Characterization of sediment from storm water tunnels

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Abstract

Tunnels used for storm water were constructed in several cities in Sweden and other countries during the 1970s. In addition to the importance of the hydraulic function of the tunnel, the environmental aspects of the storm water flowing out into the recipient as well as the contamination of the accumulated sediment in the tunnel are very important factors to consider regarding the operation and maintenance of the tunnel. Sediment accumulated in the tunnel should eventually be removed and depending upon contaminant level it could be used as soil or it has to be safely disposed of. In the city of Västerås, Sweden, four storm water tunnels were constructed in the beginning of the 1970s. This paper describes a physical and chemical characterization of sediments from three of the tunnels as well as an evaluation of the potential toxicity of the sediments. Sediment samples were analysed for dry matter, loss on ignition, particle size, total S content, heavy metals, PAH, BTEX and aliphatic hydrocarbons. The sediments had high silt-clay content and high levels of Cu, Ni and Zn but low or moderate levels of the other metals when compared to SEPA guidelines for freshwater sediment. However, if the sediment were removed from the tunnels it would be considered as a rather polluted soil based on the levels of several heavy metals, carcinogenic PAH and aliphatic hydrocarbons. The toxicity of the whole sediment was determined with the Microtox® Solid Phase test and the toxicity of the pore water was determined with the Microtox® basal test and with the crustacean Thamnocephalus platyurus. The whole sediments were toxic but no or only very slight toxicity was found in the pore water. Part of the whole sediment toxicity might be due to the presence of elemental sulphur in the sediments in combination with the loss of bacteria attached to very fine particles.
1 Introduction

Impervious areas such as highways, parking lots and roofs, generate 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.

Storm water tunnels have been built for temporary storage to reduce or eliminate flow peaks during heavy storm events. Tunnels used for storm water were constructed in several cities in Sweden and other countries during the 1970s. The tunnels were also constructed to trap sediments in runoff water, and can be useful for storm water treatment, in order to improve the quality of storm water going into the receiving waters. The contaminants are removed mainly by sedimentation, since the majority of pollutants are attached to solids. Knowledge of the sediment accumulation processes and pollutant accumulation in sediments is essential to assess the removal efficiency of the tunnels, and to get information about maintenance activities.

The quality of storm water depends on the time between two rain events and the type of impervious area that creates the runoff. The quality of the precipitation is also important. The storm water quality is changing in time and between different places. The most important sources of storm water pollution are atmospheric deposition, traffic, corrosion and debris from birds and dogs [1]. 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. There has been comprehensive research carried out to investigate the quality of storm water [2, 3, 4, 5] and snow quality and melt water [6].

In the city of Västerås, Sweden, four storm water tunnels were constructed in the beginning of the 1970s. The aim with this study was to determine the contaminant level in three of these tunnels by physical and chemical characterization and to determine the potential toxicity of the sediments.

2 Materials and methods

2.1 Storm water tunnels

Three of the tunnels in the city of Västerås were investigated. Information about the tunnels is presented in Table 1. The catchment areas for the investigated tunnels are similar for all of the tunnels, and are composed of a mixture of household and industrial areas, green open spaces and traffic routes.

The tunnels are situated approximately 10 m or more underground and the cross section area is about 10 m². The profile of the tunnels is U-shaped, which means that the tunnels are always filled with water. When there is a storm event, run-off is charged into the tunnels and the stored storm water flows out to the receiving recipient. During heavy storm events, the outflow from the tunnels contains particles which are assumed to be suspended from the sediments in the tunnels.
Table 1: Information about the investigated tunnels.

<table>
<thead>
<tr>
<th>Name</th>
<th>Year of construction</th>
<th>Length (km)</th>
<th>Catchment area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emaus</td>
<td>1960–61</td>
<td>2.14</td>
<td>75</td>
</tr>
<tr>
<td>Bäckby-Hacksta</td>
<td>1973</td>
<td>1.86</td>
<td>1900</td>
</tr>
<tr>
<td>Önsta-Gryta</td>
<td>1974–77</td>
<td>3.47</td>
<td>900</td>
</tr>
</tbody>
</table>

2.2 Sampling

The sampling of the sediment was made close to the outflow of the tunnels. The tunnels are very difficult to investigate as they are always filled with water and situated below the groundwater table. Sediment samples can thus only be taken at a few places close to the outflow through vertical shafts from the ground level above areas of the tunnels where accumulation of sediments is expected. Several core samplers used for sediment sampling in lakes were tested but we were only successful in recovering sediment with an Ekman grabber. The sampling was made in May 2002. Several samples were collected at each site, homogenized properly and transported in cool conditions to the laboratory.

