J Soils Sediments (2011) 11:1040–1051
DOI 10.1007/s11368-011-0383-y

SEDIMENTS, SEC 2 * PHYSICAL AND BIOGEOCHEMICAL PROCESSES * RESEARCH ARTICLE

Total and size-fractionated mass of road-deposited sediment in the city of Prince George, British Columbia, Canada: implications for air and water quality in an urban environment

Philip N. Owens · Katrina A. Caley · Sarah Campbell · Alexander J. Koiter · Ian G. Droppo · Kevin G. Taylor

Received: 1 February 2011 / Accepted: 10 May 2011 / Published online: 28 May 2011

Abstract

Purpose The urban sedimentary system is attracting increasing interest because of its role in influencing air and water quality. A large amount of road-deposited sediment (RDS) lies on the road network of Prince George, a city of about 80,000 people, in British Columbia, Canada. The objectives of this study were: (1) to determine the total mass of RDS within the city, and how this varied over time and space; and (2) to determine the temporal and spatial variations in the particle-size fractions of the RDS.

Materials and methods Samples of RDS were collected using a grid network during two different time periods in the snow-free season in 2009. Composite samples for each grid ($n=46$) were fractionated into five grain-size classes (>500, 250–500, 125–250, 63–125, <63 μm) using stainless steel sieves. Fractionated sediment samples were weighed to obtain a mass for each size class for each grid cell.

Results and discussion The total amount of RDS (all particle-size fractions) in the city of Prince George was estimated to be 746×10^3 and 204×10^3 kg for the summer and fall 2009 sampling periods, respectively. Based on a total road length of 1,030 km within the sampled area of the city, this equates to an average of 724 and 198 kg per km of road, for the summer and fall sampling periods, respectively. The RDS was dominated by the >500-μm fraction, and there was a trend of decreasing amounts (by mass) for the finer particle-size fractions. In terms of the most important particle-size fraction from an air and water quality perspective, the <63-μm particle-size fraction accounted for, on average, 6.5% and 4.8% of the total RDS mass for the summer and fall 2009 sampling periods, respectively; it is estimated that an additional approximately 2% was lost to the air during sample collection, and thus values may be closer to 9% and 7%, respectively. This equates to averages of between 47–61 and 10–13 kg per km of road for the summer and fall periods, respectively. Total amounts of RDS were greatest in the city centre, compared to the outlying areas, reflecting the greater density of roads in the former, although there were some hotspots which may reflect land use activities such as light-industry and pulp and paper mills.

Conclusions These findings have implications for air and water quality in the city and surrounding area, including the role of RDS in contributing to airborne fine particulates (i.e. PM_{10} and $PM_{2.5}$) and the fine-grained sediment (<63 μm) transported within storm sewers to receiving waterways, such as the Fraser and Nechako Rivers.

Keywords Air and water quality · Grain-size distribution · PM_{10} and $PM_{2.5}$ · Road-deposited sediment · Road dust · Urban sediment

---

Responsible editor: Kimberley N. Irvine

P. N. Owens (✉) · K. A. Caley · S. Campbell · A. J. Koiter
Environmental Science Program and Quesnel River Research Centre, University of Northern British Columbia,
3333 University Way,
Prince George, BC V2N 4Z9, Canada
e-mail: owensp@unbc.ca

I. G. Droppo
Environment Canada,
Burlington, ON L7R 4A6, Canada

K. G. Taylor
School of Science and the Environment,
Manchester Metropolitan University,
Manchester M1 5GD, UK

1 Introduction

Most of the world's population now live in urban centres. The percentage of urban population was approximately 30% of the total world population in 1950, and will increase from approximately 50% in the year 2007 to approximately 70% in 2050 (UNESA 2008; Charlesworth et al. 2010). As a consequence, it is likely that urban centres will put increasing pressure on water resources, which will have implications for human water security and aquatic biodiversity (Vörösmarty et al. 2010). The urban sedimentary system is attracting increasing interest because of its role in influencing air and water quality (for reviews see: Taylor 2007; Taylor and Owens 2009; Poleto et al. 2010). The role of fine-grained sediments (<63 µm) derived from the urban environment in contributing contaminants to fresh and coastal waters is now well established (Foster and Charlesworth 1996; Owens et al. 2001; Meharg et al. 2003; Owens and Walling 2002, 2003; Carter et al. 2006; Schafer et al. 2009; Xu et al. 2009). Much of this sediment and associated contaminants is derived from road ‘dust’ (here termed road-deposited sediment, RDS) that lies on the urban street network (Carter et al. 2003; Irvine et al. 2009; Poleto et al. 2009a; Zhao et al. 2010), and is flushed to the river channel network via storm or combined sewers during hydrologic events (Lee et al. 2002; Horowitz 2009). Fine sediment and RDS within the urban environment also contribute to poor air quality through the suspension of fine particulates and associated contaminants into the air column (Behera et al. 2011). Fine particulate materials (e.g. PM_{10} and $PM_{2.5}$: fine particulate materials less than 10 and 2.5 µm, respectively) within the air column are of particular concern in many cities, mainly because of their effects on human health (i.e. respiratory issues: Ostro et al. 2006; Jiménez et al. 2010), as well as social well-being (i.e. odour, visibility: Capelli et al. 2010). While several studies have documented the temporal and spatial patterns of RDS within urban centres (e.g. Vermette et al. 1987; Carraz et al. 2006), its composition (e.g. Bucko et al. 2010; Zhao et al. 2010) and the temporal and spatial patterns of associated contaminants such as metals (e.g. Vermette et al. 1991; Charlesworth and Lees 1999; Sutherland 2003; Droppo et al. 2006; Irvine et al. 2009), there are few studies that have determined the total mass of RDS, and how this varies temporally and spatially, within an urban centre. There is also a need for information on the particle-size distribution of the RDS as this has implications for the amount of sediment that may be mobilised and transported to river channels or suspended into the air column. Such information has important implications for the management of RDS in urban areas so as to minimise impacts on air and water quality. This paper describes part of an on-going investigation into the mass and composition of RDS within the city of Prince George, Canada, and its potential impacts on air and water quality within the city. The objectives were: (1) to determine the total mass of RDS within the city, and how this varied over time and space; and (2) to determine the temporal and spatial variations in the particle-size fractions of the RDS.

