Is the wash-off process of road-deposited sediment source limited or transport limited?

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HIGHLIGHTS

- Road-deposited sediment wash-off was explored by field and simulated experiments.
- Wash-off of finer and coarser particles tends to be source and transport limited.
- Smaller and larger rain events tend to be source and transport limited.
- The wash-off process is generally source and transport limited.

GRAPHICAL ABSTRACT

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ABSTRACT

An in-depth understanding of the road-deposited sediments (RDS) wash-off process is essential to estimation of urban surface runoff pollution load and to designing methods to minimize the adverse impacts on the receiving waters. There are two debatable RDS wash-off views: source limited and transport limited. The RDS build-up and wash-off process was characterized to explore what determines the wash-off process to be source limited or transport limited based on twelve RDS sampling activities on an urban road in Beijing. The results showed that two natural rain events (2.0 mm and 23.2 mm) reduced the total RDS mass by 30%–40%, and that finer particles ($<105\ \mu\text{m}$) contributed 60%–80% of the wash-off load. Both single- and multi-rain events caused the RDS particle grain size to become coarser, while dry days made the RDS particle grain size finer. These findings indicated that the bulk RDS particles wash-off tends to be transport limited, but that finer particles tend to be source limited. To further explore and confirm the results of the field experiment, a total of 40 simulated rain events were designed to observe the RDS wash-off with different particle size fractions. The finer particles have a higher wash-off percentage (F_w) than the coarser particles, and the F_w values provide a good view to characterize the wash-off process. The key conclusions drawn from the combined field and simulated experiments data are: (i) Finer and coarser particle wash-off processes tend to be source limited and transport limited, respectively. (ii) The source and transport limited processes occur during the initial period (the first flush) and later periods, respectively. (iii)

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The smaller and larger rain events tend to be transport limited and source limited, respectively. Overall, the wash-off process is generally a combination of source and transport limited processes.

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1. Introduction

Road-deposited sediments (RDS) are ubiquitous and important carriers of diffuse urban pollutants (Sansalone et al., 1998; Sartor and Boyd, 1972; Sutherland, 2003). With the rapid urbanization and industrialization that has occurred in China and other developing countries, urban diffuse pollution caused by RDS wash-off has been recognized a major problem in urban areas (Li et al., 2013; Lu et al., 2009; Zhao et al., 2011). Therefore, it is important to have a clear understanding of the process of urban diffuse pollution resulting from RDS so that it can be effectively controlled.

The generation of urban diffuse pollution (stormwater pollution) is usually divided into a two-stage process, RDS build-up over dry days and RDS wash-off during rainfall events (Goonetilleke et al., 2009; Vaze and Chiew, 2002). The build-up process is very important for characterizing pollutant accumulation on urban impervious surfaces (Miguntanna et al., 2013). However, only limited actual direct measurements of RDS build-up are available, and it has instead been inferred from the measurements of RDS wash-off (Pitt et al., 2004; Shaw et al., 2006; Vaze and Chiew, 2002). In recent years, a few studies have revealed that RDS build-up is influenced by antecedent dry periods, rainfall events and street sweeping (Deletic and Orr, 2005; Egodawatta et al., 2013; Shen et al., 2016; Tian et al., 2009).

It is well known that the wash-off process is influenced by many factors, including rainfall characteristics, surface characteristics, particle grain size of RDS, land use, urban–rural gradients, etc. (Brodie and Rosewell, 2007; Mahbub et al., 2010; Vaze and Chiew, 2003; Zhao et al., 2011). However, there is still no consensus on whether wash-off is source limited or transport limited. The decisive factors influencing

whether wash-off is source or transport limited are RDS load and wash-off capacity, respectively. Some studies support the view that wash-off is transport limited and common storms only remove a small proportion of the total RDS, after which build-up occurs relatively quickly to return the surface pollutant load back to the level before the storm (Vaze and Chiew, 2002; Zhao et al., 2010). On the other hand, most event water quality models adopt the view of source limited, assuming that most RDS is washed off during storm events and RDS then builds-up from zero over the antecedent dry days (Sheng et al., 2008; SWMM, 2010). These contradictory views highlight the fact that the complexity of wash-off processes is far greater than what process replication equations in current stormwater quality models actually consider, although RDS wash-off is the most important processes in stormwater quality modeling. Thus, further investigations are warranted.