2.3 Sediment analyses

2.3.1 Physical and chemical analysis for the determination of contamination levels

Sediment samples were analysed for dry matter content and loss on ignition according to SS 02 81 13.

For the metal analysis, sediment samples were dried at 50°C and were digested in Teflon bombs in concentrated HNO₃/water 1:1. They were analysed for total concentrations of heavy metals including; arsenic (As), cadmium (Cd), cobalt (Co), chromium (tot Cr and CrVI) copper (Cu), mercury (Hg), nickel (Ni), vanadium (V) and zinc (Zn) according to EPA 200.7 and 200.8. Analysis was performed by the accredited laboratory SCAB Analytica, Stockholm, Sweden.

The 16 EPA-PAH priority pollutants were determined by HPLC with a fluorescence detector by ECOCHEM, Czech Republic, an accredited laboratory accepted by the EAC (European Accreditation of Certification) according to EPA 610, 550 and 3550 and Czech standard CSN 75 75 54, after extracting analytes in acetone and hexane (1:1). PAH is a composition in tyres and asphalt and is found because of incomplete combustion [7]. It has also been shown that the major toxicants of sediment extracts from a stream contaminated with motorway run off were three PAHs [8].

Monocyclic aromatic hydrocarbons (BTEX) and oil fractions were determined by OMEGAM, The Netherlands accredited through EAC. Analyses of aliphatic hydrocarbons C5–C8 and C8–C10 and BTEX were made by using purge and trap GC-MS. The fractions C10–C12, C12–C16 and C16–C35 were determined using GC-FID according to NEN 5733. The BTEX was determined because it is supposed to be found in the sediment as it is a constituent in petrol.
The oil fraction was determined because it might be an important pollutant in traffic storm water.

2.3.2 Physical and chemical analysis for the determination of limiting factors

Analyses of a number of physical and chemical parameters were conducted in order to discriminate between toxic effects due to extreme values of some natural factor or natural compound, here termed limiting factor, from those due to xenobiotic contaminants.

The grain size distribution of the sediment was determined on freeze-dried sediment according to Ljung [9] after sieving through a 2 mm sieve, followed by oxidation of the organic material. It was expressed as a percentage of silt-clay (e.g. sediment particles < 0.06 mm). The analysis was conducted at the Department of Soil Science, Swedish Agricultural University, Uppsala, Sweden. For the analysis of the total sulphur content in the sediments, 6–19 mg of freeze-dried sediment was added to tin capsules. The sulphur content was determined in a LECO CHNS-932 elemental analyser. The samples were combusted at 1000°C in a flow of helium with the addition of copper oxide and oxygen to achieve total combustion. The amount of SO₂ produced was measured with IR detectors. The analysis was conducted at the Department of Limnology, Uppsala University, Uppsala, Sweden.

In the pore water, pH was determined by the Swedish Standard SS 02 81 22. Ammonium-nitrate (NH₄–N) and chloride (Cl–) was determined using a photometrical operation analysis instrument (ISiS 9000, Dr Lange, Germany). The concentration of un-ionized ammonia was calculated according to EPA 600/3-79-091. The pore water was obtained by centrifuging wet sediment at 5000 rpm (5087 rcf) for 30 min.

2.3.3 Toxicity tests

To evaluate the potential toxicity of sediments, toxicity tests with both pore water and whole sediments were conducted. The potential toxicity in the pore water was evaluated using the following bioassays: Vibrio fischeri using the Microtox® basal test following the manufacturers manual (MicrotoxOmni™ Software, Azur Environmentals USA, 1999); and Thamnocephalus platyurus using the Thamnotoxkit™ from Microbiotests, Deinze, Belgium following the manufacturers instructions. The whole sediment toxicity was assessed with Microtox® SPT using intact sediment according to SEPA [10].

