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MISSISSIPPI WATERSHED MANAGEMENT ORGANIZATION

2018 Analysis of Runoff from Impervious Surfaces in Downtown Minneapolis

MWMO Watershed Bulletin: 2018-4

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2018 Analysis of Runoff from Impervious Surfaces in Downtown Minneapolis

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2018 Analysis of Runoff from Impervious Surfaces in Downtown Minneapolis

University of Minnesota and Mississippi Watershed Management Organization

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Executive Summary

Understanding the entrainment and transport of potential contaminants from impervious surfaces is necessary for the development and implementation of sound water-management practices. Natural rainfall events are widely used to gain insight into these processes. Installation of monitoring equipment and collection of samples from these events needs to be done carefully. Impact of seasons and type of impervious surfaces on pollutant loads can be difficult to determine. Rainfall characteristics that vary between events and vary spatially for the same event are the reason pollutant loads are difficult to determine. The Mississippi Watershed Management Organization (MWMO) and the University of Minnesota Department of Bioproducts and Biosystems Engineering (UMN) worked collaboratively on a unique study investigating the impact of impervious surfaces stormwater runoff into the Mississippi River. The study focused on streets, sidewalks, parking lots, and rooftops located in the downtown Minneapolis area. A rain simulator was used to study the runoff response of streets, parking lots and sidewalks. Rain simulators allow the study to focus on the role of surface types and seasonal differences by removing difference in rainfall characteristics. Runoff characteristics of roofs were studied using natural rainfall and snowmelt events.

Three different streets, sidewalks, parking lots, and rooftops located in downtown Minneapolis, MN were used as test sites. The ground sites (streets, sidewalks and parking lots) were selected to represent a range in automobile and pedestrian traffic for Minneapolis while also representing impervious surfaces of different ages and materials. Roofs were selected based on the type of surface. Data from simulations were collected in the summer and fall of 2017 and in the spring of 2018, making a total of nine ground sampling sites. Data from natural rainfall events were obtained using semi-permanent installations between fall of 2017 and summer of 2018. Due to timing constraints and other logistical issues, not all three roof sites were installed at the same time. All but one of the street-sidewalk sampling locations (3rd Ave South in the heart of downtown Minneapolis) was located in the southeast area of downtown Minneapolis.

For the ground sites, the eight-foot simulator was centered over a rectangular plot area of 6 ft by 12 ft. The rainfall intensity was set at a constant rate of 2.5 in h^{-1} for a duration of 45 minutes. The rate and duration corresponded to a return period of approximately 2 years. At least 48 hours of dry weather was required before raining on the test plots. During the runoff, one-liter samples were collected at time intervals of 1, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 37.5, and 45 minutes after runoff first reached the catch-basin. After each sample was collected, water temperature, dissolved oxygen, conductivity, and pH were recorded using a YSI probe. Sample bottles were appropriately composited and sent to the Met Council laboratory to determine the event mean concentrations (EMCs) of total suspended solids (TSS), chloride, chemical oxygen demand (COD), E.coli, cadmium, chromium, copper, lead, nickel, magnesium, manganese, zinc, sodium, nitrate-N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), ortho-phosphate (OP), total organic carbon, turbidity, calcium, iron, mercury, and potassium. These concentrations were also measured in the source water. The concentrations in the runoff were obtained by subtracting the source water values from the composite concentrations of the runoff. In addition to the composite sample, the first sample of each event, which corresponded to the first flush flow, was sent to the laboratory for bio-chemical analyses if the site measurement of the standard deviation of conductivity was greater than two.

Because of site constraints, the experimental setup for the three roof sites was not identical. All sites used a Teledyne ISCO automated sampler, Campbell CR10X datalogger, ISCO rain gauge and a conductivity sensor. The City of Lakes site used a modified PVC pipe system and an area-velocity sensor to determine the flow rate. The ISCO sampled water in a p-trap at the top of the pipe system and was triggered by the ISCO's flow meter. The other two sites used tipping bucket rain gauges located atop the roof and a PVC pipe system to connect the roof downspout to a collection tank. The water depth was measured and changes were used to estimate flow rates. A p-trap was placed within the PVC pipe system to house the conductivity probe and provide enough volume for the ISCO automated sampler to collect a sample.

The rain simulator was used to generate events for streets, sidewalks and parking lots for summer, fall and spring conditions. Differences in EMCs for these types of surfaces were relatively minor for the summer and fall seasons. The greatest difference was observed during the spring season. The average chloride EMCs among three sites for the fall were 0.8 mg/L, 1.1 mg/L, and 0.6 mg/L streets, sidewalks and parking lots, respectively. However, the corresponding values for spring were 248 mg/L, 6 mg/L and 9 mg/L. Additional insight into the impact of season was obtained by collecting composite concentrations for two snowmelt events. Chloride and TSS concentrations for these events were generally larger than those measured from the rain simulator runs. The largest chloride EMC observed from the simulator runs was 704 mg/L; whereas the chloride concentrations for the snowmelt events were 26,331 mg/L and 2,996 mg/L for the first and second events, respectively.

