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Road sediment: characterization and implications for the performance of vegetated strips for treating road run-off

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Abstract

Increasing pressure to mitigate pollution from urban stormwater and road run-off is generating interest in vegetative treatment systems. The treatment performance of these systems depends on the characteristics of the pollutants entering them—for example, whether metals are dissolved or particle bound, and the particle size. This study sought to provide information on the characteristics of sediment derived specifically from road-use activities. A length of roadside gutter was vacuumed repeatedly at 2-day intervals. The samples obtained were found to contain predominantly fine particles (52% <250 μm). Particles <250 μm had the highest metal contents: 181–212 mg Cu/kg, 1073–2080 mg Zn/kg and 251–334 mg Pb/kg. A high percentage of the total metal load was associated with particles smaller than 125 μm (64% of Zn, 57% of Cu and 46% of Pb). These <125-μm particles are generally predicted to be poorly trapped by vegetation. In this study, these smaller particles were also found to have a lower density (<2200 kg/m^3) than normally modelled for sediment (>2600 kg/m^3), and this may further reduce predicted trapping efficiencies. The impact of sediment entering vegetative treatment systems via aerial deposition is also discussed in terms of evaluating such systems for treatment performance.

Keywords: Road run-off; Stormwater; Swale; Vegetated filter strip; Heavy metals; Urban pollution

1. Introduction

Since 1991, New Zealand has managed the use, development and protection of its natural and physical resources through effects-based legislation—the Resource Management Act 1991. This Act requires that adverse environmental effects of an activity are avoided, remedied or mitigated. Under this legislation, there has been a tightening of controls on stormwater discharges, and a growing interest in using semi-natural treatment systems to mediate both the quality and quantity of discharges. Grass swales, in particular, are being increasingly considered for use alongside motorways to provide primary treatment for road run-off. Information is needed to quantify how effective these systems are, and how their effectiveness can be improved.

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The effectiveness of a grass swale depends on many factors, especially those that influence pollutant trapping: partitioning of pollutants between solution and sediment, and between coarse and fine sediment fractions (Meyer et al., 1995; Barrett et al., 1998; Deletic, 2001). In order to optimize the performance of swale systems, the characteristics of the pollutants need to be understood. Many workers have characterized road-related pollution. Most work presents data from street sediment studies rather than open highways (Sartor and Boyd, 1972; Ellis and Revitt, 1982; Auckland Regional Council, 1992; Stone and Marsalek, 1996).

Although street sediment has traditionally been studied because of its relevance to urban stormwater pollution, it may not accurately represent the sediment derived from open highways and motorways for two main reasons. Firstly, street sediments typically include pollutant material derived from a range of sources, not just vehicle activity, and secondly, gutter sediments typically have accumulated over extended periods and they are generally enriched with coarser particles, the finer material having been lost through wind dispersion and/or washed away by rain (Sartor and Boyd, 1972). This means that the fine sediment fraction is under-represented in gutter samples.

Fine sediment is important when considering pollution mitigation because pollutant metal concentrations have been found to increase as the sediment particle size decreases (Ellis and Revitt, 1982; Sansalone and Buchberger, 1997). Sansalone and Buchberger (1997) studied sediment washed by rain from the road surface of an urban highway (no gutter), and Ellis and Revitt (1982) sampled road dust from the gutter and road-shoulder of motorways in London. Both studies found that the highest concentrations of the metal pollutants, zinc (Zn), copper (Cu) and lead (Pb) were associated with particle fractions <250 μm.

Vehicular activity has the potential to release fine material from brake and tire wear, with a high concomitant pollutant load. A study of tire and brake pads from New Zealand vehicles found that tires have Zn concentrations in the range 1190–18300 mg/kg, while dust from brake pads contains 346–9630 mg Zn/kg and 70–1980 mg Cu/kg (P. Kennedy, 2002, personal communication). In comparison, the mean concentration of these metals in uncontaminated surface soil in New Zealand is 17 mg Cu/kg and 65 mg Zn/kg (Roberts et al., 1996).

