Effects of rainfall intensity and duration on first flush of stormwater pollutants

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ABSTRACT - The relationship between rainfall intensity and duration and its effects on the water quality of resulting surface runoff is difficult to quantify due to the inherent unpredictability and natural variability in rainfall. To overcome this variability, a rainfall simulator was constructed to mimic storm events under controlled conditions. The objective of this study was to evaluate the effect of rainfall intensity and duration on the contaminant concentrations found in runoff. Within-storm variability was quantified by subsampling simulated events of varying rainfall intensities. Among-storm variability was assessed by examining event mean concentrations from storms with: (1) similar intensities, but varying durations; (2) similar durations, but varying intensities; and (3) varying intensity and duration to achieve similar storm volumes. Within-storm variability showed that concentrations of suspended solids, total and dissolved trace metals, and polycyclic aromatic hydrocarbons (PAHs) in runoff were consistently greater (averaging 2.4-fold to 5.4-fold greater) at the beginning of simulated storm events (<10 minutes) than later in the event (10-40 minutes). Among-storm variability showed that concentrations of these constituents in runoff were inversely correlated with rainfall duration or intensities; shorter rainfall durations or lower rainfall intensities produced greater runoff concentrations. Similar storm volumes, generated from varying intensities and durations, resulted in similar runoff concentrations.

INTRODUCTION

A “first-flush” effect occurs when pollutant concentrations in wet-weather discharges peak early in a storm event, typically before the peak in stormwater flows. The result is a disproportionately greater discharge of mass relative to the proportion of volume discharged during a storm event (Bertrand-Krajewski *et al*. 1998). The occurrence of a first-flush effect has been observed for suspended solids, nutrients, and trace metals in urban, transportation, and agricultural drainages (Buffleben *et al*. 2002, Sansalone and Buchberger 1997, Schiff and Sutula 2002).

Wash-off of pollutants, including first flush, is controlled by physical processes such as rainfall timing, intensity, and duration. Studies of rainfall timing, including antecedent dry period, can lead to the build-up of pollutants until they reach a maximum accumulation rate (Tiefenthaler *et al.* in press; Pitt 1985). The effect of rainfall intensity and duration, however, is not well understood (Bertrand-Krajewski *et al*. 1998). Few studies have successfully examined these processes, largely because the natural variability in rainfall makes it difficult to examine these factors in isolation (Dorman *et al.* 1988). The problem is exacerbated in arid climates, where fewer storms occur and where rainfall intensity and duration often covary (Herricks 1995).

The objective of this study was to evaluate the effect of rainfall intensity and duration on the contaminant concentrations found in runoff. To overcome the inherent unpredictability and natural variability in rainfall, a rainfall simulator was used to mimic storms in a controlled and consistent fashion. Rainfall duration and intensity were manipulated both independently and together to determine changes in runoff concentrations both within and among storm events of varying rainfall characteristics.

METHODS

Approach

This study used two experimental approaches to evaluate the effect of rainfall intensity and duration on runoff concentrations. The first approach focused on assessing within-storm variability of runoff concentrations and the second approach focused on assessing among-storm variability of runoff concentrations.

Within-Storm Variability

Within-storm variability was assessed by subsampling storms of various intensities. Two subsampling strategies were employed. First, composited runoff samples were collected every 2 minutes for suspended solids to create a time-concentration series over the course of an entire hydrograph. Second, composited runoff samples were collected every 10 minutes for suspended solids, total and dissolved trace metals, and polycyclic aromatic hydrocarbons (PAHs). This second strategy ascertained the relative magnitude of runoff concentrations for within-storm partitions, but at greater cost efficiency than every two minutes. Three storm intensities were selected for assessing within-storm variability including 6.3, 12.7, and 25.4 mm/h. These intensities were selected since they represented between the 50th and 85th percentile of storm events between 1995 and 2000 in the vicinity of the test plots. Significant differences between storm partitions were determined by analysis of variance (ANOVA) using Tukey tests for multiple comparisons for determining differences among treatments (e.g., intensities).

