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Treatment of tunnel wash water and implications for its disposal

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ABSTRACT

The use of road tunnels in urban areas creates water pollution problems, since the tunnels must be frequently cleaned for traffic safety reasons. The washing generates extensive volumes of highly polluted water, for example, more than fivefold higher concentrations of suspended solids compared to highway runoff. The pollutants in the wash water have an affinity for particulate material, so sedimentation should be a viable treatment option. In this study, 12 *in situ* sedimentation trials were carried out on tunnel wash water, with and without addition of chemical flocculent. Initial suspended solids concentration ranged from 804 to 9,690 mg/L. With sedimentation times of less than 24 hours and use of a chemical flocculent, it was possible to reach low concentrations of suspended solids ($<$15 mg/L), PAH ($<$0.1 μg/L), As ($<$1.0 μg/L), Cd ($<$0.05 μg/L), Hg ($<$0.02 μg/L), Fe ($<$200 μg/L), Ni ($<$8 μg/L), Pb ($<$0.5 μg/L), Zn ($<$60 μg/L) and Cr ($<$8 μg/L). Acute Microtox® toxicity, mainly attributed to detergents used for the tunnel wash, decreased significantly at low suspended solids concentrations after sedimentation using a flocculent. The tunnel wash water did not inhibit nitrification. The treated water should be suitable for discharge into recipient waters or a wastewater treatment plant.

Key words | metals, Microtox, nitrification, polycyclic aromatic hydrocarbons (PAH), sedimentation, toxicity

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INTRODUCTION

In densely populated cities, new road infrastructure must be constructed in tunnels owing to lack of aboveground space and/or for environmental reasons. Traffic generates pollution that soils the tunnel environment (e.g. Stockholm Vatten 2001a; Meland *et al.* 2010a). During winter, the use of studded tires and salt in cold regions further increases the contaminant load generated by vehicles. To maintain traffic safety, the built-up dirt on various surfaces in the tunnel environment must be removed by washing (e.g. Stotz & Holldorb 2008). The washing procedure and frequency of cleanings depend on, for example, tunnel length, traffic loads, ventilation and layout of the tunnel environment. The wash water volumes can vary from about 30 L to over 150 L per metre tunnel length (Jordforsk 1995; Stockholm Vatten 2001a; Meland *et al.* 2010a), and thus considerable volumes are produced during washing. A number of studies have analysed more or less treated tunnel wash water in recent decades (e.g. Jordforsk 1995; Stockholm Vatten 2001a; Barbosa *et al.* 2007; Trafikverket 2007; Meland *et al.* 2010a). It is now common knowledge that untreated tunnel wash water carries elevated pollutant loads and could cause toxicity to marine life and the environment (e.g. Meland *et al.* 2010a, b), so wash water should as a rule be treated. However, to our knowledge, no *in situ* studies have been done to assess the treatment steps needed in order to achieve an acceptable water quality for discharge to recipient waters or, in some cases, to a wastewater treatment plant.

The pollutants in tunnel wash water have a high affinity to the particulate material present in the water, which is similar to that found in road runoff and other types of stormwater. The suspended solids concentration in tunnel wash water can vary from 25 mg/L to over 30,000 mg/L (Jordforsk 1995; Barbosa *et al.* 2007; Trafikverket 2007). The suspended solids concentration in road runoff in Sweden can vary between 50 and 1,000 mg/L in summer (Hallberg & Renman 2008a) and between 10 and 1,800 mg/L in winter (Hallberg & Renman 2006). In a study by Göbel *et al.* (2007) the range of suspended solid concentrations from highly busy motorways was given as 66 to 937 mg/L. The most common and expedient treatment method for road runoff is sedimentation, which

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should also be applicable for reducing the pollutant concentrations in tunnel wash water. However, the use of detergents could interfere with the sedimentation process by dispersion of particles. Typical detergent concentrations in tunnel wash water can be 0.15–1.0 vol.% (Statens Vegvesen 2006; Trafikverket 2007; Meland *et al*. 2010a). Detergents generally contain alkaline substances, surfactants and solvents and are acutely toxic to marine organisms (Statens Vegvesen 2006). Furthermore, if the detergent gives rise to an elevated pH in the wash water, this could also hamper the conditions for some chemical coagulants. Otherwise, the use of a chemical flocculent should decrease sedimentation times and thereby reduce the size of treatment facility required.