2 Materials and methods

2.1 Study area

Prince George is a city with a population of about 80,000 people located in the centre of British Columbia, Canada (53°54′ N, 123°49′ W). The city lies within the Fraser River drainage basin (approximately 230,000 km^2): an important river in terms of water resources for the approximately three million people in the basin (including the city of Vancouver) and fish habitat (>30 million sockeye salmon returned to the basin in 2010; Pacific Salmon Commission 2010). The city of Prince George supports resource extraction, particularly forestry and mining, for the region, and there are three pulp and paper mills in the city, in addition to an oil refinery and different types of light- and medium-industry. The city has a dense network of roads and is at the junction of two major highways, ensuring high traffic volume. Most of the city is between 550 and 700 m above mean sea level (a.m.s.l.), with the hills and low mountains surrounding the city reaching approximately 1,100 m a.m.s.l. The topography of the city and surrounding region, combined with low-winds and certain meteorological factors, result in the trapping of airborne particles and pollutants within depressional areas of the city (Breed et al. 2002). Consequently, there is much concern associated with urban air quality, particularly the concentrations of $PM_{2.5}$ and PM_{10}, which has been identified as a priority environmental health issue (Breed et al. 2002). Prince George has among the highest levels of $PM_{2.5}$ in British Columbia, and frequently exceeds the provincial $PM_{2.5}$ 24-h standard of 25 µg m^{-3} (as a 98th percentile) and the annual standard of 8 µg m^{-3} (Stantec 2010). Preliminary reports based on source emissions monitoring and modelling suggest that RDS is a major source of airborne particulates (Stantec 2010). There are also concerns associated with the delivery of RDS and other sources of fine-grained sediment (<63 µm) and associated contaminants to local streams, including the Nechako (basin area is approximately 43,000 km^2) and Fraser Rivers, which pass through the city; the city centre being located near the confluence of these two large rivers. Such fine sediment is likely to cause problems for salmonids, via the clogging of river spawning gravels, and has many other detrimental affects related to contaminant delivery (cf. Owens et al. 2005; Förstner and Owens 2007).

2.2 Sample collection and sediment fractionation

Road-deposited sediment collection was conducted throughout Prince George over two sampling campaigns (each focused on a few weeks) during the snow-free season: summer (June) 2009 (n=165) and fall (October) 2009 (n=171). Sampling was based on the city road network (obtained from the City of Prince George). A sampling grid was superimposed onto the road network, the purpose of which was to maintain a consistent sampling strategy between campaigns. The grid consisted of three sampling resolutions: 1×1, 2×2 and 4×4 km. The downtown region and areas which are more densely populated were assigned a higher resolution grid, while areas outside of the downtown were assigned the lower resolution grids (Fig. 1). The purpose of this approach was to ensure adequate coverage of the city and to not collect an unnecessarily large number of samples. In total, 46 grids were sampled during each of the two sampling periods. Within most of these grids, four random RDS samples were collected: in a few cases only two or three random samples were collected due to the low road density.

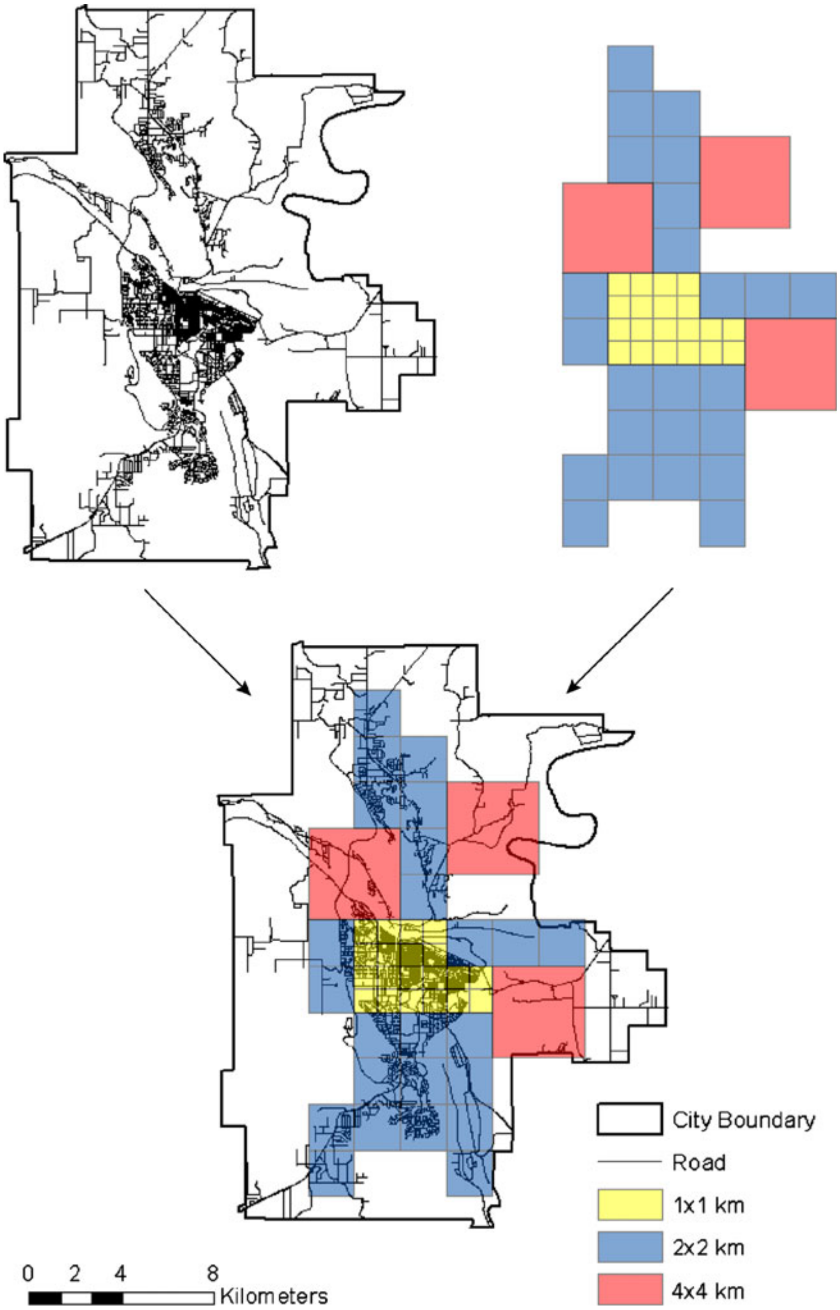


Fig. 1 Map of city of Prince George, British Columbia, with sampling grid, and overlay of road map and sampling grid

The sampling was focused along the curbs of the road as this is where the majority of the RDS was located (most roads being slightly convex) and because this approach helps to ensure some sampling consistency between sites and between the sampling campaigns. Samples of RDS were collected along a length of curb of 2 m (width=0.3 m) so as to standardise sample mass by unit area. In a few instances, there was so much RDS present that a length of curb of 1 m (width=0.3 m) was sampled and yielded >1 kg of material. UTM coordinates along with a general site description were also recorded. A summary of the characteristics for the RDS sampling campaigns is shown in Table 1. The total area and curb length within the sampling area were 163 km^2 and 2,059 km, respectively.

All samples were collected using a stainless steel trowel and a plastic-bristled brush, similar to many other studies that have used a scooping/brushing approach (e.g. Vermette et al. 1991; Kim et al. 1998; Wang et al. 1998; Robertson et al. 2003; Sutherland 2003; Droppo et al. 2006; Irvine et al. 2009; Krčmová et al. 2009). This sampling approach was adopted to enable us to compare results (especially metal contents of the RDS, as part of on-going work) with a similar study in Manchester, UK (Robertson et al. 2003; Robertson and Taylor 2007) and Ontario, Canada (Droppo et al. 2006; Irvine et al. 2009), and was also chosen due to the relatively coarse nature of much of the RDS and ease of use in collecting >330 individual samples; other studies have used small dry- and wet-vacuum devices (e.g. Bris et al. 1999; Charlesworth et al. 2003; Poleto et al. 2009b), typically for smaller numbers of samples.