In order to evaluate and optimize the ability of grassed swales to trap and remove pollution, there is a need to clarify the characteristics of vehicle-derived sediments that will enter swales in road and motorway run-off. This study aimed to characterize the particle-size distribution and associated metal load (Zn, Cu, Pb) in road sediment where the main anthropogenic influence was vehicular activity. These results are discussed in terms of their relevance to the functioning of grassed swales and vegetated filter strips.

2. Material and methods

2.1. Site description

High levels of vehicle-derived pollution are not only found on motorways, but are also found at intersections where vehicle braking and accelerating is increased (Sartor and Boyd, 1972; Muschack, 1990; Drapper et al., 2000). This fact made it possible to select a site convenient for frequent sampling and safe for workers and road-users. The site selected for collecting vehicle-derived sediment was an intersection on an arterial road with minimum input from pollutant sources other than vehicle activity—the adjacent land use is esplanade reserve. The intersection of Cobham Drive and Normandy Avenue (Hamilton, New Zealand) is controlled by traffic lights. About 25 000 vehicles pass through the intersection each day. The road surface at the sampling site is asphalt with a coarse metal chip. The gutter and kerb are concrete. A vegetated median strip separates the north- and south-bound traffic. The site has low amounts of organic detritus in the gutter and virtually no trash, and is subjected to monthly street sweeping.

2.2. Road sediment sampling

Data from Sartor and Boyd (1972) indicates that road sediment accumulates quickly—within the first day for residential areas and 3–5 days for commercial areas—and most of this material (around 88%) is found within 30 cm of the kerb. Grottker (1987) reports similar findings, although particles <25 μm were more dispersed across the road surface with 77%

of these within 50 cm of the kerb. Based on these findings, road sediment in this study was collected every second day by vacuuming a 30-cm-wide roadside gutter during 2 weeks of dry weather.

All accumulated material present in the gutter (60.7 m in length) at the start of sampling was also collected and characterized (referred to as the *one-off sample*). This sample represented a traditional street sediment sample. Subsequent samples of road sediment were collected every 2 days to give six *2-day samples*.

Vacuuming had the potential to introduce metallic contamination of the sample from the vacuum cleaner attachments. To assess contamination, a 200-g sample of acid-washed sand was vacuumed four times. The concentrations of metals in this blank sample were low (<1 mg Cu/kg; 3 mg Pb/kg; 2 mg Zn/kg) compared with the values obtained for the road sediment samples, and therefore do not affect the interpretation of the results.

2.3. Particle-size distribution

The one-off sample and each 2-day sample were sieved through stainless-steel test sieves: 2000, 1000, 500, 250, 125, 63 and 32 μm. Where practical, coarse leaf material was excluded from samples (after the method of Stone and Marsalek, 1996). Material greater than 2000 μm (2 mm) was discarded. The different size fractions were weighed on the day of collection.

Particle density was determined gravimetrically according to the standard method given in New Zealand Soil Bureau (1972).

2.4. Total metal concentrations

A composite sample for each size fraction was made by combining the material from each 2-day sample. Total Cu, Zn and Pb concentrations were determined for each fraction by X-ray fluorescence spectrometry.

3. Results and discussion

3.1. Particle-size distribution

The combined mass of sediment (<2 mm) collected in the six 2-day samples was 404.7 g. This represents an average accumulation rate of 0.55 g/kerb m/day. Accumulation rates reported in literature typically range from 3 to >100 g/kerb m/day, and depend on factors such as adjacent land use, traffic activity and type of street surface (Sartor and Boyd, 1972; Ellis and Revitt, 1982). The low accumulation rate reported here may be explained by the exclusion of the >2 mm fraction, the good condition of the road, the relatively low vehicle numbers by international standards, and few sources for additional sediment.