In general, chloride concentrations from the roofs were small for summer, fall and spring seasons. Their EMCs for summer and fall were similar in magnitude to those of the ground sites. Chloride concentrations from roofs were generally much smaller than the ground site concentrations during the spring season. The EMCs of TSS and TP from the roofs exceeded Minnesota water quality standards for some events. In contrast to the ground sites, detectable E. coli concentrations were observed for the roofs. The COD concentrations tended to be larger for roofs than the summer and fall ground site data. Measured concentrations of chloride exceeded 60 mg/L for three snowmelt events. These large concentrations are particularly interesting because the average chloride concentrations from roofs for non-winter events were less than 10 mg/L.

The first-flush process was evaluated by analyzing the concentrations in the first collected sample bottle (B1C) and by measuring the conductivity at different times during the runoff events. B1Cs were generally much larger than the EMCs. An exponential function was used to represent the first-flush process of a change in concentration with runoff volume. The project mathematically derived the EMC for this exponential function. This relationship allows EMC to vary with runoff volume. The parameters of the exponential function were determined using the conductivity data and the measured B1Cs and EMCs. The project also collected data from several natural rainfall events using a unique instrumentation system. Preliminary analysis suggests an exponential decay in concentrations similar to those obtained from the rain simulator.

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Analysis of Runoff from Impervious Surfaces in Downtown Minneapolis: Report 2018

Introduction

Background

The runoff response of urban watershed is dominated by impervious surfaces. Understanding the entrainment and transport of potential contaminants from these surfaces is necessary for the development and implementation of sound water-management practices. Most studies use natural rainfall events to gain insight into these important processes. Installation of monitoring equipment and collection of samples during runoff, especially for large events, must be done carefully and can require substantial human resources to be successful. In addition, rainfall characteristics play an important role in the runoff response. These characteristics vary between events and can vary spatially within small watersheds for a particular event. This variation can mask the impacts of seasons and type of surface on pollutant loads.

In 2016, the Mississippi Watershed Management Organization (MWMO) and the University of Minnesota Department of Bioproducts and Biosystems Engineering (UMN) embarked on a unique study of impervious surface impacts from stormwater runoff and ultimately, the Mississippi River. Specifically, the study focused on streets, sidewalks, parking lots, and rooftops located in the downtown Minneapolis area. A rain simulator was used to study the runoff response of streets, parking lots and sidewalks. Rain simulators allow the study to focus on the role of surface types and seasonal differences by removing differences in rainfall characteristics. These simulators are designed to mimic the kinetic energy of natural rainfall. Runoff characteristics of roofs were studied using natural rainfall and snowmelt events.

The study would not have been possible without the partnerships established with building owners in downtown Minneapolis as well as coordination with City staff for blocking roads and sidewalks during rain simulation events. The rain simulator was graciously provided by the Minnesota Department of Agriculture.

Project Scope

The mission of the MWMO is to protect and improve the quality of the water in its watershed. Implementation of effective stormwater plans requires knowledge as to how water and entrained contaminants move over the impervious surfaces through the storm sewers and into the Mississippi River. This study focused on the source of contaminants from different types of impervious surfaces and for different seasons. Sites and experimental methods were selected to meet the goals of the project within the time and cost constraints and the availability of personnel.

Three different streets, sidewalks, parking lots, and rooftops located in downtown Minneapolis, MN were used as test sites. Data were collected to evaluate runoff depth and concentrations of heavy metals, suspended solids, nitrogen, phosphorous, oxygen demand constituents and total carbon. A rain simulator was used to generate runoff for the streets, sidewalks and parking lots. Data from simulations were collected in the summer and fall of 2017 and in the spring of 2018, making a total of nine ground sampling sites. Data were also collected from natural rainfall events for three rooftop sites. These rooftop sites were semi-permanent installations which made it possible to collect natural rainfall samples between fall 2017 and summer 2018. One of the sites, the City of Lakes roof, had sampling equipment installed inside of the building which allowed for winter snowmelt sampling. Due to timing constraints and other logistical issues, not all of the three roof sites were installed at the same time.

Literature Review Summary

A literature review was conducted on a range of topics relating to urban impervious runoff. The goal of this review was to gain insight into data collection design systems, experimental protocols and potential problems experienced in other studies. The review is divided into studies that identified the type of pollution sources, the entrainment processes and characterization of pollutant, rain simulator, and monitoring approaches.

Stormwater Pollution Sources

Shaheen (1975), Egodawatta (2012) and Ren et al. (2008) addressed characterization of storm-water pollutants from urban surfaces. Shaheen's work suggested that urban pollutants are directly and indirectly affected by motor vehicles. Egodawatta et al. and Ren et al. looked at pollutant concentrations in runoff on roofs, sidewalks, lawns and roads in urban areas. They observed a first flush process. This process is important for understanding the water quality response of urban watersheds.

