of metals in sediment in lakes in southern Sweden (SEPA, 1999a)
3 Limit values for metals in sewage sludge on fields (SEPA, 1998)

6.4.3 Toxicity Tests

No toxicity was detected in the runoff samples with the crustacean toxicity tests using *Daphnia magna* or *Thamnocephalus platyurus* as test organisms; nor was any toxicity detected with the Microtox® comparison test or with the green algae *Raphidocelis subcapitata* or duckweed, *Lemma minor*. However, 22% of the samples (5 of 23 tested) with *Lemma minor* showed a growth stimulatory effect, which can be caused by high levels of N and/or P in the storm water.

Two toxicity tests on pore water from sediments samples taken at the inflow and the outflow were conducted, the Thamnotoxkit® and the Microtox® comparison test, but no toxicity was detected. The whole sediment from the inlet was assessed with the Microtox® Solid-phase test. According to the SEPA (1999b) guidelines the sediment from the detention pond should be classified as sediment showing a large effect from a point source.

The discrepancy between the actual sediment contaminant level and the classifications of sediment contaminant level based upon the Microtox® Solid-
phase test needs further investigation. The results from the chemical characterisation of the sediment in the detention pond, regarding the metal content, indicate low pollutant level according to the guidelines from SEPA, nevertheless, the results from the Microtox® Solid-phase test were contradictory. This may be explained by the knowledge that the toxicity of a sediment in the Microtox® Solid-phase test is influenced by factors other than the actual level of contaminants (Ringwood et al., 1997; Svensson et al., 1998), for example the particle size distribution, the concentration of elemental sulphur in the sediments, and/or the presence of de-icing compounds or hydrocarbons such as oil and grease. Similar studies made by Marsalek et al., (2002) showed sediment toxicity detected by the Microtox® Solid-phase test.

6.4.4 Constructed Filter System

Shortly after the construction of the filter system the winter period started. The constructed filter system was not permeable after the winter period and water was not able to pass through the filter wells. An investigation of the two layers of filter substrates showed that the substrate opoka had clogged. The zeolite was still permeable. No analyses of the filter materials were made and the opoka layer was removed. The clogging was supposed to be caused by cementation of the material.
7. Conclusions

The most important questions regarding the different investigations of the filter systems were the function of the filter systems and whether the selected natural materials could be used for filtration of storm water for metal sorption.

The most important findings were:

- The study of the gully-pot filters showed that the hydraulic function of the filter system was unsatisfactory. The reduction of Pb, Cu and Cr was very low, under 1%, and the content of Cd and Zn had decreased in the pine bark during the investigation. The investigated gully-pot filters need more development concerning the hydraulic function to achieve successful water flow through the filter material.

- All materials showed a high removal capacity of metals. In the pilot-scale experiments the mean metal reduction was around 80 % for Cu and 63-72 % for Zn depending on the filter substrate.

- The calcium silicate in its heated form (burned opoka) did not have satisfactory hydraulic function because of clogging of the material. The opoka in the full-scale constructed filter system in Vallby became completely clogged. Another disadvantage with the material is that the opoka is found in Poland and Russia and may demand long transportation. Therefore it has a greater environmental impact than material that can be found within a country.

- The results from the batch tests with pine bark showed that a high metal removal was achieved after a short contact time, which means that the reactions are very fast, and that a longer contact time does not have a big influence on the removal efficiency. The sorption capacity of metals is presented as g metal per kg pine bark.

- An investigation of chloride in the metal solution showed that the metal sorption to pine bark was decreased by 15-23 %, depending on the metal, compared to metal solution without chloride.
• Of the tested filter materials pine bark is interesting for further investigation. Both the pilot-scale column experiment and the batch tests showed that pine bark could reduce metals. Compared to the other tested materials, pine bark has the advantage that it can be composted or burned as biomass after use. Also, pine bark is available in Sweden and many other countries as a residual product.