Among-Storm Variability

Among-storm variability was assessed by examining event mean concentrations from storms with: (1) similar intensities, but varying durations; (2) similar durations, but varying intensities; and (3) varying intensities and durations to achieve similar storm volumes. A total of nine combinations of rainfall treatments were applied. Three rainfall durations (10, 20, 40 minutes) were tested across a single rainfall intensity (6.3 mm/h). Three rainfall intensities (6.3, 12.7, and 25.4 mm/h) were tested across a single duration (20 minutes). A single runoff volume was evaluated using three simulations of varying levels of rainfall intensity and duration (6.3 mm/h at 40 minutes, 12.7 mm/h at 20 minutes, and 25.4 mm/h at 10 minutes). All treatments were comprised of three replicate simulated storm events. Significant differences among event mean concentrations were determined by ANOVA using Tukey tests for multiple comparisons for determining differences among treatments.

Rainfall Simulator

Rainfall was simulated using spray rigs comprised of polyvinyl chloride (PVC) pipes with inline pressure gauge, flow meter, control valve, and either Rainbird™ or Hunter™ PGM rotating polyurethane spray heads (Figure 1). One fixed-rate Rainbird™ spray head at 45/36 pounds per square inch (psi) and 5.0 liters per minute (L/minute) flow produced a 3.8 m radius semicircle with an intensity of 12.7 mm/h. This system provided a relatively uniform simulated rainstorm washing off two parking stalls measuring 18 m^2; total wetted surface area was 11.9 m^2. Typical (6 mm/h) and worst-case (25 mm/h) rainfall intensities were simulated using two Hunter™ spray heads with 0.75 gallon-per-minute (gpm) emitters while also varying the pressure and flow rate. Simulating rainfall for a period of 20 minutes at an intensity of 12.7 mm/h resulted in a total runoff volume of 104.1 liters. Measurements of rainfall intensity within the semicircle at nine evenly spaced locations varied by less than 20%, and mean intensities among simulations varied by less than 10%.

All simulated rainfall events occurred within a single 400 m^2 parking lot located in Long Beach, California. The parking lot had a capacity of 50 cars and was constructed of 100% asphalt with a 4% grade. The lot operated seven days per week with five days at full capacity (averaging 45 cars per hour) and received no maintenance (i.e., street sweeping or cleaning) during the study period. All parking lots were pre-cleaned at the beginning of the study using a professional high-pressure cleaning system to ensure similar initial accumulations on each parking

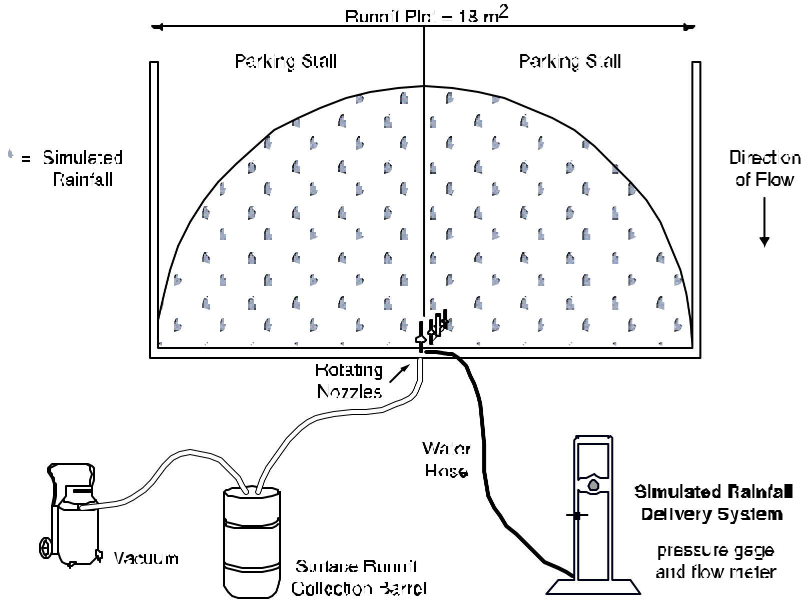

Figure 1. A schematic diagram illustrating both the simulated rainfall delivery system and the water collection system used for assessing the effects of rainfall on parking lot surface runoff.

lot surface. The parking lots were left untested for a three-month dry period to allow for accumulation before treatments were applied. All treatments were randomly assigned to parking stalls distributed throughout the parking lot.

