

Article

The Measurement of Dry Deposition and Surface Runoff to Quantify Urban Road Pollution in Taipei, Taiwan

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Abstract: Pollutants deposited on road surfaces and distributed in the environment are a source of nonpoint pollution. Field data are traditionally hard to collect from roads because of constant traffic. In this study, in cooperation with the traffic administration, the dry deposition on and road runoff from urban roads was measured in Taipei City and New Taipei City, Taiwan. The results showed that the dry deposition is 2.01–5.14 g/m²·day and 78–87% of these solids are in the 75–300 μm size range. The heavy metals in the dry deposited particles are mainly Fe, Zn, and Na, with average concentrations of 34,978, 1,519 and 1,502 ppm, respectively. Elevated express roads show the highest heavy metal concentrations. Not only the number of vehicles, but also the speed of the traffic should be considered as factors that influence road pollution, as high speeds may accelerate vehicle wear and deposit more heavy metals on road surfaces. In addition to dry deposition, the runoff and water quality was analyzed every five minutes during the first two hours of storm events to capture the properties of the first flush road runoff. The sample mean concentration (SMC) from three roads demonstrated that the first flush runoff had a high pollution content, notably for suspended solid (SS), chemical oxygen demand (COD), oil and grease, Pb, and Zn. Regular sweeping and onsite water treatment facilities are suggested to minimize the pollution from urban roads.

Keywords: urban road pollution; dry deposition; surface runoff; heavy metals

1. Introduction

Maintaining an extensive traffic network is a characteristic feature of modern urbanization. Dense roads allow for fast and convenient transportation. However, expanding roads increase the amount of impervious surfaces and the possibility of nonpoint source pollution as a result. Road surface runoff contains substantial concentrations of pollutants that accumulate on road surfaces will be carried by storm runoff to rivers or lakes [1,2] and is regarded as a critical nonpoint pollution source for receiving waterbodies and therefore is an issue of concern in watershed management and urban environment maintenance [3,4].

Urban road runoff contains sediment, nutrients, bacteria, heavy metals, and toxic substances [5–7]. Chang *et al.* [8] reported that the pollutants that settle on road surfaces will be flushed during initial storm events and potentially contaminate receiving waters. The pollutants accumulated on road surfaces usually result from a wide variety of sources, e.g., atmospheric depositions, vehicle emissions, cars, and oils [5,9–11]. Because of these diverse sources, traffic pollutants are present in the gaseous, liquid, and solid forms. This study investigates liquid and solid pollutants. The wear and corrosion of vehicle parts and fuel combustion are two potential sources of heavy metals [12,13]. These heavy metals, including copper, chrome, nickel, wolfram, titanium, manganese, and zinc, are therefore potential road contaminants [14]. Eriksson *et al.* [15] stated that urban road runoff contains Cd, Cu, Zn, TN, TP, and PAHs. Kayhanian *et al.* [11] reviewed the characteristics of highway runoff and found Cd, Cr, Cu, Fe, Pb, Ni, Zn, and other nutrients to be common. Pollution stemming from road runoff that contains heavy metals is a direct risk to biological health. Dorchin and Shanas [15] used biological assays and confirmed that road runoff is a major cause of the observed decreasing aquatic habitat quality in Israel.

The level of road pollution varies and is influenced by the local environment and artificial management practices. For example, strong winds prevent dust from depositing and frequent roadway sweeping reduces dust accumulation on the road surface. Kim *et al.* [16] suggested that land use and surface activities will produce different types of pollutants. Zhao *et al.* [7] and Zhao and Li [17] investigated the sediment deposited on roads and the runoff along urban-suburban-rural gradients and revealed differences in their composition. Variability has been observed among studies [11]. Thus, it is necessary to understand the quantity and quality of onsite road pollution to develop effective control practices. The relationship between the buildup and wash-off of road pollution needs to be clarified under different local environmental conditions.

Field sampling from heavily trafficked roads is a difficult procedure, so field data for road pollution is therefore scarce. Mahbub *et al.* [10] and Zhao and Li [17] performed investigations on both road-deposited sediment and runoff in Australia and China, respectively. Both groups discussed the relationships between particle size and heavy metal concentrations, but they used simulated rainfall, not real events. In Taiwan, Teng [18] performed preliminary field experiments on road runoff and showed that elevated express roads inside cities produced higher SS, NH₃-N, TP, COD, and Zn, Fe, Cu, Cr, Ni, and

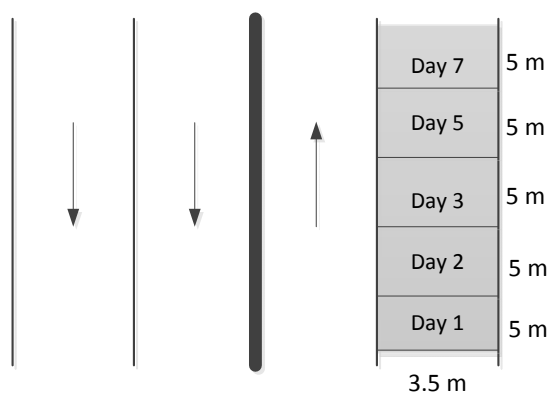
Pb than general roads. Thus, there is an urgent need to collect more data to confirm the potential risk in the urban cities of Taiwan. In this study, we cooperated with the traffic administration agency to collect onsite dry deposition and runoff from urban roads. Six road sites in Taipei City and New Taipei City were tested. In this study, we focus on road-deposited dust and the properties of runoff. A particular focus was placed on heavy metal concentrations in the deposited dust and in road runoff. The regional differences caused by land use and effects of storm variability are not discussed.