In this study, field and simulated experiments were conducted to explore (i) the roles of particle size and rainfall characteristics in the RDS wash-off process and (ii) to identify factors determining whether the RDS wash-off process is source limited or transport limited.

2. Materials and methods

2.1. Study site description

The study site was located on an urban road surface in the Haidian District of Beijing, China (Fig. 1), which is located in the northwest portion of the city. This street had two lanes for traffic (one lane in each direction), and the average traffic flow for each lane was about 3550 cars/day according to our field investigation. Both sides of the street

Fig. 1. Study area and sampling site locations in Haidian District, Beijing, China. **a** indicates the administrative region of Beijing, **b** indicates the administrative region of Haidian District, and **c** is the study area and locations of sampling sites and weather stations.

Table 1
Rainfall parameters for storm events in 2012.

Date of rain event	Rainfall (mm)	Average intensity (mm/h)	Duration (min)	Maximum intensity (10 min rainfall/mm)	Antecedent dry weather period (day)
2012-3-17	8.6	1.61	320	0.6	2
2012-3-18	2.8	3.36	50	1.9	1
2012-4-10	2	1.71	70	1.1	23
2012-4-18	4.9	3.27	90	2.3	8
2012-4-20	6.4	1.2	320	1.3	2
2012-4-24	23.2	2.78	500	2.1	4
2012-5-11	2.7	0.74	220	0.2	17
2012-5-19	9.9	2.2	270	1.6	8
2012-5-31	2.5	1.5	100	0.5	12
2012-6-1	2.9	2.9	60	1.9	1
2012-6-3	2.7	1.8	90	0.6	2
2012-6-19	3	3.6	50	2.1	16
2012-6-21	3.2	1.6	120	0.4	2
2012-6-24	63.6	7.07	540	9.2	3
2012-6-26	9.6	3.6	160	2.7	2
2012-6-28	17.9	1.51	740	1.1	2
2012-7-5	9.5	6.33	90	3.9	7
2012-7-7	3.2	2.13	90	1	2
2012-7-9	59.9	11.98	300	8.7	2
2012-7-10	20.3	20.3	60	14.5	1
2012-7-12	3.6	10.8	20	2.6	2
2012-7-21	198.3	13.07	910	13	9
2012-7-25	5.2	15.6	20	3.2	4
2012-7-27	23.3	8.74	160	7.1	2
2012-7-30	61.7	1.92	1930	4.1	3
2012-8-11	22.8	2.49	550	1.5	12
2012-8-12	2.7	2.03	80	1.6	1
2012-8-27	4.1	3.08	80	1.3	15
2012-9-1	52.4	3.93	800	1.8	5
2012-9-6	8.2	1.26	390	1	5
2012-9-11	16	24	40	7	5
2012-9-25	6.3	1.11	340	0.8	14
2012-10-9	2.2	1.32	100	0.5	14
2012-10-16	4.3	1.08	240	0.5	7
2012-10-21	10.8	1.75	370	0.9	5
2012-11-3	63.9	2.49	1540	1.7	13
2012-11-10	7.5	1.41	320	0.5	7
2012-11-15	5.5	1.22	270	0.6	5
2012-12-14	6.2	0.83	450	0.3	29

were fully developed with buildings, and practically all of the surrounding areas were made up of impervious concrete and asphalt surfaces.

Based on our on-site investigation, we assumed the street was rarely swept and the source of RDS primarily varied with the antecedent dry period, rainfall and runoff parameters. Furthermore, the rain flow conditions on this street were relatively simple and meteorological data including rainfall intensity, rainfall duration, temperature, wind direction and speed were obtained from a nearby weather station maintained by the Beijing Urban Ecosystem Research Station (Fig. 1

Table 3
Rainfall intensities, rainfall durations and particle size fraction of RDS in the simulated wash-off experiment.

Factors	Parameters
Levels of rainfall intensity	15.18, 29.99, 40.78, 58.86, 90.00 mm/h
Particle size fraction of RDS	<44, 44–62, 62–105, 105–149, 149–250, 250–450, 450–1000 μm
Sampling interval ^a	0–2, 2–4, 4–6, 6–8, 8–10, 10–15, 15–20, 20–30, 30–40, 40–50, 50–60, 60–80, 80–100, 100–120 min

and Table 1). Additionally, the street is located in our work place, which facilitated our field observations of RDS build-up and wash-off.