After treatment, tunnel wash water can be discharged to recipient waters or to a wastewater treatment plant. The type of prospective recipient governs the quality of discharge water required, as more stringent discharge demands apply to very sensitive recipients. Further evaluation of the toxicity of the wash water could also be of interest in that case. Microtox® could be used as a screening method to assess the toxicity after treatment. If the wash water is discharged to a wastewater treatment plant, the heavy metal content and toxicity, primarily for the biological nitrification process, must be assessed. Wastewater treatment plants with a strong focus on the disposal and re-use of sewage sludge place strict limits on the heavy metal content in incoming wastewater, for example, Zn (<200 μg/l) and Pb (<50 μg/l) (Stockholm Vatten 2000).

There is therefore a need for *in situ* evaluation of the reduction in pollutant levels that can be achieved using sedimentation and the optimal conditions for this process. Such information is imperative in establishing guidelines on how to handle tunnel wash water with regard to different discharge options as part of a sustainable urban stormwater management (e.g. Barbosa *et al*. 2012; Clark & Pitt 2012). Furthermore, the elevated suspended solids concentrations in tunnel wash water will require a sedimentation step before any subsequent treatment step, for example, a filtration through a sorbent to lower the concentrations of dissolved contaminants, as discussed by, for example, Hallberg & Renman (2008b).

The aims of this study were to (i) assess the effects of sedimentation on the concentrations of pollutants in tunnel wash water, (ii) study the Microtox responses and nitrification inhibition potential of tunnel wash water after sedimentation, and (iii) assess the needs of tunnel wash water treatment in relation to Swedish water quality guidelines.

METHODS

Study area

The road tunnel system studied is located approximately 20 km north of Stockholm and consists of two tunnels (Table 1). The tunnels both have two separate tunnel tubes for the traffic. The speed limit is 90 km/h.

Natural ventilation is used in the Häggvikstunnel while the Törnskogstunnel also has forced ventilation. The wash water generated during tunnel washing is collected by the tunnel's drainage system and transported by gravity to a treatment plant for stormwater and wash water. The combined tunnel wash water and stormwater drainage system is separated from the drainage system for groundwater.

Tunnel washing procedure

Tunnel washes are carried out twice a year on a regular basis in October and in April. During the tunnel washes the tunnel is closed for traffic. The tunnel wash in April was selected for our experiment. Two detergents (A, B) were used during tunnel washing in the study (Table 2). The walls, ceiling and technical installations, such as ventilation fans, traffic signs and emergency exits, were washed with low pressurised water (8 bar) using detergent A at a concentration of 0.23 vol.% (Table 2). The side barriers were washed with high pressurised water (175 bar) using 0.15 vol.% of the alkaline detergent B (pH > 9) (Table 2). The water used for washing was potable water with a pH of 8 and a calcium (Ca) concentration of 35 mg/L. The road surface was washed with high pressurised water (160 bar) by a sweeping machine. The sweeping machine removed the dirt by sweeping and vacuuming the soiled wash water from the road pavement. The vacuumed wash water was emptied from the sweeping unit storage tank into the tunnel's

Table 1 | Description of the Törnskogstunnel and Häggviktunnel. TT = Törnskogstunneln; HT = Häggvikstunneln

	TT	HT
Tunnel length (m)	2,100	289
AADT[a] (vehicles)	20,000–25,000	20,000–25,000
AADT heavy traffic (vehicles)	1,600–2,000	1,600–2,000
Road surface material	Asphalt	Asphalt
Walls and ceiling material	Shotcrete	Concrete
Side barrier (1 m high) material	Concrete	Concrete

[a]AADT = Annual average daily traffic.