Stormwater Pollutant Wash-off Characterization

Many previous studies have looked into the process of pollutant wash-off from rainfall events. Vaze and Chiew (2003) suggest that the driver behind pollutant loads in storm-water runoff is raindrop impact and shear stress from surface runoff. Li et al. (2015) discovered that pollutant species and land use had a large impact on the variability of pollutant characteristics. They suggested that different storm characteristics, like intensity, antecedent dry days and rainfall volume had different effects on event mean concentrations and the percentage of pollutant load transport. Li found that removing the first 40% of storm-water runoff volume (first flush) could reduce over half of the TSS, TP, TN and COD loads. Similarly, Di Modugno et al. (2015) concluded, after investigating urban storm-water characteristics in Italy, 60% of TSS washed off is loosened and transported with the first 30% of storm runoff volume. Alias et al. (2014) analyzed the influence of rainfall characteristics on the pollutant wash off process by partitioning off wash-off and rainfall characteristics. Partitioning showed different sectors of the wash-off process are influenced by different segments of a rainfall event, especially segments of high and low intensity. As a result, using lumped rainfall parameters, a method widely used, to represent an entire rainfall event would not be an appropriate method. Additionally, Alias et al. discovered first flush characterization could be performed by assessing pollutant loads in the first 40% of runoff volume. Shaw et al. (2010) conducted a study to improve storm-water pollutant transport modeling and through regression analysis concluded antecedent dry days, though widely thought to contribute most to particle pollutant loads in run-off, are not a significant contributor to particulate load variability. Event particulate loads were better explained by rainfall volume and rain drop kinetic energy. This is in contrast to what many other papers have stated regarding road pollutant build up over antecedent dry days and storm-water runoff pollutant loads.

Rain simulators

A review of rain simulators was done to provide background for the use of a simulator in this study. The decision to use a rain simulator is ultimately tied to the overall goals of the project. Three types of simulators are commonly used, nozzle, rotating disk nozzle and drip. Benik et al. (2003) used nozzles located on rotating booms to evaluate the effectiveness of different erosion control blankets. Morin and Cluff (1980) used a rotating disc nozzle simulator to measure infiltration rates in semi-arid watersheds. Beighley and Valdes (2009) used a Norton Ladder nozzle simulator (similar to the UMN/MWMO study) to determine the effectiveness of two common sediment control technologies on sloped surfaces. Anderson et al. (1999) constructed their own drip rain simulator to determine the hydrologic performance of permeable pavers in urban UK areas. All simulators have advantages and disadvantages regarding accuracy simulating real rain depths and intensities, simulator mobility and appropriateness of simulator type for desired experimental goals.

Rainfall Runoff Collection Methods

Experiments that focused on rain collection methods and analysis of pollutants are also of interest. To better understand wash-off processes, to investigate permeable pavement and to evaluate roof runoff, Vaze and Chiew (2003), Anderson et al. (1999) and Egodowatta et al. (2009) used a combination of drip and nozzle rain simulators to mimic rainfalls of different intensities. The source water was spiked in order to more closely match the composition of the rainwater in the individual study areas. Vaze and Chiew collected runoff in 1 L plastic bottles from the test surface outlets. Collection began at the start of runoff and ended when runoff ceased. Anderson et al. constructed a model car park with permeable paver, ran rain simulations above the model area and used water and mass balances to quantify permeable paver evaporation, storage and drainage. Erdogowatta et al. used two different roof surface plots, concrete tile and corrugated steel, to conduct rain simulations of varying intensities. The rain simulations were used for wash off analysis and the simulations were performed on half the area of the test roof plots. The wash off was collected using a roof gutter system. Particulate build-up was tested on the other half of the roof test plots by scrubbing the surface of the roof with a brush, flushing the roof with 7 L of water and collecting that water for analysis through a gutter system. The roof surfaces were raised to average building height of the study area during periods of accumulation, but were lowered closer to the surface for simulations.

Although there is an abundance of water quality data collected from urban areas in Minnesota, we were unable to identify projects specifically designed to study the washoff processes for our streets and other impervious areas.

Experimental Methodology

Site Selection

Streets, Sidewalks and Parking Lots

Site selection was done with the assistance of the MWMO. Staff from UMN and MWMO visited several sites in downtown Minneapolis. Three sampling sites were selected for each of land uses. Streets, sidewalks and parking lots were selected to represent a range in automobile and pedestrian traffic for Minneapolis and different surfaces as consequence of construction materials or aging. Roofs were selected based on the type of surface. Willingness of the owners to participate in the project also played an important role in the selection of the roofs and parking lots. Other factors included our ability to secure permits for blocking road and sidewalk during weekdays and the proximity to catch-basin for ease of runoff collection. The locations of the sites are shown in Figure 1. All but one of the street-sidewalk sampling locations (3rd Ave South in the heart of downtown Minneapolis) are located in the southeast area of downtown Minneapolis.