2.2. RDS sample collection and grain size fraction

RDS samples were collected from the fixed site (a fixed area of 8.75 m²) and vacuumed from the central road marking to the curb using a domestic vacuum cleaner (Philips FC8264). This vacuum cleaner had high efficiency, with an air filtration system and a cyclonic dustbin that effectively captures microscopic particulates. All RDS samples were dried at room temperature for 7 days, then weighed using an electronic scale. Samples were subsequently sorted into particle size fractions of <44, 44–62, 62–105, 105–149, 149–250, 250–450, 450–1000 and >1000 μm using polyester sieves.

2.3. Field observation of RDS build-up and RDS wash-off

There were 12 RDS sampling activities conducted from April to December in 2012 (Table 2). The goals of these sampling activities were to determine how the factors (rainfall events, dry weather period, and rainy season) affect RDS amount and grain size composition.

2.3.1. Effect of rainfall events

To compare variations in the amount and grain size composition before and after rainfall events, RDS sampling was carried 1 day before and 1 day after a small rain event (2 mm; 10 April 2012) and a moderate rain event (23.2 mm; 24 April 2012). Because RDS build-up over the dry days occurs relatively quickly after a rain event (Vaze and Chiew, 2002), 1 day before and after the event is the best time to collect the RDS sample to determine the effects of individual rainfall events on the RDS amount and grain size composition.

2.3.2. Effect of dry days

To compare the amount and grain size composition during the rainy season and dry season, eight additional RDS collections were carried out. Because RDS build-up over the dry days occurs relatively quickly after a rain event (Vaze and Chiew, 2002), we selected 2 days after rainfall events to observe the RDS build-up process. Although some

Table 2
RDS mass per unit area with different grain size fractions in 2012.

Date of RDS sampling	RDS mass per unit area with different rain size (unit: grain size, μm ; mass per unit area, g/m ²)							
	<44	44–62	62–105	105–149	149–250	250–450	450–1000	<1000
2012-4-9	1.12	3.52	1.93	0.53	1.55	2.37	2.28	13.31
2012-4-11	0.37	1.24	1.74	0.39	1.21	2.25	2.14	9.35
2012-4-23	0.88	2.46	3.66	0.73	1.66	1.48	1.23	12.11
2012-4-25	0.11	1.54	2.30	0.46	0.90	1.16	0.81	7.27
2012-5-21	1.23	2.66	2.67	0.62	1.30	1.11	0.69	10.27
2012-5-28	0.26	1.22	7.82	1.02	2.21	2.11	0.71	15.35
2012-7-13	0.57	1.62	4.46	0.63	2.64	2.02	0.66	12.60
2012-8-5	0.88	1.62	3.11	0.73	2.56	2.37	1.17	12.43
2012-9-27	0.88	1.54	4.13	0.85	2.01	1.54	0.65	11.59
2012-10-30	0.32	3.03	7.94	0.90	2.13	1.69	0.54	16.56
2012-11-17	0.32	1.60	16.18	1.62	5.01	3.37	1.27	29.37
2012-12-4	0.32	2.32	23.50	1.68	2.96	2.92	0.86	34.55

Fig. 2. Variations in RDS amount one day before and after rain events.

important studies indicate that the RDS build-up reaches its equilibrium at around 7–9 days (Goonetilleke et al., 2009; Pitt et al., 2004), we think that the earlier observation date of RDS build-up will not affect the purpose of this study.

2.4. Rainfall simulation experiment of RDS wash-off

To better reveal the behavior of RDS wash-off with different grain size fractions, a total of 40 different rainfall events were carried out with five rainfall intensities (15.18, 29.99, 40.78, 58.86, 90.00 mm/h) in July 2012 (Table 3). Many important factors have been shown to influence RDS wash-off. In this simulated experiment, we focused on the rainfall intensity and duration. The rainfall simulation device consisted of two rainfall simulators. The four nozzles (Veejet 80100) of the two rainfall simulators were equally distributed (with an interval of 1.1 m) along the swing nozzle boom, which stood at 2.5 m above the ground. The nozzles generated uniform raindrops with medium sizes at a constant pressure of 0.04 Mpa. The two rainfall simulators generated a total uniform rainfall area of 1.5 m × 2.2 m. We selected an area of 1.5 m × 2.0 m as our wash-off test plot. A 1.5 m × 2.0 m plastic frame was used to demarcate the plot boundary, which was sealed with a paved surface. One end of the plastic frame was kept open to affix the catch tray used for runoff collection. Further details regarding the experimental design can be found in our

previous study (Zhao et al., 2011). The road selected for the RDS wash-off experimental plot was paved with asphalt 5 years prior to the experiment. The wash-off duration was 120 min, during which time the runoff samples were collected manually at 2-min intervals in the first 10 min, 5-min intervals during the second and third 10 min, 10-min intervals during the fourth–seventh 10 min, and 20-min intervals thereafter until there was no more surface runoff.