The surface runoff generated by the rainfall simulators was collected continuously during each simulation run using a vacuum system that transferred the runoff into a 55-gallon plastic barrel. At the end of each simulated event, the runoff collected in each barrel was stirred vigorously and subsamples for chemistry samples were taken. The source water for the rainfall simulators was passed through a portable filtration system comprised of filters and activated carbon to remove potential confounding factors. All source water blank and rainfall simulator blank samples were nondetectable for the measured constituents.

Analytical Chemistry

Suspended Solids

Total suspended solids were analyzed by filtering a 10 to 100 mL aliquot of stormwater through a tared 1.2 µm (micron) Whatman GF/C filter (EPA Method 160.2). The filters plus solids were dried at 60°C for 24 h, cooled, and weighed.

Trace Metal Analysis

Samples for total and dissolved trace metal analysis were prepared using a strong acid digestion. Dissolved metals were defined as the concentration in the sample that passed through a 0.45 mm filter, whereas unfiltered samples were used for total metals. A well-mixed, 25 mL aliquot of acidified sample was dispensed to a Teflon® digestion vessel and 2 mL of ultra-pure HNO3 (Optima, Fisher Scientific) were added, and the vessel was capped and sealed. The acidified samples were digested in a CEM MSP1000 Microwave Oven by ramping to 100 psi over 15 minutes and then holding at 100 psi for 10 minutes. After cooling, the digestate was centrifuged to remove any remaining residue from the sample. The supernatant with sample digest was transferred to a 15 mL test tube prior to analysis.

Inductively coupled plasma-mass spectroscopy (ICP-MS) was used to determine total and dissolved concentrations of inorganic constituents (aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, mercury, nickel, selenium, silver, and zinc) from sample digest solutions using a Hewlett Packard Model 4500 and following protocols established by EPA Method 200.8, EPA Methods 236.1 and 236.2, and by EPA Modified Method 245.1.

Polycyclic Aromatic Hydrocarbons

Twenty-six PAHs were extracted, isolated, and analyzed using EPA Method 8270C (U.S. EPA 1991). The PAHs were separated, identified, and quantified by capillary gas chromatography (GC) coupled to mass spectrometry (MS). Twenty-five specific PAHs were determined for this study. Total PAHs (∑PAH) was computed as the sum of these values.

RESULTS

Within-Storm Variability

Suspended solids concentrations were greater at the beginning than at the end of simulated storm events (Figure 2). Peak concentrations occurred within the first four to six minutes of each simulated event, decreasing to relatively consistent baseline concentrations after 10 to 12 minutes. The magnitude of the first-flush effect varied between intensities, ranging from 112 mg/L in the 25 mm/h to 140 mg/L in the 6 mm/h rainfall intensity. The relatively consistent baseline concentrations varied from 2 mg/L in the 25 mm/h to 20 mg/L in the 6 mm/h rainfall intensity.