Sampling equipment was thoroughly cleaned and/or rinsed with distilled water and acetone to minimise contamination of each subsequent sample. Samples were placed in plastic bags to be stored for further processing. While care was taken to collect all RDS along the 2 m (or 1 m) curb length, inevitably some of the very finest material was lost via suspension to the air. Tests within a laboratory using material of a similar particle-size distribution showed that the mass of RDS lost to the air represented between 0.5% and 2% of the total mass of RDS collected and that this material was likely to be <63 μm. We have, therefore, assumed that the sampling error associated with the mass of RDS is 2% and that this material was <63 μm.

Samples collected from each grid were air-dried and then combined into composite samples representing the 46 grids for each of the fall and summer periods. Composite samples were gently disaggregated and fractionated into five grain-size classes (>500, 250–500, 125–250, 63–125, <63 μm) by dry sieving using stainless steel sieves. Fractionated sediment samples were weighed to obtain a mass for each particle-size class for each grid cell.

2.3 Spatial and statistical analysis of RDS samples

To estimate the total mass of sediment found along the curbs in Prince George it was necessary to calculate the average mass of sediment per unit length of curb for each grid cell. This value was then extrapolated to the entire road network by determining the total length of curbs in each grid cell. Thus, the mass of dry sediment was calculated by multiplying road length by the average mass per unit length of curb, and assuming that a road is bounded by a pair of curbs (i.e. on either side of the road). We calculated for each grid cell: (1) the mass of sediment per unit length of curb (i.e. per km), (2) the mass of sediment per unit area (i.e. per km^2) and (3) the percent of the total mass represented by each particle-size class. These measurements were plotted in the sampling grid to identify potential hotspots of RDS deposition. All spatial analysis was completed using ArcGIS 9.3.1.

When testing for differences between means, non-parametric statistical analysis were used because the assumptions of normality could not be justified. The statistical significance level was set at $P \leq 0.01$. Differences between particle-size fractions for each sample period were analysed on a pairwise basis using Wilcoxon signed-rank tests with the Bonferroni P value adjustment method (Abdi 2007). Temporal and spatial analyses were conducted using a Wilcoxon signed-rank test for each particle-size fraction independently. Statistical analysis was undertaken using R Statistical Software Version 2.12.0 (R Development Core Team 2010).

Table 1 Summary characteristics of the sampled part of the city of Prince George for the summer and fall 2009 sampling periods

	Number of sampling grids	Total areal coverage (km^2)	Total curb length (km)	Average total curb length per km^2 (km km^{-2})
City centre	19	19	597	31.4
Outlying area	27	144	1462	10.2
Total	46	163	2,059	12.6

3 Results

3.1 Estimates of total RDS mass

The estimated total RDS mass for each particle-size fraction for the entire city for each sampling period is shown in Fig. 2. The combined (all particle-size fractions) estimates for the total RDS mass were 746×10^3 and 204×10^3 kg for the summer and fall 2009 sampling periods, respectively. For the >500-μm particle-size fraction there was nearly three times the total amount of RDS in the summer sampling period as compared to the fall sampling period. Similarly, there was over four times the total amount of RDS in the summer sampling period as compared to the fall for the other particle-size fractions.

3.2 Particle-size composition

The average particle-size compositions for the entire city for both sampling periods are plotted in Fig. 3. For both sampling periods there is a consistent pattern of decreasing percent mass with decreasing particle-size class. For the summer 2009 sampling period, there were no significant differences between the three largest particle-size fractions, however, significant differences were found between the 63–125-μm and the <63-μm particle-size fractions and all the other particle-size fractions. For the fall 2009 sampling period, significant differences were found between all particle-size fractions. On average, the <63-μm particle-size fraction accounted for 6.5% and 4.8% of the total sediment mass for the summer and fall 2009 sampling periods, respectively; it is estimated that an additional approximately 2% was lost to the air during sample collection, and thus values may be closer to 9% and 7%, respectively.

3.3 Temporal variations

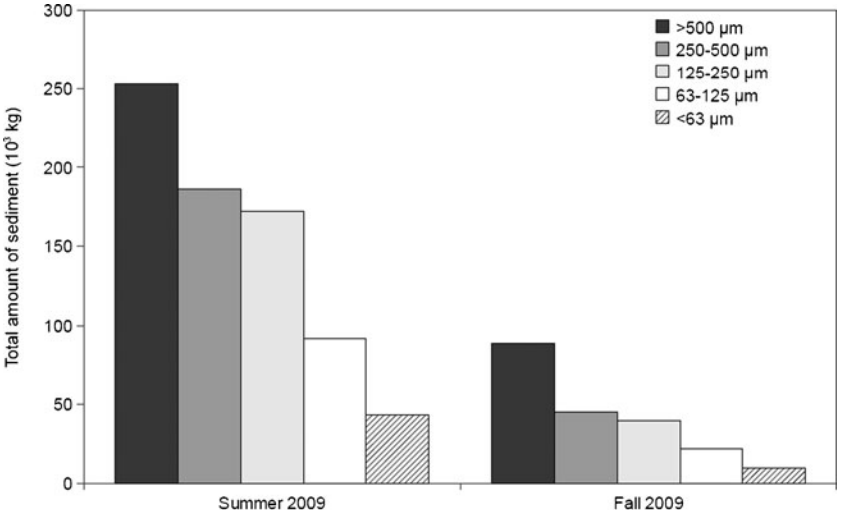
The proportion of the total RDS mass for each particle-size fraction changed between the two sampling periods (see Fig. 3). There was a significant increase in the proportion of the total RDS mass in the >500-μm particle-size fraction from the summer to the fall 2009 sampling period. Consequently, there was also a significant decrease in the proportion of the total RDS mass for all remaining particle-size fractions from the summer to the fall 2009 sampling periods.

There were temporal differences in the RDS density between the city centre and outlying sample areas (Fig. 4). Significant differences were found in the RDS mass per unit area (kilogrammes per square kilometre) between the two sampling periods for both the city centre and the outlying areas for all particle-size fractions (see Fig. 4a). On average, for all particle-size fractions and locations, the summer sampling period had 2.8 times greater RDS mass per unit area than the fall sampling period. Similarly, there were also temporal differences in the mass of RDS per metre of curb for both the city centre and outlying sample areas (see Fig. 4b). Significant differences were found in the mass of RDS per metre of curb between the two sampling periods for both the city centre and the outlying areas for all particle-size fractions: the summer sampling period had 3.3 times RDS mass per metre of curb than the fall sampling period.