2. Materials and Methods

2.1. Site Description and Collection Method for Dry Deposition Analysis

Three urban roads designated as A, B and C were selected as the study sites. Their surfaces are all asphalt and concrete. Road C is an elevated expressway. On road A, five plots 5 m in length and 3.5 m in width were collected individually from day one to day seven to estimate the continuous dry deposition accumulations. The Day 1 plot was collected on the first day, the Day 2 plot on the second day, the Day 3 on the third day, and so on (Figure 1). For roads B and C, the dimensions of the collection area were 100 m in length and 0.3 m in width. Because of heavy and fast traffic on roads B and C, the width of sampling area was reduced to 0.3 m for safety while sampling, but the length of the collection area was extended to 100 m. The sampling schedule was different from that for the road A. We collected a daily dry deposition sample from the B and C roads over 7 days. The site design and photos are shown in Figures 1 and 2. Site location is shown in Figure 3. Site sampling was completed during seven consecutive sunny days. The dry deposition is mainly from vertical transport and the effects of lateral wind-blowing and roadside barriers are assumed to be ignored. A vacuum cleaner was used as the sampling instrument. The collected dust was tested by a Laser Diffraction Submicron Particle Size Analyzer to determine the particle distribution. The heavy metal concentration, including Pb, Cu, Zn, Fe, Na, and Ni, was estimated by Inductive Coupled Plasma-Mass Spectrometry (Optima 2000 DV, PerkinElmer Inc., USA).

Figure 1. Dry deposition collection sites. (a) The Road A site was divided into five plots, which were utilized for the accumulations on days 1, 2, 3, 5, and 7. (b) The Road B and C had a 30 m² collection area, and were sampled daily over 7 consecutive days.



(a)

Figure 1. Cont.

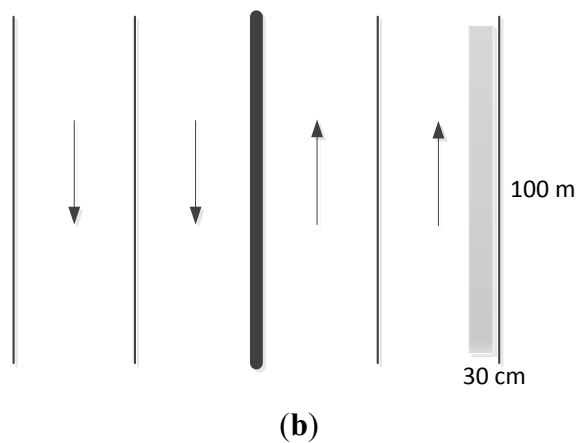


Figure 2. Photos of dry deposition collection. (a) Road A; (b) Road B; (c) Road C.

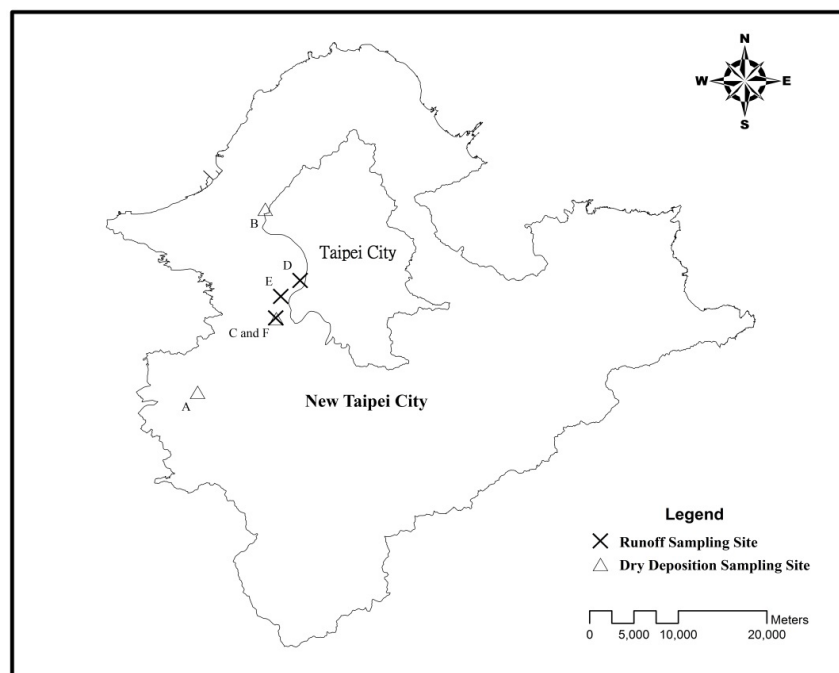


Figure 2. Cont.



(c)

Figure 3. Site locations of the dry deposition and runoff sampling sites.



2.2. Site Description and Collection Methods for the Runoff Water Quality Analysis

Road runoff usually flows into collection drainage pipes and converges into the rainwater sewage system. We sampled runoff before it flowed into the sewage system. Sampling occurred when the accumulation of rain water was larger than 3 mm with at least three successive sunny days before the rainfall event. One sample was taken every five minutes, and a total of 24 samples were taken for each event. Thus, the first two hours of runoff were measured and to obtain the first flush pollution graph. However, because of the high cost, the heavy metal concentration was tested for a single mixed sample, not for each of the 24 samples. Flow weighted method was used to obtain the composite sample. The sample volume is 2,000 mL, therefore, water volume of $(Q_i/\Sigma Q_i) \times 2,000$ mL was taken from each sample, where Q_i is the flow rate of the i th sample. Thirteen water quality parameters were analyzed,

including suspended solid (SS), ammonia-nitrogen (NH₃-N), chemical oxygen demand (COD), total phosphorous (TP), oil and grease, Cu, Zn, Pb, Cr, Hg, As, Cd, and Ni. The heavy metals were analyzed by ICP (Optima 2000 DV, PerkinElmer Inc., USA). The remaining parameters were measured following the national standard methods (the analysis standard methods are found at [19]). To ensure the quality of the runoff samples, the onsite collection drainage pipes were cleaned before sampling. We used clean water to wash the pipes. Figure 4 shows the road runoff sampling sites, and the site details are listed in Table 1.

The data for the first two hours of rainfall illustrate the first flush, however, because of the fluctuations, a mimic event mean concentration (EMC) was used, which is called sample mean concentration (SMC) to present the average water quality. An EMC is expected to monitor an entire rainfall event and obtain a mean value for the event; however, this study monitored the first two hours of runoff and did not cover the entire event period. As a result, the alternative SMC is applied. The calculation is provided in Equation (1):

$$SMC = \frac{\sum_{i=1}^n Q_i C_i}{\sum_{i=1}^n Q_i} \quad (1)$$

where Q_i is the runoff volume of the i sample (m³), C_i is the pollution concentration of the i sample (mg/L), and n is the total number of samples.