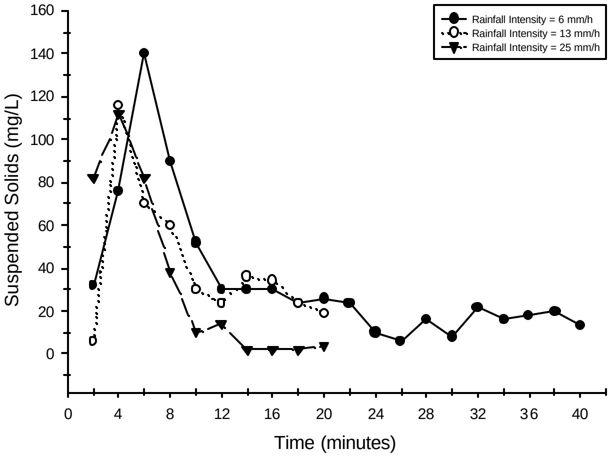

Figure 2. Time-concentration series of suspended solids concentrations (mg/L) for 6.3, 12.7, and 25.4 mm/h simulated rainfall intensities.

Similar to the suspended solids results, concentrations of total and dissolved trace metals, and total PAH were consistently higher in the first 10 minutes of the simulated events than in later portions of the storm (Table 1). The concentrations for 31 of 32 constituents were higher in runoff during the first 10 minutes of the simulated rainfall events than in runoff from the next 10-minute segment of the storm. The initial runoff concentrations for all 32 constituents were, on average, a factor of 2.4 higher than concentrations during the 10-20 minute segment of the simulated event. The concentrations of all 32 constituents were reduced even more by the last half of the simulated storm event. The concentrations from the initial 10 minutes of the simulated events were, on average, a factor of 5.4 higher than concentrations during the 20-minute to 40-minute segment of the simulated event.

Among-Storm Variability

Concentrations of all constituents were inversely correlated with rainfall duration (Table 2). Longer simulated storms significantly lowered the concentrations of contaminants in parking lot runoff. For example, mean total zinc concentrations in the 6.3 mm/h intensity simulated events significantly decreased from 430 ug/L, to 322 ug/L, to 240 ug/L as rainfall duration increased from 10, to 20, to 40 minutes, respectively (F = 12.4, p = 0.01). Similarly, mean concentrations of total zinc, and every other constituent measured, decreased between 10-minute and 20-minute simulated events at the 25.4 mm/h rainfall intensity.

Table 1. Comparison of within-storm variability. Mean concentrations (standard deviation) are reported for three different time intervals within a 40-minute storm with an intensity of 6.3 mm precipitation per hour.

	6.3 mm/h (0.25 in/h)		
Parameter	0-10 minutes Mean (SD)	10-20 minutes Mean (SD)	20-40 minutes Mean (SD)
Suspended Solids (mg/L)	72.7 (18.1)	20.3 (6.5)	11.7 (5.2)
Metals (Total)			
Aluminum (µg/L)	10,36.7 (172.7)	233.3 (177.5)	180 (55.9)
Cadmium (µg/L)	2.4 (0.6)	1.0 (0.8)	0 (0)
Chromium (µg/L)	7.7 (0.7)	4.1 (0.3)	2.2 (0.2)
Copper (µg/L)	54.3 (6.4)	27.3 (4.2)	10.3 (0.5)
Iron (µg/L)	556.7 (56.8)	446.7 (27.4)	216.7 (71.5)
Lead (µg/L)	168.7 (84.2)	93 (58)	27.7 (14.5)
Nickel (µg/L)	44.7 (7.4)	21.3 (4.7)	6.8 (0.9)
Zinc (µg/L)	430 (47.5)	213.3 (35.5)	76.7 (3.2)
Metals (Dissolved)			
Aluminum (µg/L)	78.7 (12.4)	92.7 (97.2)	0 (0)
Cadmium (µg/L)	2.1 (0.6)	0.9 (0.7)	0 (0)
Chromium (µg/L)	4.1 (0.4)	2.5 (0.2)	0.8 (0.7)
Copper (µg/L)	47.3 (5.2)	24.7 (4.8)	8.5 (0.9)
Iron (µg/L)	360 (64.4)	203.3 (40.3)	46.7 (35.5)
Lead (µg/L)	133.3 (77.4)	85.3 (63.1)	23.9 (16.4)
Nickel (µg/L)	41.3 (6.9)	19.3 (4.7)	6.4 (1.1)
Zinc (µg/L)	336.7 (52.1)	170.0 (47.5)	56.0 (11.2)
Total PAHs (ng/L)	8.5 (6.2)	4.3 (2.8)	2.7 (2.1)

Table 2. Comparison of among-storm variability. Event mean concentrations (standard deviation) are reported for a range of intensities and durations.