The results from the laboratory tests of pine bark can be applied to the filter system in the Vallby storm water treatment plant. Calculations using mean values of the pollutant loads from the actual catchment area during one year, together with the size of the constructed filter system, give information about the lifetime of the filter material. The pine bark should be saturated after approximately one year of use and should then need to be changed.

There are still questions to be answered concerning dimensioning of the filter systems to achieve an adequate hydraulic function of the system. It is important to maintain water flow through the filter material to obtain adequate metal sorption in the filter system. Filtration of storm water requires presettled water to avoid clogging of the filter system. The separation of particles may be achieved by sedimentation in detention ponds.

From the investigation of the detention pond, the following key findings were:

• The study of the concentrations of heavy metals in the storm water entering the detention pond showed that Pb and Zn were mainly particulate bound, while Cr and Cu were mainly dissolved.

• In the sediment accumulated in the detention pond, it was only the content of Ni and Cd that exceeded the Swedish guideline values for polluted soil and the limit values for sewage sludge on fields from the Swedish Environmental Protection Agency.

• The sediment accumulation rate was 30-50 mm per year at the inlet of the detention pond.

• No toxicity in the storm water was detected. The pore water of the collected sediments was not toxic but the whole sediment tested by the Microtox® Solid-phase test showed toxicity.
- The maximum metal levels in the untreated storm water implicate an increased risk of biological effects in the recipient for all the analysed metals, when compared to the guideline values from SEPA used for assessing the biological effects of metals in surface water.

Detention ponds are important for the reduction of peak flows and for the pollution reduction in storm water. Detention ponds need more investigation regarding the aspects of maintenance and operation of sediments, and the growth of vegetation and algae in the ponds.

The separation of particles from the storm water is also necessary if the pond is followed by a filter system. This is important if the purpose is to create a treatment system where the filter is supposed to sorb the dissolved metals and not to separate particles as in a mechanical filter.

The research presented in this thesis has been carried out with an applied angle of approach. Of course there has been a desire to conduct more frequent measurements and repeated tests to assure the quality of the results, especially in this research field when the circumstances are changing with time and location (storm water quality for example). Nevertheless, the results from these investigations have increased the knowledge concerning the function of filter systems and some natural filter substrates for metal removal from storm water as well as the function of detention ponds.
8. Future Research

There is a need for further knowledge concerning constructed filter systems for storm water treatment. Several filter substrates have been tested with regard to their metal sorption capacity in laboratory studies according to the literature review presented in paper I. Most of these materials have, however, not been tested in field studies in large-scale treatment plants. An interesting and important continuation of the research concerning pine bark would be to examine the filter substrate in a full-scale filter system. The constructed filter system in Vallby storm water treatment plant would be suitable for that purpose.

The environmental impact of the materials and aspects as costs, availability, treatment and use of used filter substrates need further investigation. These aspects are of great importance and must be considered to achieve a sustainable system for water treatment - not only for storm water.

The studies of the filter substrates have solely been aimed at investigating the removal of metals from water solutions and storm water. It is also interesting to know the removal efficiency of other substances and from other effluents, such as phosphorus from waste water for example. Recovery of phosphorus sorbed in filter materials may be a possible way to recycle phosphorus which is necessary for a sustainable system.

Modelling of the processes for contaminant transport through a filter substrate (porous media) is also important for designing treatment plants. The aim with such research is to develop a model for reactive media, which can predict changes in the removal efficiency of different substances depending on parameters such as the quality of the storm water and the characteristics of the filter substrate (e.g. porosity, specific area, pH).

Research of the above mentioned aspects is expected to improve the knowledge concerning constructed filter systems regarding both the function, the filter materials as well as dimensioning of the treatment plants.

Future research and development concerning detention ponds must focus on operation and maintenance aspects such as the handling of sediments and vegetation in the ponds. The differences between the sediment contaminant
level in the investigated detention pond and the classifications of the sediment contaminant level based upon the Microtox® Solid-phase test need further investigation. This is important because the handling of the sediments depends on the quality of the sediment and on environmental regulations. Strategies for the treatment and/or disposal of sediments ought to be developed.
9. References