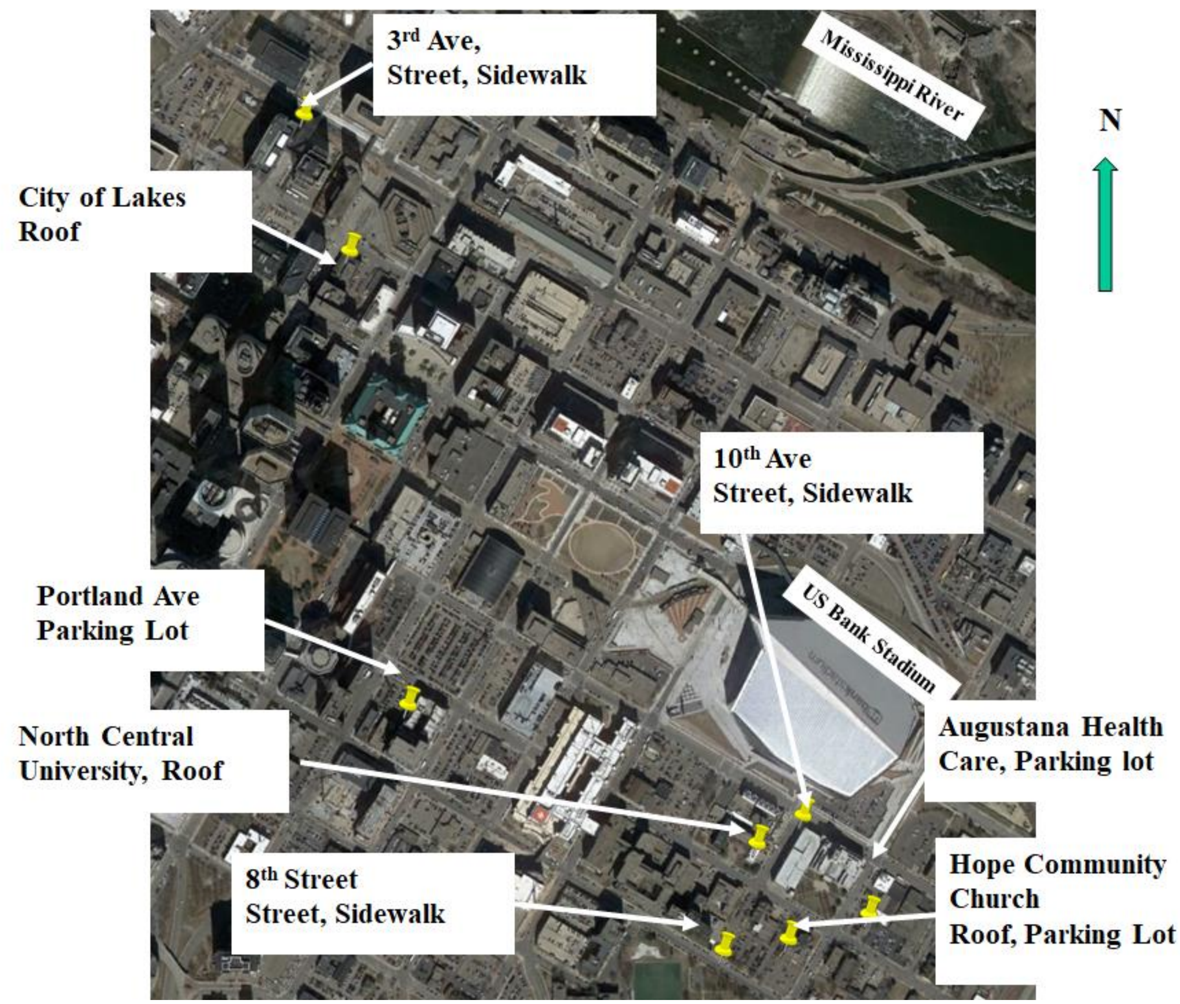


Figure 1. Location of Experimental Sites in Downtown Minneapolis. Base map obtained from Google Earth.

The street and sidewalk sites were paired for ease of sampling, accessibility, and consistency. Simulator events for the paired street and sidewalk were generally collected on the same day, improving the efficiency of gathering data. The locations of the street and sidewalk sites are shown in greater detail in Figure 2. The 3rd Ave South location is the only street and sidewalk site in the heart of downtown Minneapolis. It is located on the northwest side of 3rd Ave South from the corner of 3rd Ave South and South 3rd Street, within 150 feet south of 3rd Ave South. This site had the heaviest traffic – both automobile and pedestrian. MnDot's Traffic data (2015) estimated an average annual daily traffic volume of 8,300 vehicles on 3rd Street S, 7,900 vehicles on 2nd Avenue S, 9,500 vehicles on 4th Street S and 10,500 on 3rd Avenue S. During the winter, it was observed that there was complete snow removal in this area. The street and sidewalk sampling sites at South 8th Street are adjacent to Elliot Park. Rainfall events at the site were gathered on the south side of South 8th street from the intersection of 10th Ave S, and south-east of the nearest stormwater catch-basin. During sampling events, there was a moderate amount of pedestrian traffic along this corridor as well as a moderate volume of automobile traffic. MnDot's Traffic data (2015) estimated an average annual daily traffic volume of 7,200 vehicles on 8th Street S. The 10th Ave South site is located across the street of the US Bank Stadium at the intersection of 10th Ave South and South 6th Street. It is located on the east side of 10th Ave South. Fair to moderate automobile traffic was observed during sampling events and little to no pedestrian traffic was observed, though it is presumed that pedestrian traffic increases dramatically during events at the stadium. MnDot's Traffic data (2015) estimated an average annual daily traffic volume of 6,700 vehicles on 11th Avenue S.