	6.3 mm/h (0.25 in/h)			12.7 mm/h (0.5 in/h)	25.4 mm/h (1 in/h)	
Parameter	10 minutes Mean (SD)	20 minutes Mean (SD)	40 minutes Mean (SD)	20 minutes Mean (SD)	10 minutes Mean (SD)	20 minutes Mean (SD)
Suspended Solids (mg/L)	72.7 (18.1)	46.5 (29.8)	34.9 (29.5)	28.7 (14.6)	41 (13.3)	26.5 (17.6)
Metals (Total)						
Aluminum (µg/L)	1,036.7 (172.7)	635 (444.6)	483.3 (422.2)	316.7 (73.5)	540 (114.7)	341.7 (218.3)
Cadmium (µg/L)	2.4 (0.6)	1.7 (1)	1.1 (1.1)	0.8 (0.6)	0.5 (0.8)	0.3 (0.6)
Chromium (µg/L)	7.7 (0.7)	5.9 (1.9)	4.7 (2.4)	2.6 (0.4)	4 (1.2)	2.9 (1.4)
Copper (µg/L)	54.3 (6.4)	40.8 (14.8)	30.7 (18.9)	19.7 (1.3)	29.7 (7.6)	20 (11.3)
Iron (µg/L)	556.7 (56.8)	501.7 (71.1)	406.7 (153.3)	560 (115.4)	610 (195.4)	438.3 (222.7)
Lead (µg/L)	168.7 (84.2)	130.8 (80.6)	96.4 (82.3)	61.7 (28.6)	48.7 (18.4)	33.7 (20.4)
Nickel (µg/L)	44.7 (7.4)	33 (13.4)	24.3 (16.6)	14 (2.3)	23.7 (6.9)	15.1 (10)
Zinc (µg/L)	430 (47.5)	321.7 (118)	240 (151.2)	160 (8.5)	216.7 (26.1)	143 (77.7)
Metals (Dissolved)						
Aluminum (µg/L)	78.7 (12.4)	85.7 (68.2)	57.1 (68.8)	0 (0)	0 (0)	12.8 (29.3)
Cadmium (µg/L)	2.1 (0.6)	1.5 (0.9)	1 (1)	0 (0)	0.5 (0.7)	0.3 (0.6)
Chromium (µg/L)	4.1 (0.4)	3.3 (0.9)	2.5 (1.4)	1.6 (0)	1.9 (0.6)	1.1 (1)
Copper (µg/L)	47.3 (5.2)	36 (12.6)	26.8 (16.6)	15.3 (1.8)	24.3 (9.4)	16.2 (10.7)
Iron (µg/L)	360 (64.4)	281.7 (95.7)	203.3 (138)	133.3 (26.1)	190 (30.7)	121.7 (77.9)
Lead (µg/L)	133.3 (77.4)	109.3 (73.3)	80.8 (72.7)	45.1 (28.7)	34 (12.6)	24 (14.3)
Nickel (µg/L)	41.3 (6.9)	30.3 (12.6)	22.3 (15.4)	12 (1.5)	21 (7.4)	13.4 (9.4)
Zinc (µg/L)	336.7 (52.1)	253.3 (98.1)	187.6 (123.5)	104.7 (22.6)	156.7 (34.5)	103.7 (59.9)
Total PAHs (ng/L)	8.5 (6.2)	6.4 (5.2)	5.2 (4.7)	5.5 (2.9)	3.3 (1)	2.4 (1.2)