Figure 4. Site photos for runoff collection. (a) Pipe cleaning before sampling, Road F. (b) Runoff sampling sites. The left is Road D, and the right is Road E.

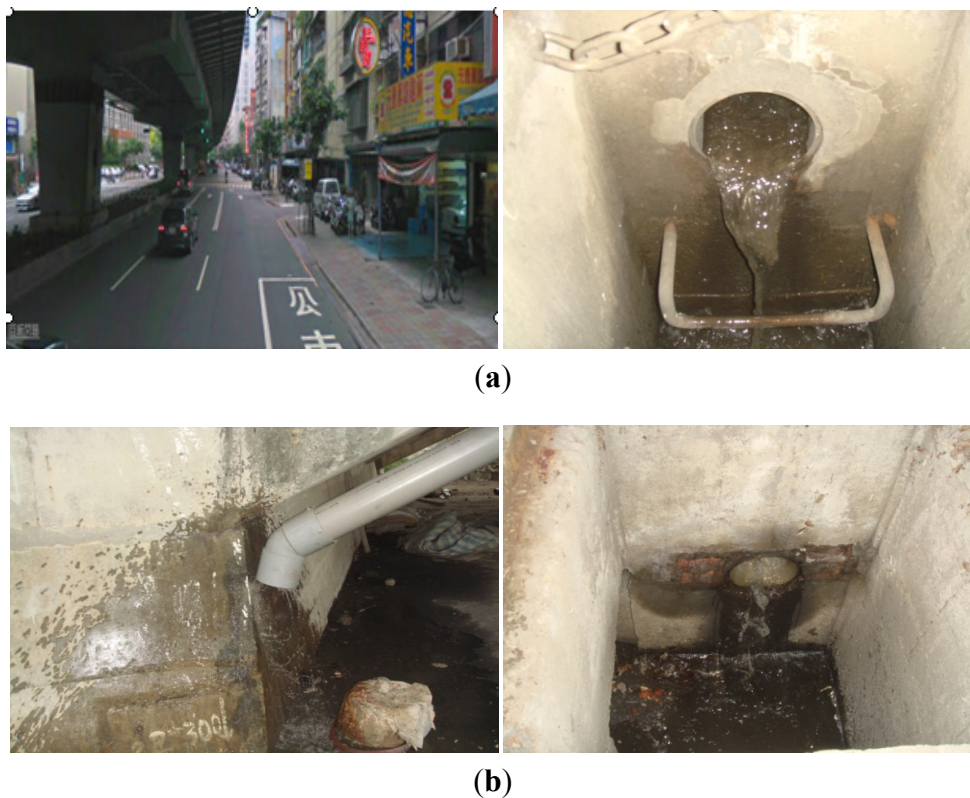


Table 1. Basic information of the road sampling sites.

Analysis Type	Site	Time	Area (m ²)	Road Type	Traffic Volume (ADT)
Dry deposition	A	2012/07/11–07/17	87.5	Surface road	11,667
	B	2012/09/30–10/06	30	Bridge road	37,354
	C *	2012/09/30–10/06	30	Elevated expressway	42,738
Runoff analysis	D	2012/04/05	363.6	Surface road	82,625
		2012/08/17			
	E	2012/12/18	1,022.25	Surface road	56,335
	F *	2013/02/27	685.85	Elevated expressway	42,738

* Site F is the location for runoff sample collection in which directly related to site C, but the collection areas for the dry deposition and runoff were different. The dry deposition area was established by our design and the runoff collection area was determined by the existing drainage system.

3. Results and Discussion

3.1. Dry Deposition Mass and Particle Size Analysis

Dry deposition samples were collected from three roads. Before the first sampling, the roads were swept and cleaned. For the daily experiment, the routine road cleaning task was performed after dry deposition collection. For the accumulation experiment of road A, the designed studied plots were not cleaned until the experiment ended. The total of five samples was collected from road A and seven samples from roads B and C. The results of the dry deposition analysis are detailed in Table 2. The total dry deposition mass is divided by the collection area to obtain the unit surface loading. The daily dry depositions for roads A, B, and C were 2.17–11.77 g/m²·day, 0.83–3.68 g/m²·day, and 3.53–6.62 g/m²·day, respectively. The average dry deposition loading for the three roads was 2.01–5.14 g/m²·day. To compare with reference data, Zhao *et al.* [7] reported the road-deposited sediment mass in a central urban area was 21 ± 24 g/m² and Kim *et al.* [20] evaluated 15.6 ± 0.7 g/m² of total solid loads on roads. The lesser amount of dry deposition in this study might be attributed to daily street sweeping. Without cleaning, the dry deposition mass can accumulate to 15–35 g/m² in 7 days. Although the average loading of road A was the highest, its cumulative rate was flat. When considering the total accumulative loadings of the three roads, the 7 day dry deposition for road C was the highest (35 g/m² versus approximately 15 g/m² for the other two roads, Figure 5). This significant difference might be because road C is an elevated expressway, and the traffic volume is higher than those for the other two roads.

The particle sizes of the collected sediments were determined by a laser particle analyzer, and the results are summarized in Table 2 and Figure 6. The analyzer measured particle sizes ranging from 4,750 to 75 µm. The results showed that most dust (70.7–85.7%) ranged from 75 to 300 µm at the three sampling sites. The mass percentage for the particle sizes less than 75 µm ranged from 12.9% to 23.2%. Fine to medium particle sizes were dominant. The three sampling roads are important roadways and are cleaned every day, therefore, the collected dust resulted solely from atmospheric deposition. Over 90%

of the dry deposition from the road A and C was less than 600 μm, and 83% of the deposition was less than 600 μm for the road B. Very fine particles, those less than 75 μm, are easily blown by the wind and re-suspended; thus, the deposition for particles in this range is low [20–22].

Table 2. Dry deposition results.