2.5. Analytical method

Runoff water samples in the simulation experiment of RDS wash-off were filtered through pre-weighed 0.45 μm millipore filter paper and solid particles remaining in the filter paper were then dried and re-weighed to quantify the total suspended solids (TSS) (APHA, 1999).

The wash-off percentage (F_w , %) of RDS on each grain size fraction was expressed as a percentage of the total RDS mass in the runoff with respect to the initial total mass of RDS on the surface. This was calculated by the following equation (Zhao et al., 2011):

$$F_w(\%) = \frac{M_{Fw}}{M_{initial}} \times 100\% = \frac{\int_0^1 C(t) \times Q(t) dt}{M_{initial}} \times 100\% \quad (1)$$

Table 4

Road-deposited sediment grain size composition one day before and after rainfall events.

Date of rainfall events ^a	Grain size composition of RDS (unit: grain size, μm; grain size composition, %)						
	<44	44–62	62–105	105–149	149–250	250–450	450–1000
9 April 2012 ^a	8.42	26.44	14.50	4.02	11.67	17.84	17.11
10 April 2012	4.00	13.24	18.65	4.18	12.94	24.05	22.94
23 April 2012 ^b	7.29	20.30	30.24	6.02	13.74	12.24	10.18
25 April 2012	1.48	21.13	31.61	6.34	12.33	15.93	11.19

^a 10 April 2012 rain event, rainfall 2.0 mm, rainfall duration 70 min, rainfall intensity 1.71 mm/h, maximum rainfall intensity 10.26 mm/10 min.

^b 24 April 2012 rain event, rainfall 23.2 mm, rainfall duration 500 min, rainfall intensity 2.78 mm/h, maximum rainfall intensity 16.68 mm/10 min.

Fig. 3. Variations in RDS amount over dry days.

where, M_{Fw} is the mass of the size fraction washed off the surface over the entire rain event (mg); $M_{initial}$ is the initial mass of RDS with a corresponding particle size on the surface (mg); $C(t)$ is the mass of RDS with a corresponding particle size in the surface runoff water (mg/L) at each sampling time; and $Q(t)$ is the surface runoff flow rate at each sampling time (m^3/min).

Similar to F_w , the accumulation rate (F_a , %) of RDS on each grain size fraction was expressed as a percentage of the increased mass over dry days with respect to the initial total mass of RDS. This was calculated by the following equation:

$$F_a(\%) = \frac{M_{increased}}{M_{initial}} \times 100\% = \frac{M_{build-up} - M_{initial}}{M_{initial}} \times 100\% \quad (2)$$

where, $M_{build-up}$ is the mass of the size fraction build-up until a RDS sampling is carried out (mg); and $M_{initial}$ has the same meaning as in Eq. (1).

3. Results

3.1. Effects of rainfall events on RDS amount and grain size composition

The variations in RDS amount one day before and after two natural rainfall events were observed (Fig. 2). Both the small rain event

(2 mm, 10 April) and the moderate rain event (23.2 mm; 24 April) reduced the total mass significantly by 4.0 g/m^2 (from 13.3 to 9.3 g/m^2) and 4.8 g/m^2 (from 12.1 to 7.3 g/m^2), respectively. The bulk RDS wash-off percentages (F_w , %) were 30% and 40% during the small and middle rain events, and increased as the amount and intensity of rainfall increased.

The effects of rainfall and rainfall intensity on F_w values with different grain size fractions were obviously different. The finer particles (<105 μm) contributed 80% and 64% of the wash-off load of the bulk RDS over the small and moderate rain events, respectively. When compared to the small rain event, the F_w values of the coarser particles (250–450 μm , 450–1000 μm) were relatively larger over the moderate rain event, while those of the finer particles showed a smaller increase, or even a decrease. These results suggest that the finer RDS particles (< approximately 100 μm) could be washed off sufficiently by the two rain events, while the coarser RDS particles (> about 150 μm) could not. Many previous studies also indirectly confirmed that suspended particles washed off from the road surface during natural rainfall events were dominated by particles of <100 μm (Brodie and Dunn, 2009; Charters et al., 2015). Our results indicate that the wash-off process of the finer and the coarser particles tended to be source and transport limited, respectively. Generally, the wash-off process tended to be transport limited.