Concentrations of most constituents were inversely correlated with rainfall intensity (Table 2). The lowest rainfall intensity consistently had the highest concentrations during simulated storm events of the same duration. For example, mean total zinc concentrations measured during the 20-minute simulated storm significantly decreased from 322 ug/L, to 160 ug/L, to 143 ug/L in the 6.3 mm/h, 12.7 mm/h, and 25.4 mm/h rainfall intensities, respectively ($F = 34.5$, $p = 0.00$). Similarly, mean total zinc concentrations decreased between the 6.3 mm/h and 12.7 mm/h intensities during the 10-minute duration simulated events. The only constituent that did not routinely decrease with increasing intensity was iron, which had similar concentrations among intensities at 10-minute and 20-minute durations.

Simulated storm events of longer duration and less intensity generally produced runoff with similar mean constituent concentrations compared to simulated events of shorter duration with higher rainfall intensities (Table 2). While the 6.3 mm/h, 40-minute duration events had consistently higher mean concentrations than the 25 mm/h, 10-minute duration events, these differences were typically small and were not statistically significant. For example, the short-duration/high-intensity simulated event generated approximately 104 L total runoff volume and a total zinc concentration of 240 ug/L. The long-duration/low-intensity event, which produced the same runoff volume, contained a zinc concentration of 217 ug/L ($p > 0.05$).

Median dissolved metals concentrations comprised up to 90% of the total metals concentrations (Table 2). Among the eight metals analyzed, five metals (Ni, Cd, Cu, Pb, and Zn) were present mostly in dissolved form (90.1, 89.9, 84.5, 76.0, and 75.3%, respectively). The proportion of dissolved metals remained relatively similar among rainfall intensities and durations. For example, dissolved zinc comprised 78.2-78.7% of the total zinc measured at all three durations during the 6.3 mm/h intensity simulated events. Similarly, dissolved zinc comprised 65.4-78.7% of the total zinc measured at all three intensities during the 20-minute simulated events.

DISCUSSION

The first-flush effect was a dominant feature during our simulated events and likely accounted for the decrease in runoff concentrations with increased duration or intensity. The within-storm variability experiments consistently measured a distinctive peak in concentrations within the first few minutes of our simulated events. Concentrations then declined to some baseline level, as much as an order of magnitude lower than first-flush concentrations, for the remainder of the event. The result of additional rainfall, whether it is in the form of longer durations or greater intensities, serves to dilute the concentration maxima of the original first flush. This hypothesis was corroborated by the last experiment, where rainfall intensity and duration were manipulated, but similar rainfall volumes were constantly reproduced and similar runoff concentrations were consistently found.

Other studies have documented the first-flush effect, but the correlation among rainfall duration and intensity we produced in our study of simulated rainfall has not been routinely identified. For example, Bertrand-Krajewski (1998), and Dorman *et al.* (1988) found a first flush of pollutants in runoff from urban catchments in France, but could not identify a predictable relationship between rainfall characteristics such as intensity and duration. First flush has also been found in urban arid environments, such as Los Angeles (Buffleben *et al.* 2002), but the occurrence of first flush was not related to rainfall characteristics. Sansalone and Buchberger (1997) routinely found a first flush of suspended solids, and total and dissolved trace metals during five storm events in runoff from an urban roadway catchment in Cincinnati, Ohio. The first flush of solids in roadway runoff was related to antecedent dry period, flow intensity and duration, and vehicle activity (Sansalone *et al.* 1998). Longer duration storms were termed mass-limited, meaning that increased runoff did not deliver more solids, but only more volume, which will lead to a reduction in the overall event mean concentration.

Based on the results of the intensity and duration experiments herein, stormwater capture and/or treatment systems that focus on the initial portion of stormwater discharge from parking lots are likely to provide the greatest benefit in reducing constituent concentrations. For example, management actions that focused on the first 10 minutes of one of our 40-minute simulated storm events would mitigate 69.4% of the suspended solids mass emissions. However, several factors need to be considered when designing BMPs including sizing, trapping, and treatment efficiency for specific constituents of concern, and flood protection among others.

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