3.4 Spatial variations

There were spatial differences in the RDS density for all particle-size fractions (see Fig. 4). Significant differences were found in the RDS mass per unit area between the city centre and the outlying areas for both sampling periods and

Fig. 2 Mass of road-deposited sediment for each particle-size fraction for the summer and fall 2009 sampling periods (i.e. at a point in time)



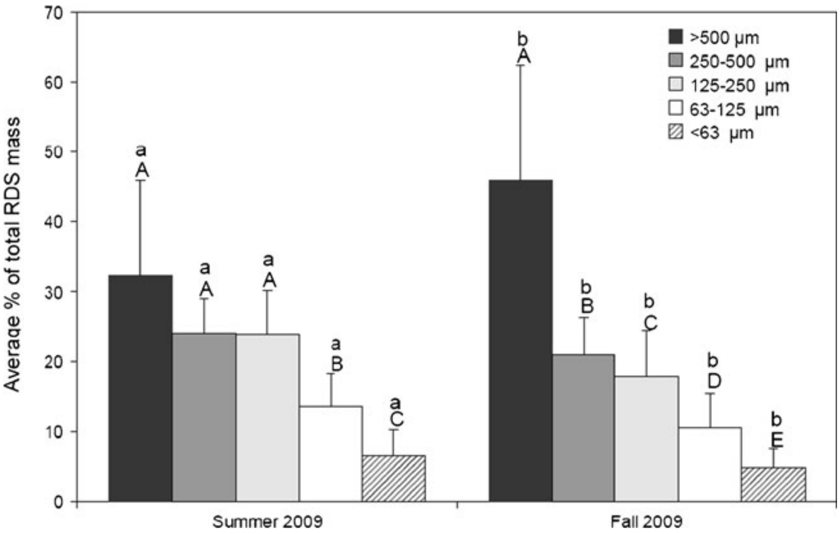


Fig. 3 Grain-size mass distribution for the summer and fall 2009 sampling periods. Differences in *lowercase letters* denotes significant ($P \leq 0.01$) differences between summer 2009 and fall 2009 sampling periods for each particle-size fraction separately (i.e. between-period differences). Differences in *uppercase letters* denotes significant ($P \leq 0.01$) differences between particle-size fractions for the summer 2009 and fall 2009 sampling periods separately (i.e. within-period differences). *Error bars* represent +1 standard deviation

for each of the particle-size fractions (see Fig. 4a). For all particle-size fractions and both sampling periods combined, the city centre had on average 3.2 times the RDS density compared to the outlying areas. There were also spatial differences in the RDS per metre of curb between the city centre and outlying sample areas (see Fig. 4b). No significant difference was found in the RDS per metre of curb between the city centre and the outlying areas for the summer 2009 sampling period for all particle-size fractions. However, there were significantly higher amounts of RDS per metre of curb in the city centre compared to the outlying areas for the fall 2009 sampling period for all particle-size fractions with the exception of the >500-μm particle-size fraction.

Given that the fine-grained RDS has important implications for air and water quality, Figs. 5 and 6 show the spatial patterns for the <63-μm particle-size fraction for the summer and fall 2009 sampling periods, respectively. In general, RDS mass per unit area was greatest in the city centre. The contrast between city centre and outlying areas was greatest in fall 2009 compared to summer 2009, although masses were significantly greater in the summer sampling period. In fall 2009, RDS was concentrated in the city centre. In summer 2009, while the pattern was generally similar to the fall period, there was also an area to the north-east of the city centre, at the confluence of the Fraser and Nechako Rivers, which had an elevated value of RDS mass per unit area. This area coincides with an area of medium- to light-industry, and traffic to two pulp and paper mills.

4 Discussion

4.1 Total mass of RDS

The total amount of RDS (all particle-size fractions) in Prince George was estimated to be 746×10^3 and 204×10^3 kg for the summer and fall 2009 sampling periods, respectively. Based on a total curb length within the sampled area of the city of 2,059 km (see Table 1), and thus a total road length of 1,030 km, this equates to an average of 724 and 198 kg per km of road, for the summer and fall sampling periods, respectively. These average values of RDS throughout the city centre and outlying areas appear to be high, although there are few equivalent data from other studies with which to compare these values. The average values collected in the present study also mask considerable spatial variation. Indeed, several 1-m curb samples yielded >1 kg of RDS (all particle-size fractions; e.g. >3.3 kg m^{-2} of sampled road surface area), with a maximum total mass of approximately 20,000 kg km^{-2} estimated for one of the 1×1-km-grid cells in the city centre in the summer 2009 period. It is important to recognise that such estimates are essentially instantaneous values (i.e. a point in time), and that amounts of RDS vary considerably over time. In terms of the most important particle-size fraction from an air and water quality perspective, the <63-μm particle-size fraction accounted for, on average, 6.5–8.5% and 4.8–6.8% (allowing for loss during sampling) of the total sediment mass for the summer and fall 2009 sampling periods, respectively, which equates to averages of between 47–61 and 10–13 kg per km of road, respectively.

There are, however, some important caveats to consider when interpreting these values. Firstly, while the samples were collected from four random sampling points within each grid cell, inevitably there may have been some bias in sampling areas with a significant amount of RDS. Indeed, at locations where there was no RDS, then a nearby area of curb containing RDS was sampled. Furthermore, sample masses were extrapolated over fairly large areas: it is estimated that the total length of curb sampled was approximately 0.34 km out of a total curb length of approximately 2,059 km (i.e. <0.02%). It is, therefore,