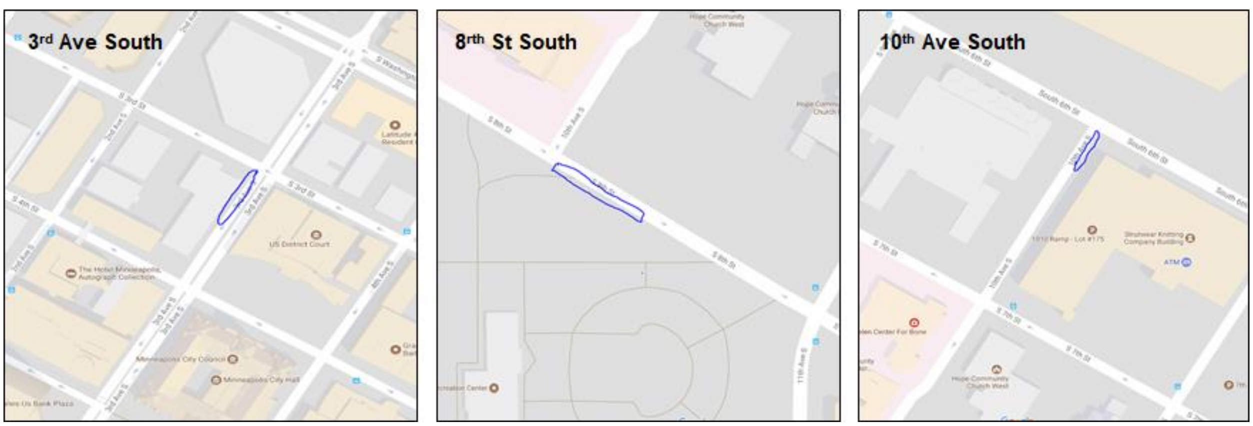


Figure 2. Sites for Streets and Sidewalks. Base map from Google Map.

The locations of the parking lot sites are shown in greater detail in Figure 3. Parking lot sites were a little more difficult to secure due to the typically heavy daily use of parking lots in downtown Minneapolis. MWMO and the UMN partnered with Augustana Health Care, Hope Community Church (HCC), and Hennepin County Health Services (Portland Ave) to use space in their parking lots. The Hope Community Church parking lot is the largest parking lot at one-quarter of a city block with approximately 50 parking spaces. The sampling site is located in a handicap parking spot on the west side of South 11th Ave. A system of PVC pipes was used to transfer water from the sampling location to the curb where a plastic box marked in 1-liter increments could collect runoff flow. This asphalt parking lot was repaved in early summer 2017. The Augustana parking lot consists of 24 parking spaces and is a narrow area with a large tree near the building. The slope of this parking lot is moderate and PVC pipes were used to decrease the overall slope of the simulated runoff and allow for measuring flow in a five-liter plastic box. The pavement appears to be older but in good condition. The Portland Ave parking lot is made of concrete and is the smallest of the parking lot sampling sites. This plot area is mainly used for contractor parking for the Hennepin County building and includes about 5 parking spots. The sampling location is near a stormwater manhole. A low amount of pedestrian traffic was observed, and mainly large trucks were traveling in and out of the area.