Table 2 | Components of detergents A and B according to their Safety Data Sheets

Name	CAS number	Detergent A (% by wt)	Detergent B (% by wt)
Sulfonic acids, C13-17-sec-alkanesulfonic, sodium	85711-69-9	N/A	1–5
Alcohols, C9-11, ethoxylated	68439-46-3	5–10	5–10
Propanol, 1 (or2)-(2-methoxymethylethoxy)	34590-94-8	N/A	1–5
Sodium carbonate	497-19-8	N/A	1–5
Dodecanoic acid, octylester	5303-24-2	90–95	N/A
Water	7732-18-5	N/A	Up to 100

N/A = Not applicable.

combined drainage system for wash water and storm water. No detergents were used for washing the road surfaces.

Experimental setup

The incoming flow to the treatment for wash water and storm water was measured using one Parshall flume for flows between 0 and 5 L/s and a second Parshall flume for flows exceeding 5 L/s. The water level in the Parshall flumes was measured with ultrasonic level sensors of type Lange PU2001/U2000. The pH was measured on-line using a pH probe of type Knick Protos 3400 C/Unical 900/WA160, which had an automated calibration system using pH 7 and pH 10 buffer solutions. In total, two field trials were conducted in 2012, during week 16 and week 17, respectively. Both washings were carried out between late Monday evening and early Tuesday morning during dry weather conditions (from 22:30 p.m. to 04:30 a.m.).

The wash water in the inlet channel was pumped and diverted to six sampling vessels, each with a total volume of 200 L. The sampling pump was placed after a mechanical screen (3 mm). A WTW field instrument type Multiline F/SET-3 probe was used to measure pH, conductivity and temperature during the sedimentation trials.

At the start of the sedimentation trials, the collected wash water was thoroughly homogenised. All samples were taken from the fourth sample tap, counted from the top of the sedimentation vessel. The distance from the top water level to the sampling tap was 400 mm. The total depth of the vessel was 740 mm. Within each field trial, six sedimentation tests were carried out, yielding a total of 12 sedimentation tests. A polyaluminium chloride flocculent, PAX ($pH < 2$), was used to increase sedimentation rate in 9 of the 12 trials. The selection of flocculent and dosing volumes (e.g. 10 g Al/m^3) was based on experience from treatment of road runoff (Hallberg, unpublished data). The decision not to adjust pH in the trials using flocculent was also based on previous experience (Hallberg, unpublished data).

Wash water samples for toxicity analysis were collected in 500-mL PE bottles and delivered to the laboratory within 12 hours after sampling. The samples were frozen until analysis. The Microtox analysis was carried out according to ISO 11348-3. The Microtox toxicity is expressed as the added relative (%) wash water volume to reach EC50, i.e. half the maximum light emission from the Microtox bacteria, after 30 min. Inhibition of nitrification was analysed using VKI screening according to the Swedish EPA report 4424 (SEPA 1995).

All sample bottles for metals and polycyclic aromatic hydrocarbons (PAH) were provided by a laboratory accredited by SWEDAC (ISO/IEC 17025, Reg. number 2030). Analysis of metals was carried out using EPA (modified) methods 200.7 (ICP-AES) and 200.8 (ICP-SFMS). Suspended solid concentrations were determined using CSN EN 872. Chloride concentration was determined using CSN EN ISO 10304-1 (ion chromatography) and sulfate concentration using CSN EN ISO 10304-1&2 (ion chromatography). Determination of PAH was carried out according to CSN EN ISO 11396 using gas chromatography mass spectrometry.

RESULTS AND DISCUSSION

The pH was elevated during tunnel washing due to the use of detergents. Both tunnel washes were carried out using the same washing procedure. In both field trials the initial temperature was 7 °C at the start of sedimentation and 12 °C when the final sample was drawn for analysis.

The suspended solids concentrations showed good correlations to the metal concentrations (Table 3). The relative reduction in suspended solids in the field trials ranged from 87% to over 99%, with initial concentrations ranging from 804 to 9,690 mg/L (Table S4). The use of chemical flocculants led to suspended solids concentrations below 100 mg/L (Table S5). (Tables S4 and S5 are available online at http://www.iwaponline.com/wst/069/113.pdf).