Road	A	B	C
Loads and size	(n = 5) *	(n = 7)	(n = 7)
Average mass loads (g/m ² ·day)			
Particle loads (g/m ² ·day)	5.14	2.01	4.78
Average percentages for the particle sizes (%)			
<75 μm	23.2	17.4	12.9
75–150 μm	21.5	13.9	20.5
150–300 μm	21.4	16.5	26.1
300–600 μm	20.0	16.8	22.5
600–1,180 μm	8.5	6.9	10.6
1,180–2,360 μm	2.9	5.8	4.3
2,360–4,750 μm	2.0	11.1	2.4
>4,750 μm	0.4	0.0	0.0

* Dry deposition analysis was performed for each sample. The number of samples (n) is 5 for road A and 7 for road B and C.

Figure 5. Accumulative dry deposition of the studied roads.

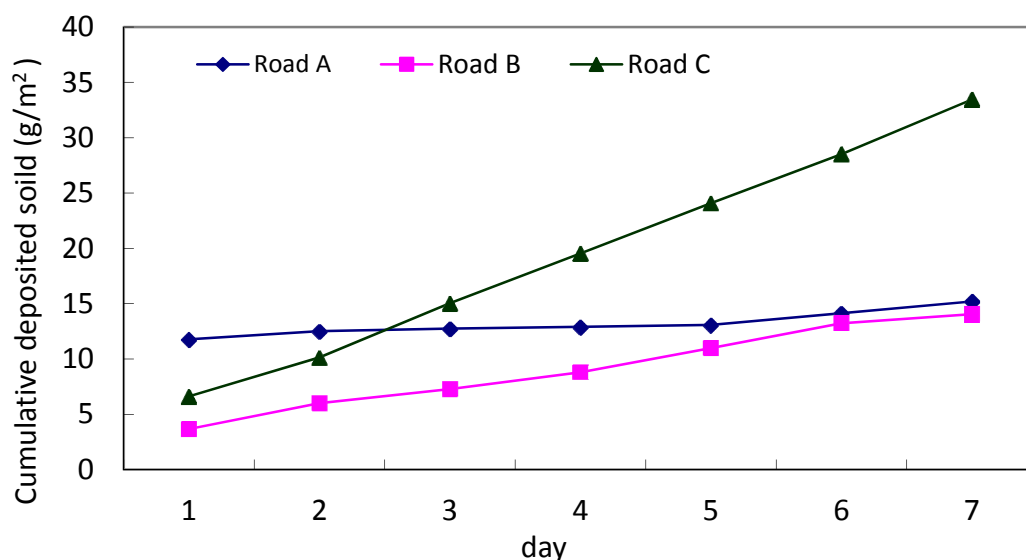
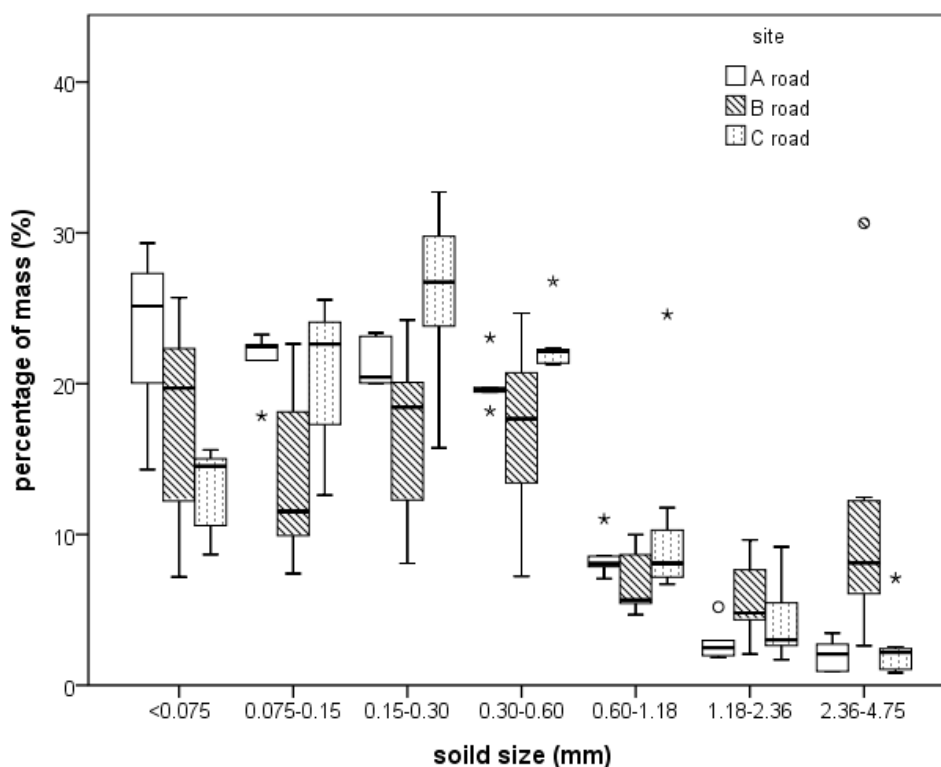


Figure 6. Particle size distribution of dry deposition.

In addition, we further analyzed the particles with sizes less than $10\ \mu\text{m}$ (PM_{10}), which is usually regarded as a potential air pollutant affecting human health. The percentage of PM_{10} in the dry deposition experiments ranged from 1.25% to 1.46%, and these particles might result from vehicle emissions, dust re-suspensions, local burning, and construction. The understanding of dry deposition loads and size distributions would be beneficial for designing adequate control policies for road nonpoint pollution. Mahbub *et al.* [10] found that heavy metal concentrations in particulate sizes ranging from $75\text{--}300\ \mu\text{m}$ were influenced by high traffic activities, so that Ni, Cu, Pb, Cd, Cr, and Zn can be removed from the build-up control practices.