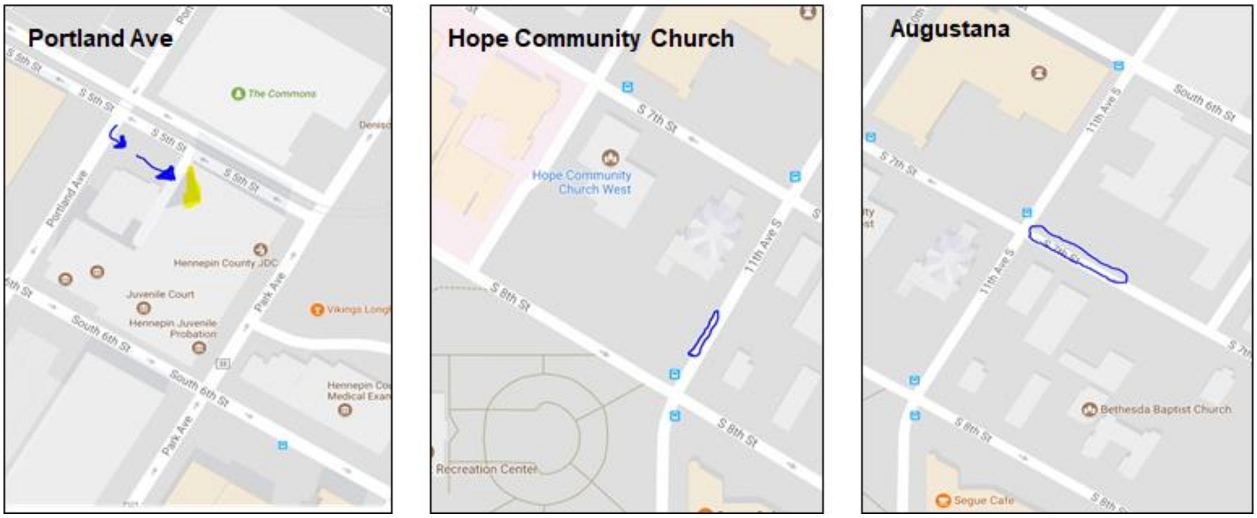


Figure 3. Parking Lot Sites. Base map from Google Map.

Rooftop Sites

Two rooftop locations, Hope Community Church roof and North Central University roof, are shown in Figure 1. The three roof locations used for sampling were City of Lakes (CoL) building (309 2ndAve S), Mensing Hall of North Central University (2 10th Ave S), and a small roof at Hope Community Church (704 11th Ave S, Minneapolis, MN 55415). Images of these rooftops are shown in Figures 4 through 6. Runoff characteristics were obtained from natural rainfall and snowmelt events.

Figure 4. City of Lakes Rooftop

City of Lakes Building is a four-story building located at the southern corner of S 3rd Street and 2nd Avenue S. The building is part of the Downtown West neighborhood in the downtown area of Minneapolis, MN. City of Lakes building has one large roof with two smaller structures with roofs atop the larger roof. The roof of interest (ROI) is the larger of the upper two rooftops and is centrally located on top of the larger roof. The ROI is rectangular in shape, has dimensions of 36 ft by 74.5 ft. The ROI is paved with asphalt covered in a layer of gravel and has one downspout. A PVC pipe system was constructed to route the roof rainwater indoors.

Hope Community Church roof is located at the southwest corner of 7th Street and 11th Avenue South. The building is part of the Elliot Park neighborhood in the downtown area of Minneapolis, MN. Hope Community Church roof is comprised of several different rooftops. The roof of interest is located in the southwest corner of the Hope Community Church East Building. Of the two rooftops located in the southwest corner of Hope Community Church, the smaller, more eastern roof was decided as the roof of interest. The roof is a trapezoidal prism and composed of a rubber membrane covered in a layer of gravel. The height from the top of the roof down to the rubber membrane bottom is 0.4 ft. The roof is 10 ft by 30 ft for an area of 300 ft^2.

Figure 5. Rooftop Material for Hope Community Church.

Mensing Hall is located at the north corner of S 7th Street and 10th Avenue S. The building is part of the Elliot Park neighborhood in the downtown area of Minneapolis, MN. The roof area of interest is approximately 20 ft by 60 ft. The roof is approximately 15 ft. above the ground. Mensing Hall roof is white in color and there is no rock medium.

Figure 6. Rooftop of Mensing Hall at North Central University.

Data Collection and Sampling Procedures

Streets, Sidewalks and Parking Lots

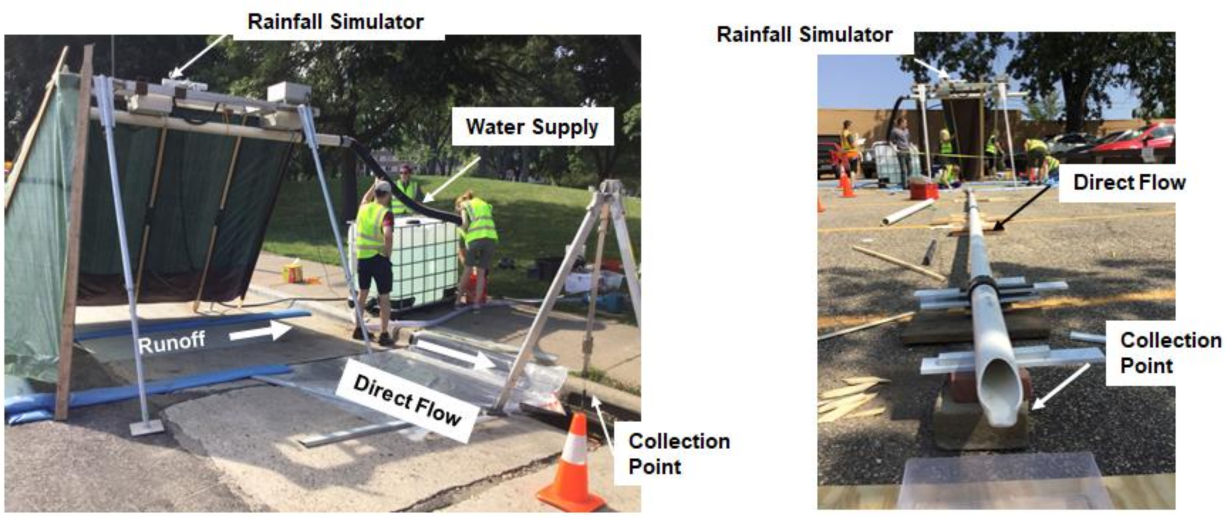
A rain simulator was used to collect samples from the street, sidewalk, and parking lot sites. The rain simulator was borrowed from the Minnesota Department of Agriculture. Details of the experimental procedures selected for the site using this simulator are given in Appendix C. A summary is given here.