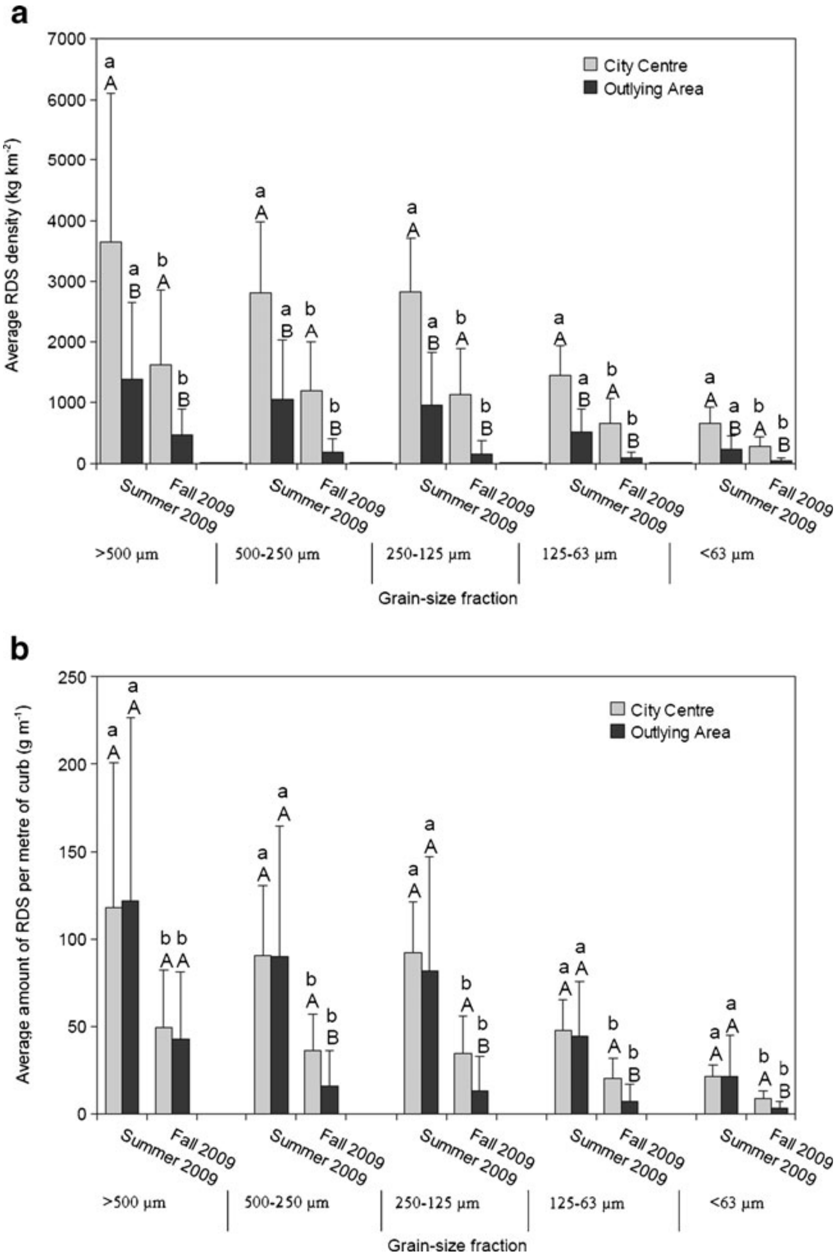


Fig. 4 Average road-deposited sediment mass: (**a**) per unit area and (**b**) per metre of curb. Differences in *lowercase letters* denotes significant ($P \leq 0.01$) differences between summer 2009 and fall 2009 sampling periods for the City Centre and Outlying areas separately for each particle-size fraction. Differences in *uppercase letters* denotes significant ($P \leq 0.01$) differences between City Centre and Outlying areas for the summer 2009 and fall 2009 sampling periods separately for each particle-size fraction. *Error bars* represent +1 standard deviation

possible that the values presented above are overestimates of true values of RDS. However, it is also likely that sampling did not collect all RDS on the surface of the road (as samples were collected from the curbs and RDS was not collected between the curbs, i.e. the middle of the road). Some studies (e.g. Sartor and Boyd 1972) have identified that RDS can be present across the full road width. However, visual observations at the times of sampling showed that the majority of the RDS was concentrated along the curbs, typically within 30 cm of the edge of the curb; a finding consistent with other studies (cf. Amato et al. 2010). Furthermore, some of the fine-grained RDS was suspended into the air during sampling and was not collected for analysis. Given these limitations of the sampling approach, emphasis should be placed on the order of magnitude of mass of RDS.

4.2 Temporal and spatial patterns

There are large differences between the two sample periods for all the metrics used to describe the characteristics of RDS for Prince George (see Figs 2, 3, 4, 5 and 6). The larger amounts of RDS found for the summer sampling period could be, in part, due to road maintenance operations during the preceding winter months as Prince George has a long winter with snow on the roads between early November and late March (later in the outlying areas), and temperatures can drop below −30°C. The City of Prince George

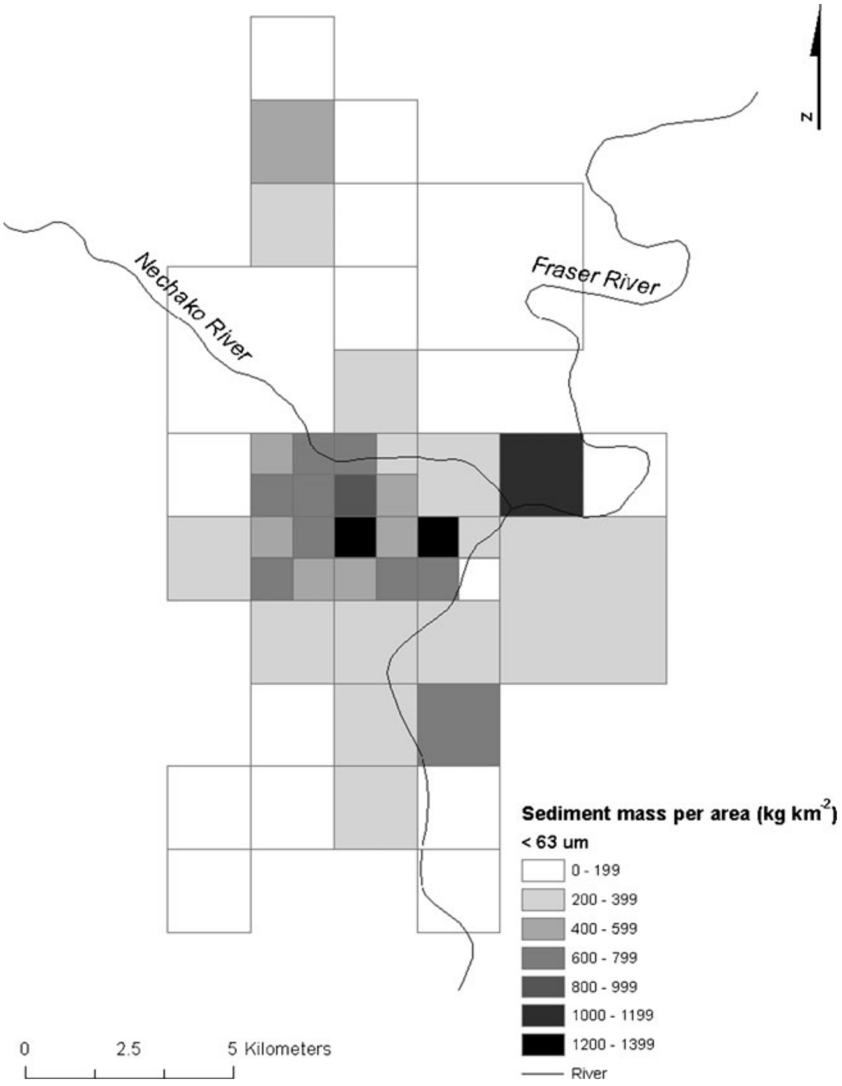


Fig. 5 Map showing the spatial distribution of the <63-μm particle-size fraction for the summer 2009 sampling period

typically applies approximately 15,000 to 20,000 tonnes of sand and gravel as part of the winter road maintenance programme (City of Prince George 2011). In 2009, sand was applied during the periods January to March and October to December (Table 2). Thus the larger amount of RDS in the summer sampling period (i.e. June 2009) may reflect, in part, this source of material. The noticeable difference between the amount of material applied by the City (typically >10,000 tonnes in the preceding 8 months) and that measured here (approximately 746 tonnes in late June) suggests that a considerable amount is removed either during street sweeping operations and/or is lost to air by resuspension and to watercourses by runoff. In addition, a considerable amount is also removed from the surface of the roads by snow ploughing, which tends to push snow (and any entrained RDS) off of roads and onto adjacent pathways and gardens, in addition to that snow (and entrained RDS) which is physically removed from the roads to storage areas (Jocelyn White personal communication 2011). Visual observations in late April through to early June suggest that the road sweeping operations are fairly efficient, and that the applied road sand and gravel is removed fairly quickly once the snow has fully receded (i.e. between April and June).