3.2. Heavy Metal Concentration of Dry Deposition Material

Ten gram samples from the seven day collections of the three road sites were randomly taken and measured using ICP to investigate the heavy metal concentrations. The results are shown in Table 3. Fe, Na, and Zn were the predominant heavy metals in the collected dust. The average Fe concentration was 34,978 ppm, and the average Na and Zn contents were approximately 1,500 ppm. According to Drapper *et al.* [5], the common sources of these road pollutants are as follows: Fe most likely results from vehicle corrosion, steel used in road construction, and car engine rust. Na results from ice-removal equipment and machine lubricants. Zn originates from wheel surface damage and machine lubricants. USEPA [12] also indicated that highway surfaces contained high levels of heavy metals, resulting primarily from wheel wear, engine and vehicle corrosion, machine lubricants, and fuel combustion. In addition to Fe, Na, and Zn, the dry deposition also contained Pb, Cu, and Ni. Notably, Ni was not present in the samples from roads A and B, and only road C, the elevated expressway,

showed any Ni in the collected dust. This may result because the road C is an elevated expressway that is subject to car speeds that are higher than the other two roads. This could result in frequent braking.

The dry deposition experiments showed that the heavy metal concentration of the settled dust is higher on the elevated expressway than on surface roads. Because the test roads are located in an urban environment, the traffic volume is high with no significant differences among the three roads. The primary difference is the speed limit, which is 70 km/h on the elevated expressway and 50 km/h on the surface roads. This might be the reason for the high heavy metal concentration on the Road C, where the Pb, Zn, Fe, and Ni concentrations were the highest.

Table 3. Heavy metal concentrations for the dry deposition experiments.

Metal Site	Pb (ppm)	Cu (ppm)	Zn (ppm)	Fe (ppm)	Na (ppm)	Ni (ppm)
Road A	72	153	845	22,000	3,507	N.D *
Road B	74	296	1,799	35,733	633	N.D
Road C	120	207	1,912	47,200	366	42
Average	89	219	1,519	34,978	1,502	14

* N.D. refers to non-detected value and the detection limit is 0.02 ppm.

3.3. Road Runoff Quality

The road surface runoff samples were collected every 5 min during a 2 h period, and 24 sample bottles were collected for one storm event. A total of four rainfall events and 96 samples were collected. For road D, two rainfall events were sampled, which were on 5 April and 17 August 2012. The April event had a total accumulative rainfall of 21.6 mm, and the rainfall duration was 10 h. For the August event, the accumulative rainfall was 12.6 mm, and the duration was 5 h. The rainfall event for road E was a relatively small storm with 8 mm accumulative rainfall and a duration of 1 h. This is a typical rainfall pattern for winter in Taipei. The event was on 18 December 2012. The rainfall event for road F occurred on 27 February 2013. The accumulative rainfall was 23 mm, and the rainfall duration was 8 h. The runoff water quality is significantly affected by storm patterns for most nonpoint source pollution. However, the studied roads are swept every day, so that it is assumed that no pollutants were previously accumulated on the road surface. Pavement properties are assumed to not change during storms, so the effect of storm variability is not considered in this study.

Table 4 displays the runoff SMC results. The average SS concentration was 360 mg/L. The second sampling of road D showed the highest SS concentration, 801.2 mg/L. This is 10 times higher than the first sampling of the same road. This high SS concentration might be related to nearby construction activity during that sampling time, thus resulting in high SS concentrations in the runoff. Regardless of the unusual disturbance, the elevated expressway, road F, showed a higher SS concentration than the other roads. This is consistent with its higher dry deposition loadings. Factors such as the total event rainfall, runoff, antecedent dry period, and daily traffic volume could affect the runoff EMC [23,24]. Among the factors, the higher traffic volume will result in a high SS concentration in the runoff [25–27]. In addition to SS, the COD concentration of road F was also the highest. However, the TP and NH₃-N concentration was the highest for road E, 0.65 mg/L and 3.24 mg/L, respectively. These results are

significantly different from those at the other sampling sites. Ideally, the nutrient concentrations should be similar for the urban road runoff because there is no obvious nutrient emission source. Source possibilities include atmospheric deposition and roadside sediment [5]. Because the sampling are for road E was the largest (Table 1), this site may collect the largest amount of dry deposition, resulting in high TP and NH₃-N in the runoff. Figure 7 shows the discharge and SS graphs for the three road sites.

Table 4. Sample mean concentration (SMC) for runoff analysis (mg/L, ppm).

Sites	D		E	F	Average
Date	2012/04/05	2012/08/17	2012/12/18	2013/02/27	
SS	73.5	801.2	148.4	416.9	360
NH ₃ -N	1.8	1.0	3.24	1.06	1.77
TP	0.15	0.26	0.65	0.35	0.35
COD	160	200	104	192	164
Oil and Grease	-	10.8	2.5	1.8	5.03
Cu	0.009	0.009	0.009	0.05	0.02
Zn	0.46	0.21	0.22	0.72	0.40
Pb	0.07	<0.05	0.14	<0.05	0.08
Cr	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	<0.0005	0.0007	<0.0005	0.0007	0.001
As	0.0036	0.0006	<0.0005	0.0005	0.001
Cd	<0.002	<0.002	<0.002	<0.002	0.002
Ni	<0.02	<0.02	<0.02	0.05	0.028

-: not test.

Figure 7. The runoff quality graphs for the road sampling sites. (a) Road D; (b) Road E; (c) Road F.