Table 5
Road-deposited sediment grain size composition over dry days.

Dry weather period		Grain size composition of RDS (unit: grain size, μm ; grain size composition, %)						
		<44	44–62	62–105	105–149	149–250	250–450	450–1000
7 dry days	2012-5-21	12.0	25.9	26.0	6.0	12.7	10.8	6.7
	2012-5-28	1.7	8.0	50.9	6.7	14.4	13.7	4.6
17 dry days	2012-11-17	1.1	5.4	55.1	5.5	17.1	11.5	4.3
	2012-12-4	0.9	6.7	68.0	4.9	8.6	8.4	2.5

Fig. 4. Variations in RDS amount during rainy season. a and c are the proportion of RDS mass on the road one day before and after a rainfall event.

The rainfall events also impact variations of RDS grain size composition (Table 4). Specifically, the RDS grain size composition became coarser after both natural rain events. A possible explanation for this is that selective wash-off of RDS particles occurred and finer particles have higher F_w values than coarser particles. Our results indicate that common rain events only removed a small proportion of the coarser particles, but could remove a large proportion of the finer particles.

3.2. Effects of dry weather periods on RDS amount and grain size composition

Variations in RDS amount and grain size composition during two dry weather periods are shown in Fig. 3. Two rain events (19 May, 9.0 mm; 15 November, 5.5 mm) occurred two days before the start of the observation of RDS build-up during the dry weather periods. Both short-term (7 days, during summer) and long-term (17 days, during winter) dry days increased the total mass significantly (by 5.08 and 5.18 g/m², respectively), while the RDS accumulation rate (F_a , %; 50% and 16%, respectively) was not proportional to the time span of dry weather. The F_a values with different grain size fractions differed. Over the dry days during summer, there were no obvious variations in grain size composition, and finer particles (<105 μm) accounted for 63.8% of the total on 21 May and 61.6% on 28 May (Table 5). Conversely, the finer particles (<105 μm) increased from 61.6% on 17 November to 75.0%

on 4 December over dry days during winter. Generally, dry days would increase the amount of RDS build-up on urban road surfaces. Although more data are needed to verify the effects of dry weather periods on grain size composition, the build-up process was not from zero over antecedent dry days, which indirectly indicates that the wash-off process is transport limited.

3.3. Effects of rainy season on RDS amount and grain size composition

To investigate the effects of multi-rain events on RDS build-up and wash-off, eight RDS sampling activities were conducted from April to December in 2012, during which time there were about 40 rain events and 760 mm of rainfall. The variation in RDS amount and grain size composition over the rainy season is shown in Fig. 4. The RDS amount increased as rain events decreased from April to December. The RDS mass per unit area was about 12 g/m² over the rainy season (from April to October), indicating that the RDS load remained largely the same throughout the rainy season. Conversely, it reached about 30 g/m² over the dry season (November and December). Additionally, as rain events decreased, the RDS grain size composition became finer. Overall, the multi-rainfall events could only remove a small proportion of RDS load, and the build-up process is not from zero over the antecedent dry days. Obviously, the wash-off process is transport limited.

Fig. 5. Effects of rainfall intensity and duration on RDS wash-off percentage of each grain size fraction using simulated rainfall.

4. Discussion

4.1. Effects of particle grain size on RDS wash-off process

Understanding the RDS wash-off process is essential to runoff water quality estimation and the development of pollution control strategies from RDS wash-off. Previous studies suggested that a range of parameters such as urban road surface characteristics, land use, rainfall characteristics, particle size and street sweeping have important effects on RDS wash-off processes (Liu et al., 2014; Miguntanna et al., 2013; Sheng et al., 2008; Vaze and Chiew, 2002). Vaze and Chiew (2002) found that the wash-off process of a typical rainfall event could only remove a small proportion of total RDS and tended to be transport limited. Miguntanna et al. (2013) found that nitrogen wash-off was a source limited process, while phosphorus wash-off was transport limited. Liu et al. (2014) suggested that wash-off processes on asphalt and concrete surfaces tended to be source and transport limited, respectively. However, it was still unclear how particle size influenced the wash-off process and whether it is source or transport limited. Many previous studies demonstrated that finer particles ($<100\ \mu\text{m}$) account for 70% of the suspended solids in most rain events (Kim and Sansalone, 2008; Roger et al., 1998; Zhao et al., 2010). In this study, we found that wash-off of finer and coarser particles tended to be source and transport limited, respectively, based on the effects of rainfall events on RDS amount and grain size composition. In this context, a total of 40 simulated rain events were designed to explore the role of particle size in determining whether processes were source or transport limited.