The shift that occurred from the summer to the fall sampling periods, in regards to the proportions of the total RDS mass for each particle-size fraction (i.e. a relative increase in the coarse fraction, and decrease in the finer fractions), was unexpected. For example, if there was mechanical break-down of RDS (i.e. applied sand and gravel during road maintenance) by vehicular traffic then one would expect RDS to get finer over time. In addition, one might expect that road sweeping operations preferentially collect the coarser particle-size fractions leading to an increase in the proportion of the finer particle-size fractions in later periods. For example, Sutherland (2003) states that the road sweeper efficiency for the >500 and <63 μm fractions of RDS were >80%

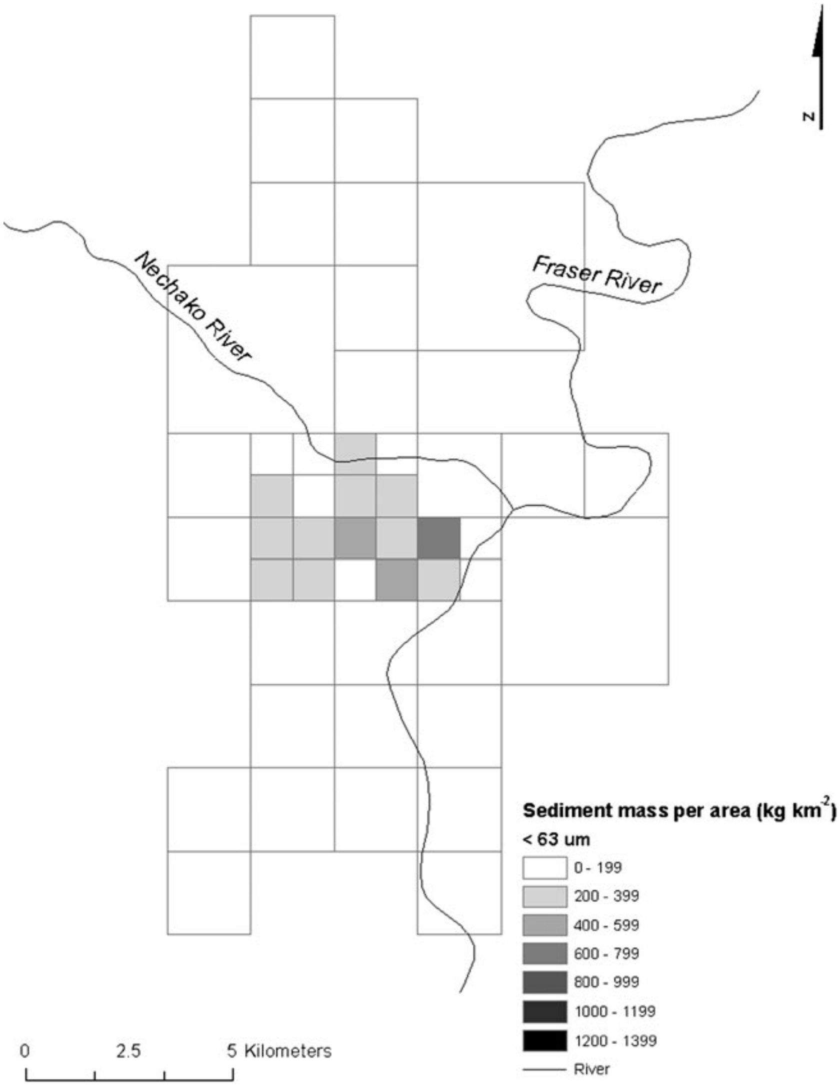


Fig. 6 Map showing the spatial distribution of the <63-μm particle-size fraction for the fall 2009 sampling period

and <50%, respectively, for Palolo Valley, Hawaii. This has important implications for pollution abatement as the finest particle-size fraction (i.e. <63 μm) of RDS often has the highest concentration of contaminants such as metals (Sutherland 2003; Robertson and Taylor, 2007). One possible reason for the finer nature of the summer RDS, compared to the fall RDS, may be antecedent rainfall. However, the total rainfall in the 10 days prior to the summer and fall sampling periods was 37.8 and 6.9 mm, respectively (Environment Canada 2011), and thus the greater rainfall in early summer would have washed the finer fraction of the RDS from the roads into the sewer network. Coarsening of RDS over time could reflect different meteorological conditions (e.g. more inversions during summer) or different sources (e.g. increased building activities etc.) between the two sampling periods.

Table 2 Application of sand and other clastic material to the roads of Prince George during the 2009 winter season (data courtesy of the City of Prince George: Gina Layte Liston and Alan Clark, personal communication 2010)

Month	Sand (tonnes)	Fracture (tonnes)
January	1,749.21	593.00
February	3,712.46	834.98
March	846.70	210.55
October	84.07	27.31
November	1,105.10	184.82
December	2,944.57	838.23
Total	10,442.02	2,688.90

There were large spatial and temporal variations for all particle-size fractions and for every metric used to describe the characteristics of RDS as seen by the large error bars in Figs. 3 and 4. These variations may be a reflection of different sources of RDS, as well as management activities (e.g. road sweeping schedules) and hydro-geomorphic processes (e.g. antecedent rainfall conditions, preferential removal of fines by wind and precipitation events: Droppo et al. 2002), in addition to variations in sampling and to measurement errors. The city centre had the highest RDS density (see Fig. 4a), by a factor of about 3, and this is due to the fact that the city centre had the highest road density (see Table 1). However, when the difference in the total curb length between the city centre (31.4 km km^{-2}) and outlying areas (10.2 km km^{-2}) is taken into account, the amounts deposited (mass per surface area per length of curb) in the two areas are similar, especially for the summer period (Fig. 4b).

4.3 Implications for air and water quality

This study has demonstrated that there is a considerable amount of RDS on the Prince George road network. Emissions inventory studies (e.g. Stantec 2010) have demonstrated that dust source emissions, particularly 'on-road dust' (i.e. RDS), are the dominant source of airborne fine-particulate material (i.e. PM_{10} and $PM_{2.5}$) in the city (Table 3). The present study adds support to this earlier work (which was based on a limited number of RDS samples) and suggests that RDS presents a potential threat to human health due to respiratory problems associated with airborne fine particulates. The greater mass of RDS within the city centre (Figs 4, 5, 6), due to the greater density of roads, identifies this as the area with high potential for air quality concerns. An important future research direction may include determining the sources of RDS, as it may be an important step in developing strategies for reducing the total amount of RDS. In this context, source apportionment and fingerprinting studies, and receptor modelling (e.g. chemical mass balance modelling) offer much promise for source identification of RDS and associated chemicals (e.g. Kowalczyk et al. 1982; Sweet et al. 1993; Behera et al. 2011).

Studies have demonstrated that a significant proportion of the fine-grained sediment (<63 μm) transported in urban streams is derived from the urban road network (i.e. RDS). For example, Carter et al. (2003) determined that RDS contributed about 20% of the sediment load of the River Aire downstream of the city of Leeds, UK. During snowmelt and precipitation events, surface runoff connects the urban road and river channel networks, and sediment is transported to receiving rivers via the urban stormwater system (Taylor and Owens 2009). Excessive amounts of fine-grained sediment can be detrimental to potable water supplies through high suspended sediment concentrations (i.e. turbidity) and through clogging of river gravels, which can be detrimental to aquatic organisms such as fish and invertebrates (Bilotta and Brazier 2007). Excessive sedimentation often requires maintenance dredging, which can be costly and time-consuming (Owens et al. 2005).