The particle-size distribution is shown in Fig. 1. Error bars are given for the six 2-day samples and represent the standard error of the mean for each size fraction (n=6). More than half the material (52%) was less than 250 μm, of this 36% was less than 125 μm, and 6% was less than 32 μm. The one-off sample contained less fine particles than the 2-day samples (Fig. 1), with 28% less than 250 μm, 16% less than 125 μm, and 1.5% less than 32 μm. Compared with the 2-day samples, the one-off sample overestimated the proportion of particles in the size range 500–2000 μm (55% versus 30%), and underestimated the proportion of particles below 250 μm (25% versus 52%). This can be attributed to the influence of air turbulence and rain on the particle-size distribution of material that accumulates in gutters. Over extended periods, the accumulating material typically becomes

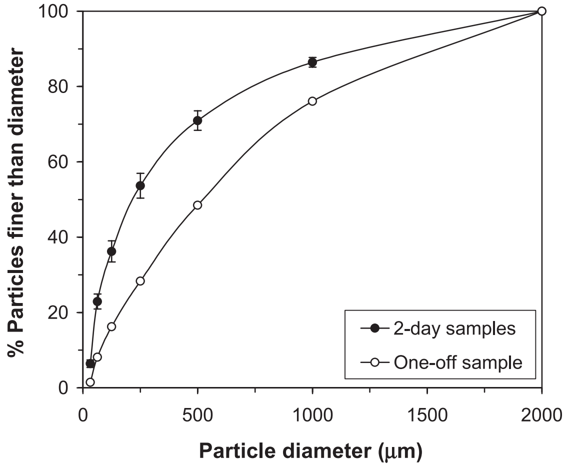

Fig. 1. The particle-size distribution of road sediment that has accumulated in a gutter (a) over 2 days (2-day sample), and (b) over a prolonged period (one-off sample). Data are presented for the particle fraction less than 2 mm. Error bars represent standard error of mean for six 2-day samples.

Table 1
Total metal concentrations and particle densities determined for each particle-size fraction of road sediment collected over six 2-day intervals, and the average metal concentration of the road sediment sample as a whole

Particle-size fraction (μm)	Total metal concentration (mg/kg)			Particle density (kg m^{-3})
	Cu	Zn	Pb	
0–32	181	2080	316	2140
32–63	197	1695	322	2150
63–125	212	1628	334	2190
125–250	184	1073	251	2330
250–500	85	507	193	2530
500–1000	26	268	323	2540
1000–2000	21	226	36	2390
Whole sample	124	962	249	

enriched with coarser particles through the re-suspension and loss of finer sediment (Sartor and Boyd, 1972; Auckland Regional Council, 1992). Previously reported data on particle-size distributions in road sediment generally shows closer agreement with the distribution found in the one-off sample of this study (Fergusson and Ryan, 1984; Auckland Regional Council, 1992; Stone and Marsalek, 1996). This is consistent with these previous studies reporting results for one-off gutter samples. Consequently, the proportion of fine material found in the 2-day samples of this study is higher than generally reported for road dust.

3.2. Total metal concentrations

The total metal concentrations of Zn, Cu and Pb for each particle-size fraction in the 2-day (composite) samples are shown in Table 1. The metal load of the whole sample and the contribution to this load of each particle-size fraction has been calculated using the metal concentration data (Table 1), and the particle-size distribution (Fig. 1). The metal load of the whole sample is given in Table 1. The metal load contributed by each particle-size fraction to this load is shown in Fig. 2.

Zinc and Cu concentrations were markedly higher for particle sizes below 250 μm (Table 1). Zinc concentrations continue increasing as particle size decreases, exceeding 2000 mg/kg in the finest fraction (<32 μm). Copper concentrations in particle-size fractions <250 μm are twice those in the coarser material, but within the finer size fractions Cu concentrations stay constant—in contrast to the observations for Zn. Lead concentrations show less relationship to particle size, though they are generally higher for particles <125 μm. This data indicates that,