3 Results and discussion

3.1 Physical and chemical analyses for the determination of contamination level

The physical analyses of dry matter content and loss on ignition are presented in Table 2. The sediments were rather loose with a low content of dry substance
and this in turn may explain the problems we had in sampling the sediment with conventional core sediment samplers.

Table 2: The results from the analyses of dry matter content (DMC) and loss on ignition (LOI).

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>DMC (%)</th>
<th>LOI (g/kg)</th>
<th>LOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Önsta-Gryta</td>
<td>24</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>Bäckby</td>
<td>25</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>Emaus</td>
<td>31</td>
<td>40</td>
<td>4</td>
</tr>
</tbody>
</table>

The results from the metal analyses of the sediment samples are presented in Table 3. The metal content has been compared with the Environmental Quality Criteria for contaminated sites developed by SEPA [11], see Table 3.

Table 3: Metal content in the tunnel sediments.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Emaus</th>
<th>Class</th>
<th>Bäckby</th>
<th>Class</th>
<th>Önsta-Gryta</th>
<th>Class</th>
<th>Ponds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/kg dw</td>
<td></td>
<td>mg/kg dw</td>
<td></td>
<td>mg/kg dw</td>
<td></td>
<td>mg/kg dw</td>
</tr>
<tr>
<td>As</td>
<td>10.2±3.5</td>
<td>3</td>
<td>13.5±4.6</td>
<td>3</td>
<td>20.7±7.1</td>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>Ag</td>
<td>1.70</td>
<td>-</td>
<td>0.73</td>
<td>-</td>
<td>0.314</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cd</td>
<td>1.15±0.25</td>
<td>2</td>
<td>2.93±0.65</td>
<td>3</td>
<td>1.69±0.38</td>
<td>3</td>
<td>4.1</td>
</tr>
<tr>
<td>Co</td>
<td>19.6±2.8</td>
<td>-</td>
<td>24±3.1</td>
<td>-</td>
<td>34.7±4.3</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>Cr</td>
<td>51.0±8.2</td>
<td>3</td>
<td>75.7±12.2</td>
<td>3</td>
<td>65.5±10.5</td>
<td>3</td>
<td>59</td>
</tr>
<tr>
<td>Cr (VI)</td>
<td>&lt;0.3</td>
<td>-</td>
<td>&lt;0.3</td>
<td>-</td>
<td>&lt;0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>152±22</td>
<td>4</td>
<td>159±24</td>
<td>4</td>
<td>106±16</td>
<td>4</td>
<td>66</td>
</tr>
<tr>
<td>Hg</td>
<td>0.151±0.082</td>
<td>1</td>
<td>0.128±0.058</td>
<td>1</td>
<td>0.12±0.054</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>1300±141</td>
<td>-</td>
<td>937±101</td>
<td>-</td>
<td>1740±180</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ni</td>
<td>32.0±5.3</td>
<td>3</td>
<td>47.8±7.8</td>
<td>4</td>
<td>50.5±8.2</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>Pb</td>
<td>61.4±10.3</td>
<td>2</td>
<td>98.2±16</td>
<td>2</td>
<td>74.5±12.5</td>
<td>2</td>
<td>230</td>
</tr>
<tr>
<td>V</td>
<td>732.±11.8</td>
<td>-</td>
<td>106±17</td>
<td>-</td>
<td>106±17</td>
<td>-</td>
<td>54</td>
</tr>
<tr>
<td>Zn</td>
<td>609±113</td>
<td>3</td>
<td>948±176</td>
<td>4</td>
<td>974±180</td>
<td>4</td>
<td>500</td>
</tr>
</tbody>
</table>

These criteria make it possible to conduct a risk classification of the sediments. The classification is divided into five classes as follows: 1, very low content; 2, low content; 3, moderate high content; 4, high content; 5, very high content.