The reduction in total PAH ranged from 67% to over 99% (Tables S4, S5). The PAH showed a correlation to the particulate material (Table 3).

After sedimentation, the Hg concentrations were below the detection limit for the analytical method (<0.02 μg/L).

Table 3 | Correlation factor (r^2) between suspended solids concentrations and listed constituents

	ΣPAH	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	Ca
LCF	0.42	0.96	0.96	0.96	0.96	0.98	0.96	0.74	0.96	0.96	0.97	0.93	0.93
N	23[a]	23[a]	21[a]	16[a]	22[a]	24	22[a]	12[a]	23[a]	23[a]	16[a]	23[a]	24[a]

LCF = Linear correlation factor.
N = Number of samples.
[a] = Samples below detection limit for analytical method are not included.

This was also the case for Cd, except in the trials without a chemical flocculent (Table S5). The metals Al, As, Ca, Cr, Cu, Fe, Mn, Ni, Pb and Zn were readily reduced by sedimentation (Tables S4, S5) and showed a good correlation to the particulate material (Table 3).

The results from the Microtox analysis showed a notable decrease in measured toxicity of the treated water at lower suspended solids concentrations (<11 mg/L) (Table S5, Figure 1). The sampled wash water did not induce nitrification inhibition, but increased the nitrification rate compared to the reference in the analysis, irrespective of suspended solids concentration.

The pollutants in the tunnel wash water had an affinity to the particulate material, which is in agreement with other studies (e.g. Jordforsk 1995; Barbosa *et al*. 2007; Trafikverket 2007). The concentration of suspended solids after sedimentation is dependent on the properties and initial concentration of suspended solids, the sedimentation rate, the sedimentation period, the water quality and when flocculants are used, the dose of flocculants. Elevated concentrations of road salt increase the sedimentation rate (Hallberg 2007). Here, the total suspended solids concentration in treated water was considerably lower in Trial 1 than in Trial 4, even though the initial suspended solids concentrations were comparable (Tables S4 and S5). The difference in final suspended solids concentrations could be attributable to the elevated chloride concentration in Trial 1. However, the higher pH suggests a higher concentration of detergents in Trial 4, which could have hampered sedimentation.

The Swedish Transport Administration has a guideline of 36 hours when using batch-wise sedimentation for