In addition to the physical aspects of fine sediment and its impact on air and water quality, much of the fine RDS is likely to be enriched in contaminants, such as metals (Stone and Marsalek 1996; Sutherland 2003; Droppo et al. 2006; Robertson and Taylor 2007; Krčmová et al. 2009), much of which is in a bioavailable form (Irvine et al. 2009). While the <63-μm fraction is often the most important fraction for many sediment-associated contaminants, some studies (e.g. Sutherland et al. 2008) have demonstrated that larger size fractions (i.e. >63 μm) may be more important for some contaminants, like platinum-group elements. Thus information is required on the full particle-size composition of RDS in order to

Table 3 Emissions source inventory for airborne fine particulate material (PM_{10} and $PM_{2.5}$) for Prince George for 2005 (modified from: Stantec 2010)

Source category	Sub-category	PM_{10} g s^{-1}	PM_{10} %	$PM_{2.5}$ g s^{-1}	$PM_{2.5}$ %
Mobile	On-road dust	137.26	56.31	19.64	20.93
	On-road mobile	1.03	0.42	0.74	0.79
	Locomotive	5.44	2.23	5.21	5.55
Industrial	Permitted users	69.55	28.53	50.67	54.15
Commercial	Commercial burning	0.20	0.08	0.20	0.21
	Commercial misc	1.33	0.55	1.26	1.43
	Commercial dust	13.74	5.64	1.58	1.68
	Commercial restaurants	6.28	2.58	5.83	6.21
Residential	Residential heating	5.30	2.17	5.22	5.56
	Residential others	0.52	0.21	0.52	0.55
Other	City open burns	0.99	0.36	0.98	0.87
	BC Ministry of Forests open burns	2.11	0.76	1.84	1.63
Airshed emission sources	Sum of above	243.75		93.82	
Expressed as tonnes year^{-1}			8,772		3,549

understand the complete environmental implications of RDS within urban environments. On-going work is determining the contaminant content of these RDS samples and linking this information to equivalent values for channel bed sediment samples in urban rivers in Prince George.

From a management perspective, there is a need to: (1) reduce the amount of RDS on the urban road network; and (2) limit the amount of RDS that is transported to the air column and to watercourses. The former can be achieved by emissions control (e.g. reduced application of sand and gravel to roads, reduced industrial particulate emissions) and road management (e.g. road sweeping). The latter could be achieved through improvements in road sweeping efficiency (to remove the finest fraction) and through improvements in the stormwater sewer system (e.g. gully pots, settling ponds) and the creation of sediment retention systems, such as wetlands and buffer features.

5 Conclusions

A large amount of sediment (RDS) lies on the road network of Prince George. Sampling during two different time periods in the snow-free season showed considerable variation in amounts of RDS, but the order of magnitude for the two time periods was similar. The total amount of RDS (all particle-size fractions) in the city of Prince George was estimated to be 746×10^3 and 204×10^3 kg for the summer and fall 2009 sampling periods, respectively. Based on a total road length of 1,030 km within the sampled area of the city, this equates to an average of 724 and 198 kg per km of road, for the summer and fall sampling periods, respectively. The RDS was dominated by the >500-μm fraction, and there was a trend of decreasing amounts (by mass) for the finer particle-size fractions. In terms of the most important particle-size fraction from an air and water quality perspective, the <63-μm particle-size fraction accounted for 6.5–8.5% and 4.8–6.8% (allowing for loss during sampling) of the total RDS mass for the summer and fall 2009 sampling periods, respectively, which equates to averages of between 47–61 and 10–13 kg per km of road, respectively. Amounts of RDS were greatest in the city centre, compared to the outlying areas, mainly reflecting the higher density of roads in the city centre, although there were some hotspots outside of this which may reflect land use activities such as light-industry and pulp and paper mills. These findings have implications for air and water quality in the city and surrounding area, including the Nechako and Fraser Rivers, and help to identify management options to reduce potential environmental and human health problems.

Acknowledgements We would like to acknowledge financial support from a Forest Renewal BC Operating Grant, an NSERC Discovery Grant and a UNBC Seed Grant to PNO. We would also like to thank Gina Layte Liston and Jocelyn White (City of Prince George) for supplying data and information. We are grateful to the helpful and insightful comments from two referees and the submission editor.

References

Abdi H (2007) The Bonferroni and Šidák corrections for multiple comparisons. In: Salkind N (ed) The Encyclopedia of Measurement and Statistics. Sage, Thousand Oaks

Amato F, Querol X, Johansson C, Nagl C, Alastuey A (2010) A review of the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. Sci Total Environ 408:3070–3084

Behera SN, Sharma M, Dikshit O, Shukla SP (2011) GIS-based emission inventory, dispersion modeling and assessment for source contributions of particulate matter in an urban environment. Water Air Soil Pollut. doi:10.1007/s11270-010-0656-x

Bilotta GS, Brazier RE (2007) Understanding the influences of suspended solids on water quality and aquatic biota. Water Res 42:2849–2861

Breed CA, Arocena JM, Sutherland D (2002) Possible sources of PM in Prince George (Canada) as revealed by morphology and in situ chemical composition of particulate. Atmos Environ 36:1721–1731

Bris F-J, Garnaud S, Apperry N, Gonzalez A, Mouchel J-L, Chebbo G, Thévenot DR (1999) A street deposit sampling method for metal and hydrocarbon contaminant assessment. Sci Total Environ 235:211–220

Bucko MS, Magiera T, Pesonen LJ, Janus B (2010) Magnetic, geochemical, and microstructural characteristics of road dust on roadsides with different traffic volumes—case study from Finland. Water Air Soil Pollut 209:295–306

Capelli L, Sironi S, Del Rosso R, Centola P, Rossi A, Austeri C (2010) Olfactometric approach for the evaluation of citizens' exposure to industrial emissions in the city of Terni, Italy. Sci Total Environ 409:595–603

Carraz F, Taylor KG, Stainsby S, Robertson DJ (2006) Contaminated urban road deposited sediment (RDS), Greater Manchester, UK: a spatial assessment of potential surface water impacts. North West Geogr 6:10–19

Carter J, Owens PN, Walling DE, Leeks GJL (2003) Fingerprinting suspended sediment sources in a large urban river system. Sci Total Environ 314–316:513–534

Carter J, Walling DE, Owens PN, Leeks GJL (2006) Spatial and temporal variability in the concentration and speciation of metals in suspended sediment transported by the River Aire, Yorkshire, UK. Hydrol Process 20:3007–3027

Charlesworth SM, Lees JA (1999) The distribution of heavy metals in deposited urban dusts and sediments, Coventry, England. Environ Geochem Health 21:97–115

Charlesworth SM, Everett M, McCarthy R, Ordóñez A, Miguel E (2003) A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK. Environ Intern 29:563–573

Charlesworth S, De Miguel E, Ordóñez A (2010) Trace elements in urban environments: a review. In: Poleto C, Charlesworth S (eds) Sedimentology of Aqueous Systems. Blackwell Publishing, Oxford, pp 108–128

City of Prince George (2011) Street sweeping. http://www.city.pg.bc.ca/city_services/transportation/streetsweeping/. Accessed 10 January 2011