It is mostly Cu, Ni and Zn, which are found in large amounts in the sediment samples, and they are all classified in class 4, high content of metals. The metal content has also been compared to Swedish guideline values for metal content in lake sediments in the south of Sweden [11]. The content of Cu and Ni showed a large to a very large discrepancy from the guideline values.
The metal content in the tunnel sediment has also been compared to an average value of metals in sediment from storm water ponds. The values for the pond sediments have been obtained from a literature review [12], which summarizes a large number (55) of investigated ponds. The comparison shows that the tunnel sediment is more polluted than the pond sediments with regard to all the analysed metals except for Cd and Pb. The values are approximately twice as high in the tunnel sediment as in the pond sediments.

For the content of monocycle aromatic hydrocarbons (BTEX), oil fractions and polyaromatic hydrocarbons (PAH) there are no applicable guidelines for the classification of sediment. The amounts in the sediment has therefore been compared with Swedish guidelines for contaminated soil [10], which is divided into a four graded scale describing the degree of contamination of the soil from “less severe” to “very severe” conditions, see Table 4. This comparison showed that the amount of oil fraction \( > C_{12-C_{16}} \) was “severe” while the oil fraction \( > C_{16-C_{35}} \) was “very severe” (Table 4). These amounts were found in the tunnels Bäckby and Önsta-Gryta. These oil fractions can be derived from both natural organic material and from anthropogenic sources. The fraction of anthropogenic material should therefore be further investigated.

Table 4: The amount and the classification of the heavy oil fractions and the carcinogenic PAH.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Emaus (mg/kg dw)</th>
<th>Class</th>
<th>Bäckby (mg/kg dw)</th>
<th>Class</th>
<th>Önsta-Gryta (mg/kg dw)</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt; C_{12-C_{16}} )</td>
<td>570</td>
<td>severe</td>
<td>440</td>
<td>severe</td>
<td>66</td>
<td>less severe</td>
</tr>
<tr>
<td>( &gt; C_{16-C_{35}} )</td>
<td>7500</td>
<td>very severe</td>
<td>5900</td>
<td>very severe</td>
<td>4000</td>
<td>very severe</td>
</tr>
<tr>
<td>carcinogenic PAH</td>
<td>2.6</td>
<td>severe</td>
<td>1.8</td>
<td>severe</td>
<td>0.87</td>
<td>moderate severe</td>
</tr>
</tbody>
</table>

Swedish guideline values for PAH content [11] are only available for the total amount of carcinogenic PAH and other PAH and the first was found to be “severe” in the Emaus and Bäckby tunnels (Table 4).

3.2 Physical and chemical analysis for the assessment of limiting factors for organisms used in toxicity tests

The tunnel sediments had a very high percentage of silt-clay varying between 95–98%. Previous studies have shown that particle size distribution may strongly influence the toxicity of sediment in the Microtox® Solid-Phase Test and sediment with a high percentage of silt-clay tends to have a high natural toxicity [13, 14].
The total sulphur content in the sediment was determined because previous studies have concluded that $S_8$ present in organic extracts of sediments is highly toxic to the Microtox test bacteria *Vibrio fischeri* [15, 16, 17]. Furthermore, toxicity of elemental sulphur has also been indicated in the direct contact test, as used in this study, by Svenson et al. [18]. Other sulphur compounds such as hydrogen sulphide which might also be present in anoxic sediments is also toxic to *Vibrio fischeri* but to a much lower extent. However, the oxidation of hydrogen sulphur will cause a 5000 times increase in Microtox toxicity [18]. The determination of the concentration of elemental sulphur available to the bacteria in the direct contact test is difficult. This because it is not known if the bacteria are exposed to all of it and chemical transformations might take place during the preparation of the sediment and during the toxicity test. We choose to determine the total sulphur content in the sediment by elemental analysis and then to calculate the elemental sulphur concentration. Calculations were based upon the assumption that in a moderately eutrophic lake the elemental sulphur content in sediment is approximately 1% of the total sulphur content [19]. The calculated elemental sulphur content of the analysed sediments is presented in Table 5 and discussed below in conjunction with the toxicity results.