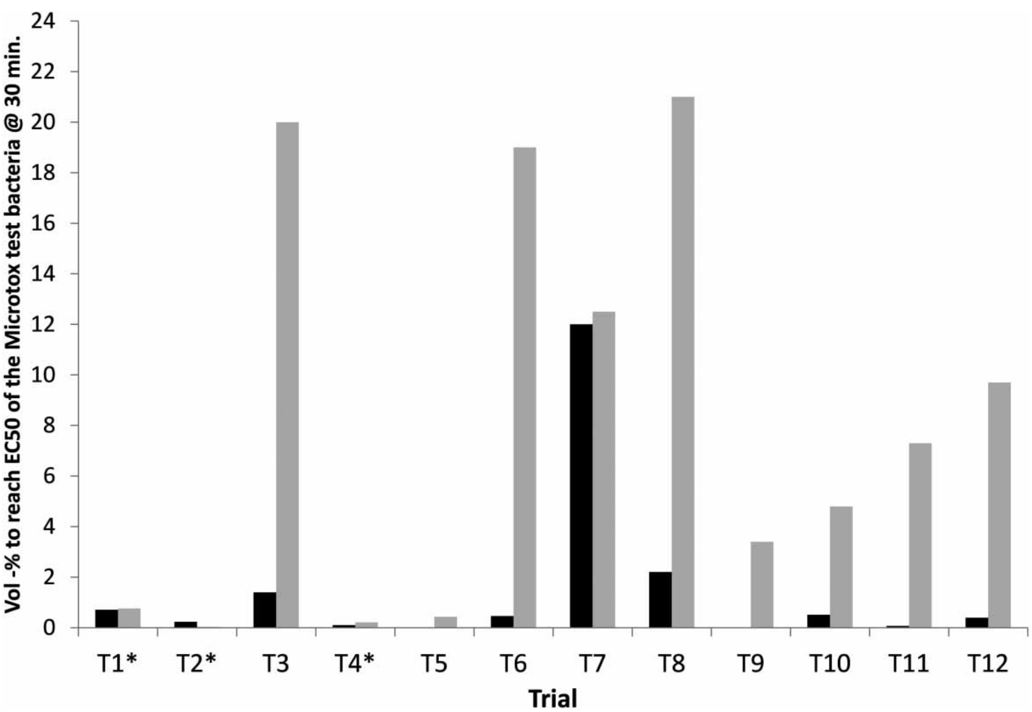

Figure 1 | Difference before and after sedimentation in the volume percentage to reach EC50 concentration after 30 min exposure of the Microtox bacteria in the 12 trials (T1–T12). A higher relative volume indicates lower toxicity of the wash water. Black bars = raw wash water; Grey bars = treated water; * = treatment without flocculent.

treatment of road runoff. In the present study, it was not possible to achieve low suspended solids concentrations (below 50 mg/L) in a sedimentation time less than 36 hours without the use of a chemical flocculent (Table S5). By using a chemical flocculent and with sedimentation times less than 24 hours, it was possible to further reduce the concentrations of suspended solids, PAH and metals in the tunnel wash water. However, Trial 5 showed elevated suspended solids concentration after sedimentation (49.9 mg/L). Trial 5 had the highest initial pH (9.25) and accordingly the highest detergent concentration. The pH after addition of flocculent was 8.0, which could have been unfavourable for the chemical flocculent used, this could also suggest that the detergents could have interfered with the flocculation in Trial 5. In the other trials using a chemical flocculent (Trials 3, 6–12) the pH after addition of the flocculent was 6.8 to 7.7, yielding suspended solid concentrations below 11 mg/L within 24 hours of sedimentation. This would suggest that a pH less than 8 is necessary to achieve good flocculation properties in the water with the used flocculent, considering the fact that a pH optimum for aluminium based coagulants is between pH 5 and 7 (Metcalf & Eddy 2003).

In a study by Stockholm Vatten (2001b) in which stormwater was classified with regard to pollutant concentrations, it was concluded that stormwater with low pollutant concentrations (SV2 Low Level) could be discharged without treatment (Table 4).

The Swedish EPA classifies lakes and streams from Class 1 to Class 5, where Class 1 entails very low concentrations of metals, and Class 5 very high concentrations (SEPA 1999). For Class 2 there is a low risk of biological effects and for Class 3 biological effects may occur (SEPA Classes 2 and 3 in Table 4). The Stockholm Vatten guideline (2000) for discharge to wastewater treatment plants is shown in Table 4 (SV1).

With the use of chemical flocculent, concentrations of suspended solids and PAH corresponding to low stormwater concentrations (SV2 Low Level in Table 4) appear feasible with sedimentation of tunnel wash water (Table S5). For As, Cd, Ni, and Pb, it was possible to achieve concentrations in accordance with SEPA Class 2 and for Zn and Cr in accordance with SEPA Class 3 when a flocculent was used (Table S5). With regard to Al, the concentrations in the treatment without a chemical flocculent were elevated compared with the concentrations found with chemical flocculent.

The low suspended solids concentrations are similar to those in filters in the study by Hallberg & Renman (2008b). The concentrations of total PAH and metals after sedimentation using a chemical flocculent are comparable to those found after filtration by Paruch & Roseth (2008a, b). This suggests that the use of flocculent could be an alternative to filtration, or an efficient pre-treatment before filtration through a fixed medium.