The rain simulator required care in the transport, maintenance, and set up. Each sampling event involved running a rain simulator over an isolated section of pavement and collecting samples of the runoff. The eight-foot simulator was centered over a rectangular plot area of 6 ft by 12 ft. The rainfall intensity was set at a constant rate of 2.5 in h^{-1} for a duration of 45 minutes. The return period for this type of event is approximately 2 years (NOAA Atlas 14) for Minneapolis. To reduce the impact of recent runoff events, at least 48 hours of dry weather was required before raining on the test plots.

Before raining on the plot, the boundaries of the test area were isolated from the surrounding area. This was done by first pressing an adhesive tape on the watershed boundaries. Water-filled bags were then carefully situated on tape to ensure that rainfall outside these boundaries did not contribute to the measured runoff characteristics. Water from the test area was funneled to a collection point. The collection point for streets and sidewalks was a catch basin. Plastic sheets were used to allow water to flow alongside street gutters to the catch-base. The initial steps in the rain simulator runs are shown in Figure 7. The setup of the rain simulator for the 8th Street and Augustana parking lot is shown in Figure 8. Convenient catch-basins were not readily available for the Augustana and Hope Community Church parking lots. Runoff from these sites was directed to shallow pans. A relatively long pipe was needed for the Augustana site to have a sufficient vertical drop for the shallow collector. Wind screens were used with the simulator to ensure that the spatial depth over the plot was relatively uniform. The use of wind screens and the setup of the simulator for the Hope Community Church parking lot are shown in Figure 9.

Establishing Watershed Boundaries **Directing Runoff to Collection Point** **Collecting Flow and Samples**

Figure 7. Initial Steps in Rain simulator Runs.



8th Street Site **Augustana Parking Lot**

Figure 9. Setup of the Simulator at 8th Street and Augustana Parking Lot Sites.

Hope Community Church Parking Lot

Wind Screen: 8th Street Site

Figure 10. Simulator Setup at Hope Community Church Parking Lot and Simulator with Wind Screen.

After the plot area was marked and sealed, the simulator was set up and connected to a tank of tap water from the University of Minnesota's St Paul campus (otherwise referred to as "source water") and a pump connected to a generator. The source water tank is made of plastic and is shown in Figure 9. The rain simulator operates by pumping water out of a tank to two nozzles. The nozzles move back and forth spraying water in a rain-like pattern. The pressure of the water in the simulator is controlled using a manifold and return line and the speed of the simulator is changed using a control box. For the purpose of this study, the rain simulation area, simulator speed, and pressure were all held constant. The rain simulator was first rinsed with source water while the sweep function was disarmed. Afterwards, tank level and water characteristics (temperature, dissolved oxygen, pH, and conductivity) were recorded. Once all of the components were ready, the simulator was started simultaneously with a stopwatch. The water pressure was constantly monitored to ensure stable rainfall intensity. After precisely 45 minutes, the rain simulator was stopped. Runoff from the simulation was monitored until it stopped flowing into the five-gallon bucket or shallow pan.

During the runoff, one-liter samples were collected at time intervals of 1, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 37.5, and 45 minutes after runoff first reached the catch-basin. After each sample was collected, water quality measurements were taken on site using a YSI multiparameter sonde. Water temperature, dissolved oxygen, conductivity, and pH were recorded. Sample bottles were then stored on ice until the simulation was completed and samples were ready for compositing. Once sampling was completed, the one-liter bottles were composited using an event mean concentration (EMC) spreadsheet created by Dr. Bruce Wilson to determine the appropriate volume from each sample.

The composite sample was then sent to the Met Council laboratory to determine concentrations of total suspended solids (TSS), chloride, chemical oxygen demand (COD), *E. coli*, cadmium, chromium, copper, lead, nickel, magnesium, manganese, zinc, sodium, nitrate-N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), ortho-phosphate (OP), total organic carbon, turbidity, calcium, iron, mercury, and potassium. These concentrations were also measured in the source water. The concentrations in the runoff were obtained by subtracting the source water values from the composite concentrations of the runoff. In addition to the composite sample, the first sample of each event, or the first flush flow, was sent to the laboratory for bio-chemical analyses if the standard deviation of conductivity was greater than two. Additional grab samples of the remaining water and sediment on the plastic after the event were also analyzed.

Rooftop sampling

Natural rainfall and snowmelt events were used to determine the runoff characteristics from the three test roofs. The setups for all three sites are shown in Figure 11. The three sites were not set up identically to one another because of site constraints. Common instrumentation components are the Teledyne ISCO automated sampler, Campbell CR10X datalogger, an ISCO rain gauge and a conductivity sensor.