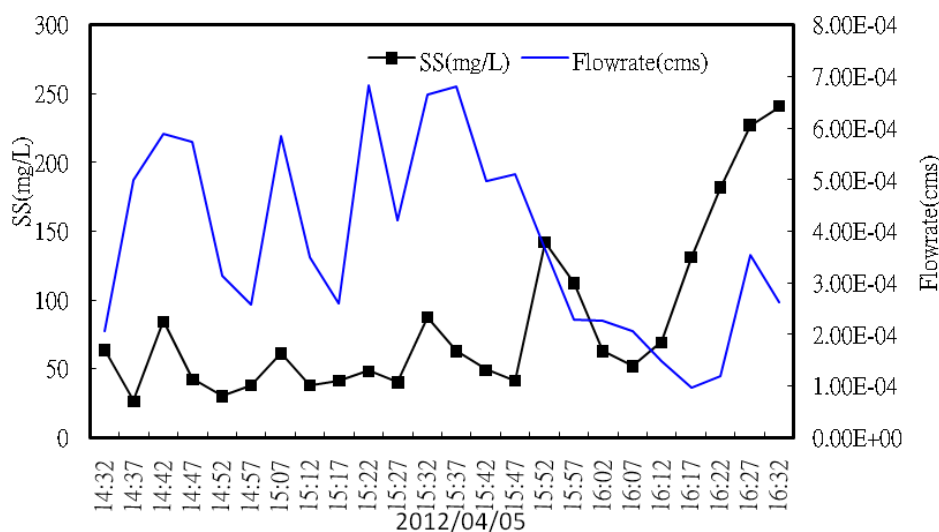
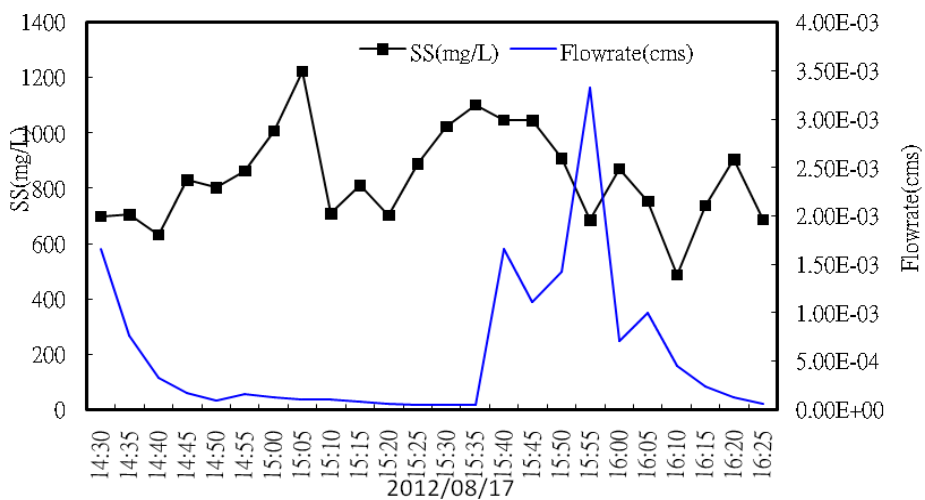
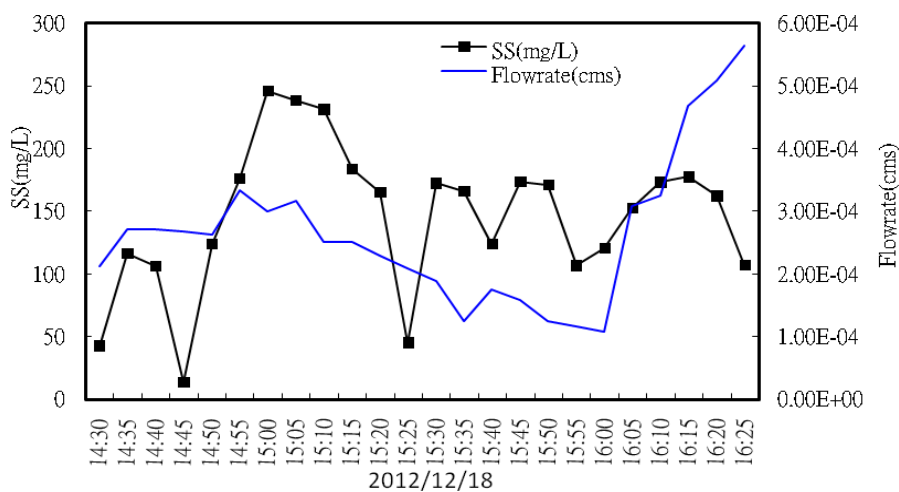


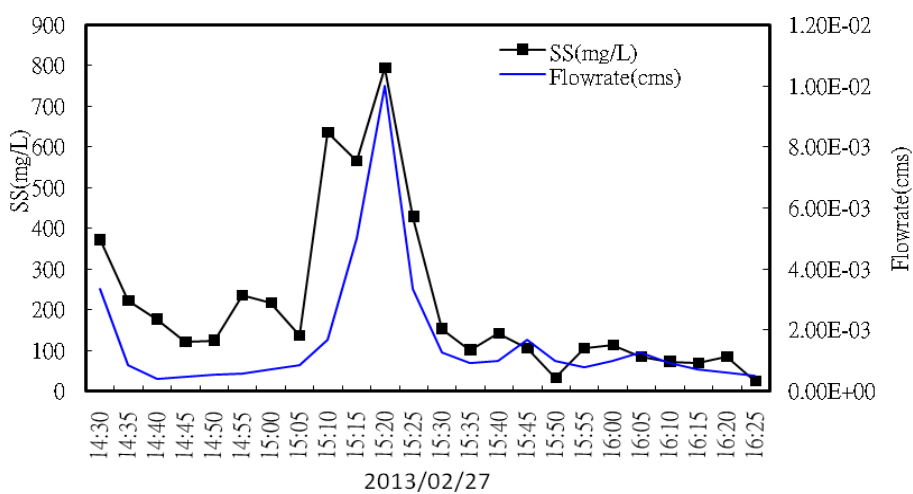
Figure 7. Cont.



(a)



(b)



(c)

The results for the heavy metal analysis of the runoff showed that the Pb, Zn, and Cu concentrations were higher than those of the other metals. The average concentrations of Pb, Zn, and Cu were 0.08, 0.40 and 0.02 ppm, respectively. The Ni concentration was under the detection limit, <0.02 ppm; however, the road F runoff contained 0.05 ppm Ni. This is consistent with the dry deposition results, in which only the collected dry deposition samples of the elevated express road contained Ni. Basically, the heavy metal concentration in runoff agreed with the dry deposition analysis results. High metal deposition results in high metal concentrations in the runoff, so that the Pb, Zn, and Cu contents are higher than those for other metals. Unfortunately, the Fe and Na levels in the runoff samples were not examined. High Fe and Na concentrations would have been expected in the runoffs well. The Cr and Cd concentrations were below the detection limits in all runoff samples. Barbosa and Hvitved-Jacobsen [28] reported similar results in that the Cr and Cd concentrations are low in road runoff and are not a threat to biological systems. The average oil and grease concentration was 5.03 mg/L, with the highest concentration of 10.8 mg/L for road D. Berman *et al.* [29] stated that surface oils result from street vehicles, car engine leakage in parking lots, and oil leakage at gas stations and restaurants. The leaked grease consists of nitrides and hydrides and is toxic to aquatic habitats [30], thus contaminated urban road runoff must be treated before flowing to the receiving water bodies.