Table 4 | Guidelines for comparative assessment of treatment results

Parameter	SV2 Low Level	SEPA Class 2	SEPA Class 3	SV1
Inhibition of nitrification* (%)				<50
Total suspended solids (mg/L)	<50			
ΣPAH (μg/L)	<1			
As (μg/L)		0.4–5	5–15	
Cd (μg/L)	<0.3	0.01–0.1	0.1–0.3	
Cr (μg/L)	<15	0.3–5	5–15	<50
Cu (μg/L)	<9	0.5–3	3–9	<200
Hg (μg/L)	<0.04			
Ni (μg/L)	<45	0.7–17	15–45	<50
Pb (μg/L)	<3	0.2–1	1–3	<50
Zn (μg/L)	<60	5–20	20–60	<200

SV1 = Stockholm Vatten (2000).
SV2 = Stockholm Vatten (2001b).
*Inhibition at a mixture of 40 vol.% of wash water.
SEPA = SEPA (1999).

All samples, raw and treated, displayed acute Microtox toxicity. The Microtox bacteria are cloned from the bacterial species *Vibrio fischeri* and have a modified cell membrane with increased permeability to larger molecules (>1,000 g/mol) and/or molecules with elevated net charge. Molecules in detergents are both large and display high charges, thus yielding a strong Microtox response. Here, the Microtox toxicity decreased significantly at suspended solids concentrations below 11 mg/L after sedimentation (Table S5, Figure 1). However, Trial 7 water had an elevated suspended solids concentration (9,690 mg/L) but showed toxicity comparable to water with a suspended solids concentration below 11 mg/L. The wash water for Trial 7 was pumped up at the very beginning of the second washing event. The drinking water used as wash water has a pH of 8.0, which is very similar to the pH in the untreated wash water in Trial 7. Accordingly, it is likely that the detergent concentration in this sample was low, yielding a lower Microtox response. This confirms findings by Jordforsk (1995), which suggested a low toxicity in Microtox in tunnel wash water where no detergents were used. Karlsson *et al.* (2010) studied the toxicity in road runoff collected from roads with AADT ranging from 4,700 to 113,000 vehicles. The suspended solids concentrations in the studied road runoff ranged from 1 to 91 mg/L. Karlsson *et al.* (2010) found that the studied road runoff was non-toxic to the bacteria *Vibrio fischeri*. The findings of Jordforsk (1995) and Karlsson *et al.* (2010) would suggest that found toxicity in our study is primarily caused by the detergents. The results from the present study would suggest that two parallel processes affect the Microtox response, i.e. co-precipitation of the detergent molecules to the particulate material and to the formed flocs, resulting in decreased Microtox responses at lower suspended solids concentrations. The Ca concentrations in the treated water in this study were high compared with those in Meland *et al.* (2010a), but the Microtox organism is a salt water organism and thus elevated salt concentration would not have an influence on the Microtox responses observed in this study. In contrast to the Microtox test, the wash water did not have a negative impact on the nitrification process. On the contrary, the results showed that addition of the wash water increased the nitrification rate, compared to the reference sample in the analysis. Detergent B contains sodium carbonate (Table 2). Organic carbon is used in the nitrification process and the presence of carbonate in the wash water may have contributed to the relative increase in nitrification rate in the wash water.

Further toxicological studies with other organisms would be of interest at low suspended solids concentrations, as would sedimentation studies with other flocculants to assess elevated flocculation pH and detergent concentrations. Evaluations of the sedimentation of tunnel wash water without detergents would also be of interest.

CONCLUSIONS

Low concentrations of suspended solids (<15 mg/L), total PAH (<0.1 μg/L), As (<1.0 μg/L), Cd (<0.05 μg/L), Hg (<0.02 μg/L), Fe (<200 μg/L), Ni (<8 μg/L), Pb (<0.5 μg/L), Zn (<60 μg/L) and Cr (<8 μg/L) were achieved with sedimentation times of less than 24 hours and use of a chemical flocculent. The Microtox toxicity was acute in all samples. However, the Microtox toxicity decreased significantly at low suspended solids concentrations in the water treated using a chemical flocculent. The tunnel wash water did not inhibit nitrification. The results show that with the use of a chemical flocculent, it should be possible to discharge treated tunnel wash water to recipient waters or to a wastewater treatment plant. However, for very sensitive recipients, further toxicological studies should be conducted at low suspended solids concentrations.

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