As shown in Fig. 5, there were notable differences in RDS wash-off processes with different rainfall characteristics. The F_w values vary with the particle size of RDS, with smaller particle sizes being associated with higher values of F_w . Additionally, RDS wash-off with different grain sizes using simulated rain provides valuable data regarding this process. Furthermore, the F_w values of each grain size fraction may be a direct reflection of their being source or transport limited. Therefore, the finer particle ($<105\ \mu\text{m}$) wash-off tends to be source limited, while the coarser particle ($>105\ \mu\text{m}$) wash-off tends to be transport limited.

These findings will facilitate selection of appropriate treatment systems for sediment removal because the performance of each treatment method strongly depends on particle size, associated settling velocity, and hydraulic retention time (Charters et al., 2015; Li et al., 2008; Selbig and Bannerman, 2012).

4.2. Effects of rainfall characteristics on the RDS wash-off process

It is well known that the entire process of RDS wash-off varies with rainfall duration and intensity. During the initial period of RDS wash-off, during which the concentration of pollutants is substantially higher than later periods, a phenomenon known as the first flush commonly occurs (Deletic, 1998; Lee et al., 2002; Li et al., 2007; Sansalone and Buchberger, 1997). However, it is still not clear how rainfall intensity and duration influence whether the wash-off process is source or transport limited.

Fig. 6. Effects of rainfall intensity and duration on suspended solid concentrations of each RDS grain size using simulated rainfall.

In this study, a total of 40 simulated rain events were designed to explore RDS wash-off characteristics during different wash-off periods. As shown in Fig. 6, the suspended solids (SS) of each particle size fraction in surface runoff water were higher during initial periods than later periods, indicating that the first flush phenomenon was occurring. Furthermore, the magnitude of the first flush phenomenon became greater for finer particle sizes and higher rain intensity. The first flush load is primarily influenced by the initial finer RDS particles and hence could be a source limited process. Therefore, common rain events could be transport limited because of the occurrence of first flush, suggesting that common rain events only removed a small proportion of the total RDS. Based on this finding, the entire wash-off process during a typical rainfall event could be divided into two processes, a source limited wash-off during the initial period (the first flush) and a transport limited process during later periods. On the other hand, smaller and larger rain events tended to be transport and source limited, respectively. The higher intensity in the larger rain events has greater transport capacity; therefore, most of the finer particles and some coarser particles are removed (Fig. 6).

Further work will be needed to identify differences in the RDS wash-off process between rainfall simulations (under idealized conditions) and natural rainfall events. For example, there was not enough data to relate the intensity to transport capacity or detachment from the impervious surface. In this study, we assumed that the RDS wash-off process occurred mainly via transport, and the detachment process could be ignored based on our field site investigation.

5. Conclusions

Based on field observations, two natural rain events (2.0 mm and 23.2 mm) reduced the total RDS mass by 30%–40%, and finer particles (<105 μm) contributed 60%–80% of the wash-off load. These results indicate that small and moderate rain events are transport limited processes on RDS. Additionally, both single- and multi-rain events caused RDS grain size composition to become coarser and only removed a small proportion of the RDS load. Short-term and long-term dry days increase the total RDS mass and cause its grain size composition to become finer. Furthermore, the build-up process is generally not from zero over the antecedent dry days, which indirectly indicates that the wash-off process is transport limited.

To investigate the effects of grain size and rainfall characteristics on the wash-off process, a total of 40 simulated rainfall events were designed. The following conclusions can be made based on these experiments: 1) Particle grain sizes influence the RDS wash-off process, and finer (<105 μm) and coarser (>105 μm) particles tend to be source and transport limited, respectively. 2) The entire wash-off process during a typical rainfall event could be divided into two processes, a source limited one during the initial period (first flush) and a transport limited one during later periods. Furthermore, the magnitude of the first flush phenomenon becomes greater for finer particle sizes and larger rain intensity. 3) The smaller and larger rain events tend to be transport limited and source limited, respectively. This is because the higher intensity in larger rain events results in greater transport capacity, and finer particles and some coarser particles can be removed.

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