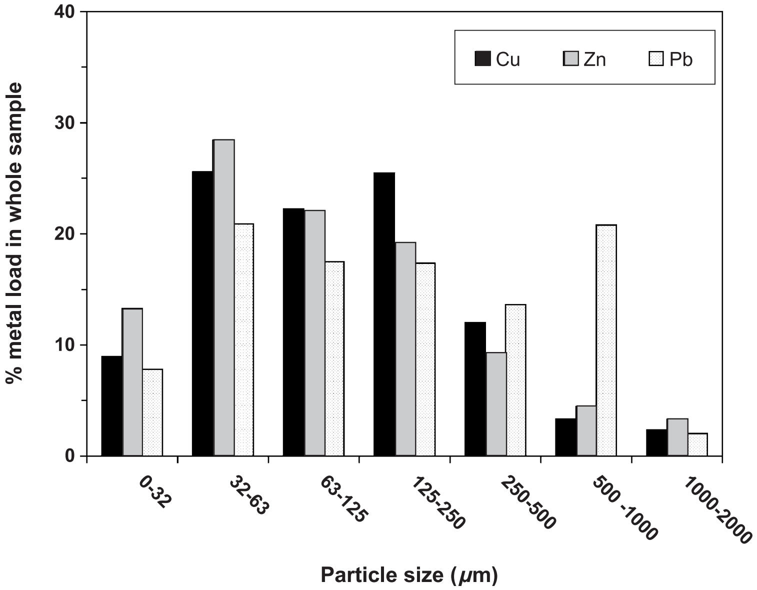

Fig. 2. The contribution of each particle-size fraction to the total Cu, Zn and Pb load in road sediment accumulated over 2 days (averaged for the six 2-day samples).

for vehicular pollution, finer particles carry the higher pollutant load (Fig. 2)—though if large fragments of metal, e.g., lead balancing weights off wheels, are found in larger size fractions this relationship is disrupted (Auckland Regional Council, 1992).

The very high concentrations of Zn present (Table 1) in fine particles could be explained by the high Zn concentrations in tires (1190–18 300 mg/kg) and dust from brake pads (346–9630 mg/kg) (P. Kennedy, 2002, personal communication). Copper concentrations are generally low in tires (<1–3 mg/kg) but higher in brake pad dust (70–1980 mg/kg, average 219.5 mg/kg) (P. Kennedy, 2002, personal communication). These vehicle sources tend to release fine particles and this is consistent with the higher metal concentrations in the fine fractions of road sediment (Table 1).

A small percentage of the total metal concentration was found to be soluble in simulated rainwater (data not shown). More Cu (2%) was soluble in the simulated rainwater than Zn (0.4%), while the proportion of soluble Pb was very low (<0.1%). These values indicate most of the metal will remain associated with the particles during run-off, and particle trapping will significantly reduce pollution.

4. Discussion

4.1. Gutter samples and their relevance to vegetative treatment systems

Where kerb and gutter systems lead into storm drain networks, the accumulated material found in gutters (the one-off sample in this study) represents the reservoir of pollution that can contribute to pollutant loads in urban stormwater. However, such material has less relevance if the kerb and gutter is replaced by a vegetated treatment system (e.g., a grass swale) because of the marked difference between accumulated gutter sediment and recently deposited road sediment.

The different particle-size distributions found for the two types of samples (2-day and one-off) can be attributed to the loss of fine material from the one-off sample by wind dispersion and run-off (Sartor and Boyd, 1972; Revitt and Ellis, 1980). If the kerb and gutter were replaced by a roadside swale, this 'lost' material would probably have been washed or blown into the swale (Burch et al., 1985; Lind and Karro, 1995). The reservoir of road sediment available to a vegetated treatment system is more likely to be represented by the 2-day gutter samples with their high proportion of fine particles rather than the one-off sample with a greater proportion of coarse material. The following discussion on pollutant removal by vegetative treatment systems is therefore based on the particle-size distribution and metal concentrations of the 2-day samples.

4.2. Implications for treatment of road run-off by vegetative systems

The proportion of the metal load contributed by each particle-size fraction is important for pollution mitigation by vegetated buffer strips and grassed swales because the ability of these systems to remove pollutant load from run-off varies with particle size (Meyer et al., 1995; Deletic, 2001). Particles greater than 125 μm appear to be easily trapped by vegetated treatment systems, but trapping efficiency decreases for particles less than 60 μm and becomes poor between 6 and 32 μm (Meyer et al., 1995; Deletic, 1999, 2001).