In several studies determining sediment toxicity, *Thamnocephalus platyurus* has been found to be sensitive to contaminants in sediment pore water [20, 21] but it is also very sensitive to salt (e.g. chloride) and ammonia (i.e. un-ionized ammonia). From the analysis of the sediments pore water we concluded that all sediments had chloride levels below the threshold levels (EC$_{10}$) given by Persoone and Vangheluwe [21] but in pore water from Önsta-Gryta and from Emaus toxic effects due to the presence of un-ionized ammonia should be expected giving a calculated effect of 15 and 25%, respectively.

### 3.3 Acute toxicity of pore water and whole sediment

No toxicity (i.e. EC$_{20} > 80$ vol-%) of the pore water was detected with *Thamnocephalus platyurus* although a low effect due to the presence of un-ionized ammonia should be expected for two of the sediments. As the toxic effect expected from un-ionized ammonia was rather low, it is possible that variation of test conditions in our laboratory with the laboratory establishing the threshold values can account for the lack of toxicity. Alternatively, all un-ionized ammonia in the pore water was not available for the test organism.

No toxicity (i.e. EC$_{20} > 80$ vol-%) was detected in the pore water from the Bäckby and the Emaus tunnel with the Microtox® basic test. For the pore water from the Önsta-Gryta tunnel a 15 min-EC$_{20}$ at 38 vol-% indicates, according to the Swedish guideline values for pore water from contaminated sediment [11], a probable influence from a point source.

The sediment toxicity as assessed with the Microtox® Solid Phase Test is presented in Table 5. According to the Swedish guideline values for sediments they should then all be classified as sediments with a very large influence from a point source [11]. In the Emaus sediment, the calculated concentration of elemental sulphur at EC$_{50}$ is close to or within the EC$_{50}$ value reported for
elemental sulphur (Table 5). Thus, for this sediment, the concentration of elemental sulphur can fully account for the Microtox® toxicity. In addition, all three tunnel sediments consisted of very fine particles. It is likely that the natural Microtox® SPT toxicity is also high in these sediments as it has been shown in several instances previously [13, 14]. According to the manufacturer of Microtox®, uncontaminated reference sediment with the same particle size distribution should be used to correct for this "natural toxicity" but as far as we know this is almost impossible for this type of sediment.

For the analysed sediments in this study we therefore conclude that the sediments as assessed with the Microtox® SPT might be toxic due to both natural and anthropogenic causes. This clearly needs to be further investigated with other test organisms. The pore water was of low or no toxicity and the presumptive contaminants should therefore be primarily particle bound.

Table 5: Sediment toxicity with the Microtox® Solid Phase Test and the content of total sulphur and elemental sulphur at EC50.

<table>
<thead>
<tr>
<th>Site</th>
<th>30 min-EC50 (% w/v)</th>
<th>total sulphur content at 30 min-EC50 (mg/l)</th>
<th>elemental sulphur content at 30 min-EC50 (µg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bäckby</td>
<td>0.075</td>
<td>0.62</td>
<td>6.2</td>
</tr>
<tr>
<td>Emaus</td>
<td>0.48</td>
<td>3.02</td>
<td>30.2</td>
</tr>
<tr>
<td>Önsta-Gryta</td>
<td>0.1</td>
<td>0.63</td>
<td>6.3</td>
</tr>
</tbody>
</table>

EC50 of elemental sulphur has been established to 24.7–35.8 µg/l by Jacobs et al. [15] and to 15–29 µg/l by Svenson et al. [16].

4 Conclusions

This study shows that sediments in storm water tunnels in Västerås, Sweden:

- Contain high levels of the metals Cu, Ni and Zn. The metal values are approximately twice as high in the tunnel sediment as in sediment from storm water detention ponds.
- The level of PAH and aliphatic hydrocarbons is high according to Swedish guidelines.
- The toxicity of the sediments appears to be mainly associated with the particles and part of the toxicity might be caused by elemental sulphur in combination with loss of bacteria attached to fine particles.

Based upon these results we suggest that further studies are conducted to establish the potential environmental impact expected from discharges of tunnel sediment to the receiving ecosystems. This would at least involve determination of the amount of oils derived from anthropogenic sources. Assessment of the toxicity of the sediment to sediment-dwelling organisms is also desired.
Acknowledgements

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References