R Development Core Team (2010) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/. Accessed 15 September 2010

Droppo IG, Irvine KN, Jaskot C (2002) Flocculation of cohesive sediments in the urban continuum: implications for stormwater management. Environ Technol 23:27–41

Droppo IG, Irvine KN, Curran KJ et al. (2006) Understanding the distribution, structure and behaviour of urban sediments and associated metals towards improving water management strategies. In Owens PN, Collins AJ (Eds) Soil Erosion and Sediment Redistribution in River Catchments: Measurement, Modelling and Management. CAB International, pp 272–286

Environment Canada (2011) Prince George Archive Climate. http//:www.climate.weatheroffice.gc.ca. Accessed 26 April 2011

Förstner U, Owens PN (2007) Sediment quantity and quality issues in river basins. In: Westrich B, Förstner U (eds) Sediment Dynamics and Pollutant Mobility in Rivers. Springer, Berlin, pp 1–15

Foster IDL, Charlesworth SM (1996) Metals in the hydrological cycle: trends and explanation. Hydrol Process 10:227–261

Horowitz AJ (2009) Monitoring suspended sediment and associated chemical constituents in urban environments: lessons from the city of Atlanta, Georgia, USA Water Quality Monitoring Program. J Soils Sediments 9:342–363

Irvine KN, Perrelli MF, Ngoen-klan R, Droppo IG (2009) Metal levels in street sediment from an industrial city: spatial trends, chemical fractionation and management implications. J Soils Sediments 9:328–341

Jiménez E, Linares C, Martínez DJ (2010) Role of Saharan dust in the relationship between particulate matter and short-term daily mortality among the elderly in Madrid (Spain). Sci Total Environ 408:5729–5736

Kim K-W, Myung J-H, Ahn JS, Chon H-T (1998) Heavy metal contamination in dusts and stream sediments in the Taejon area, Korea. J Chemical Explor 64:409–419

Kowalczyk GS, Gordon GE, Rheingrover SW (1982) Identification of atmospheric particulate sources in Washington, D.C., using chemical mass balances. Environ Sci Technol 16:79–90

Krčmová K, Robertson D, Cvečková V, Rapant S (2009) Road-deposited sediment, soil and precipitation (RDS) in Bratislava, Slovakia: compositional and spatial assessment of contamination. J Soils Sediments 9:304–316

Lee JH, Bang KW, Ketchum LH, Choe JS, Yu MJ (2002) First flush analysis of urban storm runoff. Sci Total Environ 293:163–175

Meharg AA, Wright J, Leeks GJL, Wass PD, Owens PN, Walling DE, Osborn D (2003) PCB congener dynamics in a heavily industrialized river catchment. Sci Total Environ 314–316:439–450

Ostro B, Broadwin R, Green S, Feng WY, Lipsett M (2006) Fine particulate air pollution and mortality in nine California counties: results from CALFINE. Environ Health Perspect 114:29–33

Owens PN, Walling DE (2002) The phosphorus content of fluvial sediment in rural and industrialized river basins. Wat Res 36:685–701

Owens PN, Walling DE (2003) Temporal changes in the metal and phosphorus content of suspended sediment transported by Yorkshire rivers, UK, over the last 100 years, as recorded by overbank floodplain deposits. Hydrobiologia 494:185–191

Owens PN, Walling DE, Carton J, Meharg AA, Wright J, Leeks GJL (2001) Downstream changes in sediment-associated contaminant (P, Cr and PCBs) transport and storage in agricultural and industrialized drainage basins. Sci Total Environ 266:177–186

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA (2005) Fine-grained sediment in river systems: environmental significance and management issues. River Res Appl 21:693–717

Pacific Salmon Commission (2010) News Release 11, September 17th 2010. Pacific Salmon Commission, Vancouver

Poleto C, Merten CH, Minella JP (2009a) The identification of sediment sources in a small urban watershed in southern Brazil: an application of sediment fingerprinting. Environ Technol 30:145–1153

Poleto C, Bortoluzzi EC, Charlesworth SM, Merten GH (2009b) Urban sediment particle size and pollutants in Southern Brazil. J Soils Sediments 9:317–327

Poleto C, Charlesworth S, Laurenti A (2010) Urban aquatic sediments. In: Poleto C, Charlesworth S (eds) Sedimentology of aqueous systems. Blackwell Publishing, Oxford, pp 129–146

Robertson DJ, Taylor KG (2007) Temporal variability of metal contamination in urban road-deposited sediment in Manchester, UK: implications for urban pollution monitoring. Water Air Soil Pollut 186:209–220

Robertson DJ, Taylor KG, Hoon SR (2003) Geochemical and mineral magnetic characterisation of urban sediment particulates, Manchester, UK. Appl Geochem 18:269–282

Sartor JD, Boyd GB (1972) Water pollution aspects of street surface contaminants. Report EPA-R2-72-08. USEPA, Washington, DC

Schafer J, Norra S, Klein D, Blanc G (2009) Mobility of trace metals associated with urban particles exposed to natural waters of various salinities from the Gironde Estuary, France. J Soils Sediments 9:374–392

Stantec (2010) Prince George air quality: dispersion modelling—a revision. Final Report. Project 1231–10153, Stantec, Burnaby, British Columbia

Stone M, Marsalek J (1996) Trace metal composition and speciation in street sediments: Sault Ste. Marie, Canada. Water Air Soil Pollut 87:149–169

Sutherland RA (2003) Lead in grain size fractions of road-deposited sediment. Environ Pollut 121:229–237

Sutherland RA, Pearson DG, Ottley CJ (2008) Grain size partitioning of platinum-group elements in road-deposited sediments: Implications for anthropogenic flux estimates from autocatalysts. Environ Pollut 151:503–515

Sweet CW, Vermette SJ, Landsberger S (1993) Sources of toxic trace elements in air in Illinois. Environ Sci Technol 27:2502–2510

Taylor KG (2007) Urban environments. In: Perry CT, Taylor KG (eds) Environmental sedimentology. Blackwell, Oxford, pp 191–222

Taylor KG, Owens PN (2009) Sediments in urban river basins: a review of sediment-contaminant dynamics in an environmental system conditioned by human activity. J Soils Sediments 9:281–303

UNESA (2008) World urbanization prospects: the 2007 Revision. UN Department of Economic and Social Affairs, United Nations

Vermette SJ, Irvine KN, Drake JJ (1987) Elemental and size distribution characteristics of urban sediments: Hamilton, Canada. Environ Technol Lett 8:619–634

Vermette SJ, Irvine KN, Drake JJ (1991) Temporal variability of the elemental composition in urban street dust. Environ Monitor Assess 18:69–77

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467:555–561

Wang WH, Wong MH, Leharne S, Fisher B (1998) Fractionation and biotoxicity of heavy metals in urban dusts collected from Hong Kong and London. Environ Geochem Health 20:185–198

Xu WH, Zhang G, Wai OWH, Zou SC, Li XD (2009) Transport and adsorption of antibiotics by marine sediments in a dynamic environment. J Soils Sediments 9:364–373

Zhao H, Li X, Wang X, Tian D (2010) Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. J Hazard Mater 183:203–210