Results from the 2-day samples show that particles greater than 125 μm carry 43% of Cu, 54% of Pb and 36% of Zn (Fig. 2). These particles are likely to be trapped by vegetated treatment systems. Particles less than 125 μm carry: 57% of Cu, 64% of Zn, and 46% of Pb, and may be only partially trapped-depending on other factors such as infiltration rate and run-off volume. Particles less than 32 μm carry 9% of Cu, 13 % of Zn and 8 % of Pb and may not be trapped (Meyer et al., 1995; Deletic, 2001).

Particle density also influences trapping efficiency in swales. Deletic (2001) used a sediment density of 2700 kg/m^3, Meyer et al. (1995) assumed a value of 2600 kg/m^3, while Stone and Marsalek (1996) report an average density for street sediment as 2780 kg/m^3. However, the particle densities of the road sediment material collected in the current study are lower than these values (Table 1). In particular, particles <125 μm were found to have particle densities <2200 kg/m^3. These lower particle densities could reflect the influence of oil and grease coatings on the particles and the presence of ground rubber from tires. A lower particle density will reduce the particle settling velocity and could mean that trapping efficiency by grass filter strips and hedges is less than predicted by the models of Meyer et al. (1995) and Deletic (2001). Using Stokes' Law, the settling velocity of a 63-μm particle with density 2190 kg/m^3 is only 70% that of a particle with density 2700 kg/m^3.

4.3. Wind-deposited road sediment and implications for treatment performance

Although vehicle-derived sediment contains high proportions of fine particles with a high carrying-capacity for heavy metals (as demonstrated in this study, Fig. 2), these fine particles may not necessarily enter the swale in road run-off. Burch et al. (1985) suggest that fine road sediment is likely to be blown off the road onto the roadside by air turbulence caused by passing vehicles. Lind and Karro (1995) suggest that this wind transport may be a more important mechanism for pollutants entering vegetated treatment systems than run-off. But, the traditional method for determining pollutant inputs to a swale (on which we then base our assessment of treatment performance) is collection and analysis of road run-off. This points to a discrepancy between actual pollutant inputs and measured pollutant inputs, and has implications for our calculations of treatment performance.

Material re-distributed through air turbulence will be dominated by finer particles. These particles are likely to be of the size where metal concentrations are high (Table 1) but removal from run-off by trapping is low. If these particles are blown into the treatment system and become re-suspended in through-flow during a rain event, they may contribute to the pollutant load exiting the system without ever having been accounted for as an input. The pollutant removal by the vegetative treatment system will be under-estimated. The potential for wind-deposited sediment to contribute to pollutant loads in vegetated treatment systems should perhaps be considered when monitoring these systems for treatment performance.

5. Conclusions

There is growing evidence for the potential of run-off from roads and motorways to pollute the receiving environment. This study found that freshly sampled, vehicle-derived sediment contained a high proportion of material finer than 250 μm (52%), and that these particles carried the highest concentrations of metals: 181–212 mg Cu/kg, 1073–2080 mg Zn/kg and 251–334 mg Pb/kg. The increase in metal concentration associated with particles smaller that 250 μm was marked for both Zn and Cu. Of the total metal load, 64% Zn, 57% Cu and 46% Pb were associated with particles <125 μm, and these particles are of a size that may evade trapping in vegetated treatment systems. Furthermore, the density of these particles (<2200 kg/m^3) was lower than normally assumed or reported for sediment (>2600 kg/m^3) and therefore trapping efficiencies predicted in literature may over-estimate removal rates.

Because fine material is blown off roads and deposited on roadside verges, the fine material may represent an important, but unquantified pollutant input to vegetative treatment systems installed alongside roads. This input should be considered when evaluating the treatment performance of swales and vegetated filter strips.

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