3.4. Comparison of This Study to International Experiences

Comparing the runoff quality results of this study with international studies, the SS, COD, and NH₃-N are higher in Taipei than in other countries (Table 5).

Table 5. Comparison of international road runoff quality and the results from this study (mg/L, ppm).

Reference	Legret and Pagotto [31]	Huang, C.C. [1]	Kayhanian <i>et al.</i> [24,32]		Kim <i>et al.</i> [33]	Flint and Davis [34]	This study (2012–2013)
Site	Nantes, France	Tainan Taiwan	California, USA	California, USA	Korea	Maryland, USA	Taipei, Taiwan
ADT	12,000	10,000	-	-	-	-	42,738–82,625
SS	77	59	148.1	112.7	155	420	360
COD	-	70	123.8	-	43	-	164
NH ₃ -N	-	1.6	1.1	1.07	1.66	1	1.78
TP	-	2.47	0.3	0.29	0.22	0.56	0.35
Cu	0.045	0.05	0.051	0.015	-	0.11	0.019
Zn	0.356	0.06	0.203	0.069	-	1.18	0.402
Pb	0.058	-	0.080	0.008	-	0.22	0.078
Cr	-	-	-	-	-	-	0.020
Hg	-	-	-	-	-	-	0.001
As	-	-	-	-	-	-	0.001
Cd	0.001	-	0.001	0.002	-	0.035	0.002
Ni	-	-	-	-	-	-	0.028

This could be caused by the higher number of vehicles and nearby construction activities. Because of the high SS, high COD and NH₃-N values will result. The TP concentration, 0.35 mg/L, fell in the reference range, implying that the urban road is not the main nonpoint source for phosphorus. In regards to heavy metal concentrations, the Cu, Pb, and Zn concentrations in this study were within the reference ranges, but Cr, Hg, As, and Ni was not detected in the references and cannot be compared.

Kayhanian *et al.* [11] found exponentially decreased Pb concentrations in highway runoff, attributed to the lead-free gasoline policy. The average Cd concentration, 0.002 mg/L, was lower than in previous studies. It should be noted that the even Pb and Zn concentration was within reference ranges, they are higher than the others, except for the study of Flint and Davis [34] in the US. These high concentrations should be related to the high vehicle volume for the studied roads. The results confirm the need of pollution control in crowded urban roads.

4. Conclusions

As a city with one of the highest population densities in the World, the roads in Taipei City and New Taipei City have high traffic volumes. The dry deposition and runoff quality of the urban roads must be monitored and understood to avoid potential urban nonpoint pollution. We collected a total of 19 samples from three roads for dry deposition analysis and the total of 96 samples from four rainfall events to determine the road runoff quality. Heavy metal concentration of deposited sediment and runoff was analyzed for composite samples. The effect of storm variability is not considered in this study because that daily street-sweeping results in no differences in road prior conditions and the four events are not sufficient to assess inter-storm effects. The dry deposition analysis shows that 2.01–5.14 g/m² of solids remain on the road each day and that 78–87% of these solids are distributed in the 75–300 µm size range. The PM₁₀ accounted for 1.25–1.46% of the particles. When determining the characteristics of the deposited solids, we found that the Fe, Zn, and Na concentrations were high, and the highest concentrations were found at an elevated expressway site. Only the samples from the elevated expressway contained Ni, implying that the deposited solids from the roads with high car speeds might contain more residues from vehicle body corrosion, engine corrosion, or wheel wear, thus resulting in high metal concentrations. Identical results were found in the runoff quality analysis, as the SS and COD from the elevated express road runoff were higher than those from the other roads. In addition to the vehicle numbers, car speeds should be considered to be one of the factors influencing urban road pollution, which is mentioned infrequently in previous studies.

Comparing these study results with previous reports, the runoff SS, COD, and NH₃-N concentration in the studied roads in Taipei were higher than those for other countries. This might be because the volume of vehicles on the studied roads was higher. Pb, Zn, and Cu were the predominant metals in the urban road runoff in Taipei and sites in other countries. The results of this study confirmed that even after implementing daily street-sweeping, the fine dry deposition contains pollutants that might be released as nonpoint source pollution. In summary, the SS, COD, NH₃-N, Pb, Zn, and Cu in road runoff were at levels sufficient to cause concern. At high pollution sites, regular sweeping and best management practices (BMP) are necessary.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Huang, C.C. *A Study on the Characterization and Control of Highway Runoff Pollution*; National Science Council: Taipei, Taiwan, 2003 (in Chinese).
2. Sutherland, R.A. Lead in grain size fractions of road-deposited sediment. *Environ. Pollut.* **2003**, *121*, 229–237.
3. Zhao, H.; Yin, C.; Chen, M.; Wang, W. Runoff pollution impacts of polycyclic aromatic hydrocarbons in street dusts from a stream network town. *Water Sci. Technol.* **2008**, *58*, 2069–2076.
4. Zhao, H.; Li, X.; Wang, X.; Tian, D. Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. *J. Hazard. Mater.* **2010**, *183*, 203–210.
5. Drapper, D.; Tomlinson, R.; Williams, P. Pollutant concentrations in road runoff: Southeast Queensland case study. *J. Environ. Eng.* **2000**, *126*, 313–320.
6. Lu, C.J.; Chih, Y.C. *Nonpoint Source Pollution and Urban Water Management*. Hsiao Yuan Publication: Taipei, Taiwan, 2000 (translated form).
7. Zhao, H.; Li, X.; Wang, X. Heavy metal contents of road-deposited sediment along the urban-rural gradient around Beijing and its potential contribution to runoff pollution. *Environ. Sci. Technol.* **2011**, *45*, 7120–7127.
8. Chang, G.C.; Parrish, J.H.; Souer, C. *The First Flush of Runoff and Its Effect on Control Structure Design*; Environmental and Conservation Services: Austin, TX, USA, 1990.
9. Sartor, J.D.; Boyd, G.B.; Agardy, F.J. Water pollution aspects of street surface contaminants. *J. Water Pollut. Control Fed.* **1974**, *46*, 458–467.
10. Mahbub, P.; Ayoko, G.A.; Goonetilleke, A.; Egodawatta, P.; Kokot, S. Impacts of traffic and rainfall characteristics on heavy metals build-up and wash-off from urban roads. *Environ. Sci. Technol.* **2010**, *44*, 8904–8910.
11. Kayhanian, M.; Fruchtman, B.D.; Gulliver, J.S.; Montanaro, C.; Ranieri, E.; Wuertz, S. Review of highway runoff characteristics: Comparative analysis and universal implications. *Water Res.* **2012**, *46*, 6609–6624.
12. USEPA. Controlling Nonpoint Source Runoff Pollution from Roads, Highways and Bridges. Available online: <http://www.epa.gov/owow/nps/roads.html> (accessed on 12 October 2013).
13. Lindgren, A. Road Construction Materials as a Source of Pollutants. Doctoral Thesis, Luleå University of Technology, Luleå, Sweden, 1998.
14. Hääl, M.L.; Sürje, P.; Rõuk, H. Traffic as a source of pollution. *Estonian J. Eng.* **2008**, *14*, 65–82.
15. Dorchin, A.; Shanas, U. Assessment of pollution in road runoff using a *Bufo viridis* biological assay. *Environ. Pollut.* **2010**, *158*, 3626–3633.
16. Kim, L.H.; Kayhanian, M.; Zoh, K.D.; Stenstrom, M.K. Modeling of highway stormwater runoff. *Sci. Total Environ.* **2005**, *348*, 1–18.
17. Zhao, H.; Li, X. Understanding the relationship between heavy metals in road-deposited sediments and washoff particles in urban stormwater using simulated rainfall. *J. Hazard. Mater.* **2013**, *246–247*, 267–276.
18. Teng, Y.C. A Study of Nonpoint Source Pollution Unit Areal Loadings for Highway Runoff. Master thesis, National Taiwan University, Taipei, Taiwan, 2010 (in Chinese).

19. Monitoring Items and Methods—Environmental Water Quality Information. Available online: <http://wq.epa.gov.tw/WQEPA/Code/Business/ItemMethod.aspx> (accessed on 12 October 2013).
20. Kim, D.G.; Jeong, K.; Ko, S.O. Evaluation of Road Sweeping For the Reduction of Nonpoint Source Pollutants Load from Highway Runoff, The 4th IWA-ASPIRE Conference & Exhibition, Tokyo, Japan, 2–6 October 2011.
21. Chang, Y.M.; Chou, C.M.; Su, K.T.; Tseng, C.H. Effectiveness of street sweeping and washing for controlling ambient TSP. *Atmos. Environ.* **2005**, *39*, 1891–1902.
22. Calabrò, P.S. Impact of mechanical street cleaning and rainfall events on the quantity and heavy metals load of street sediments. *Environ. Technol.* **2010**, *31*, 1255–1262.
23. Deletic, A.B.; Maksimovic, C.T. Evaluation of water quality factors in storm runoff from paved areas. *J. Environ. Eng.* **1998**, *124*, 869–879.
24. Kayhanian, M.; Suverkropp, C.; Ruby, A.; Tsay, K. Characterization and prediction of highway runoff constituent event mean concentration. *J. Environ. Eng.* **2007**, *85*, 279–295.
25. Driscoll, E.D.; Shelly, P.E.; Strecker, E.W. *Pollutant Loadings and Impacts from Stormwater Runoff*; Federal Highway Administration: Washington, DC, USA, 1990; Volume III.
26. Barrett, M.E.; Malina, J.F.; Charbeneau, R.J.; Ward, G.H. *Characterization of Highway Runoff in the Austin, Texas Area*; University of Texas: Austin, TX, USA, 1995.
27. Wu, J.S.; Allan, C.J.; Saunders, W.L.; Evett, J.B. Characterization and pollutant loading estimation for urban and rural highway runoff. *J. Environ. Eng.* **1998**, *124*, 584–592.
28. Barbosa, A.E.; Hvitved-Jacobsen, T. Highway runoff and potential for removal of heavy metals in an infiltration pond in Portugal. *Sci. Total Environ.* **1999**, *235*, 151–159.
29. Berman, L.; Hartline, C.; Ryan, N.; Thorne, J. *Urban Runoff: Water Quality Solutions*; American Public Works Association: Washington, DC, USA, 1991.
30. Driscoll, E.D.; Palhegyi, G.E.; Strecher, E.W.; Shelley, P.E. *Analysis of Storm Event Characteristics for Selected Rainfall Gages throughout the United States*; Woodward-Clyde Consultants: Oakland, California, USA, 1989.
31. Legret, M.; Pagotto, C. Evaluation of pollutant loadings in the runoff waters from a major rural highway. *Sci. Total Environ.* **1999**, *235*, 143–150.
32. Kayhanian, M.; Singh, A.; Suverkropp, C.; Borroum, S. Impact of annual average daily traffic on highway runoff pollutant concentrations. *J. Environ. Eng.* **2003**, *129*, 975–990.
33. Kim, L.H.; Ko, S.O.; Jeong, S.; Yoon, J. Characteristics of washed-off pollutants and dynamic EMCs in parking lots and bridges during a storm. *Sci. Total Environ.* **2007**, *376*, 178–184.
34. Flint, K.R.; Davis, A.P. Pollutant mass flushing characterization of highway stormwater runoff from an Ultra-Urban area. *J. Environ. Eng.* **2007**, *133*, 616–626.