City of Lakes **Hope Community Church** **NCU: Mensing Hall**

Figure 11. Monitoring Equipments for Rooftops.

The City of Lakes set-up included a modified PVC pipe system to control the water flow regime as it traveled down the pipe. This allowed for use of an area-velocity sensor, so samples could be collected based on flow. This setup is shown in the left-sided picture of Figure 11. The pipe system allowed for flow, conductivity and rain depth measurements by including a p-trap and a horizontal pipe channel for the rainwater to flow through. The ISCO sampled from the p-trap at the top of the pipe system and was triggered by the ISCO's flow meter. A Campbell Scientific CR10X data logger and a battery tender were attached to the wall above the ISCO. The CR10X logged conductivity and water level data.

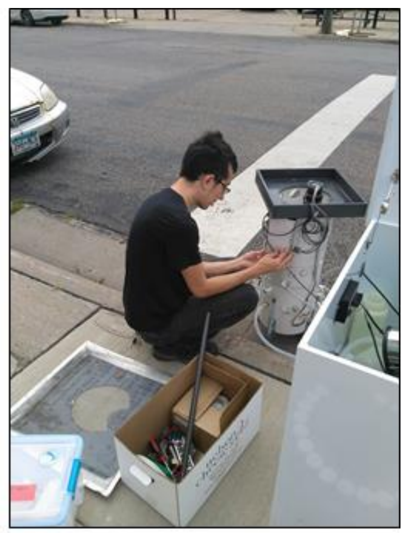
The roof for Hope Community Church is roughly 10 ft above the ground surface and has one downspout where all of the water from the roof was transported to the ground. A tipping bucket rain gauge was located atop the roof. A PVC pipe system was attached to the roofs downspout inlet and connected to a collection tank as shown in Figure 11. The water depth in the tank was obtained by pressure transducer located within the tank. A p-trap was placed within the PVC pipe system to house the conductivity probe and provide enough volume for the ISCO automated sampler to collect a sample. A white weatherproof cabinet was placed to the right of the collection tank to house weather sensitive electronics. The ISCO automated sampler and the Campbell Scientific CR10X data logger were located inside the cabinet. The ISCO sampler was used to collect rain event samples while the CR10X was used to log conductivity data, tank depth data and to trigger the ISCO to sample based on rainfall runoff depth in the tank.

Mensing Hall roof has at least 3 downspouts transporting water from the roof to the ground. In order to isolate the water going into the downspout of interest, water-filled plastic bags were strategically placed on the roof. The collection system for Mensing Hall was similar to that used for Hope Community Church. A tipping bucket rain gauge was located on the roof, a PVC pipe system was attached to the downspout that drained to the tank where a pressure transducer measured the water depth, a p-trap was again used for a conductivity probe and a weather proof cabinet was placed to the right of the collection tank to house weather sensitive electronics. Inside the cabinet was the ISCO automated sampler, and the Campbell Scientific CR10X data logger. The ISCO was used to collect rain event samples while the CR10X was used to log conductivity data and tank depth data. The ISCO was triggered by the tipping bucket rain gauge.

Sampling natural rainfall sampler

In addition to determining the characteristics of runoff using a rain simulator, the runoff from natural rainfall events were also examined at the 10th Ave S site. An important goal of this work was to evaluate a novel design to measure and collect data from natural rain events. This design required calibration of the flow rate that occurs through numerous orifices created in a circular pipe. The flume used for calibration of the sampler and field installation of the sampler are shown in Figure 12.

Flume for Calibration



Field Installation

Figure 12. Natural Rainfall Event Sampler.

Representation of Runoff-Depth Dependent EMC

General Framework

In this section, we are interested in developing relationships to vary the event mean concentration (EMC) for different runoff depth or runoff volumes. We start with the definition of EMC as:

$$\text{EMC} = \frac{\text{Total Runoff Mass}}{\text{Total Runoff Volume}} = \frac{\text{M}_{\text{ro}}}{\text{V}_{\text{ro}}} = \frac{\int_0^{t_{end}} QC\ dt}{\int_0^{t_{end}} Q\ dt} = \frac{\int_0^{V_{ro}} C\ dV}{\int_0^{V_{ro}} dV} \qquad 1$$

where differential change in the cumulative runoff volume (V) is defined as dV = Qdt. We are interested in the change of the event mean concentration with the magnitude of the runoff event, that is, EMC=f(V). To illustrate how we can consider this change, we assume that the concentration of the analyte is well represented by the relationship of

$$\text{C} = (\text{C}_\text{o} - \text{C}_\text{f})\exp(-\kappa\,\text{V}) + \text{C}_\text{f} \qquad 2$$

where C_o is the initial concentration corresponding to runoff volume of V=0, C_f is the final concentration corresponding to $V \rightarrow \infty$ and κ is a decay coefficient. Substituting this relationship into Eq. 1, we obtain

$$\text{EMC} = \frac{\int_0^{V_{ro}} \left((\text{C}_\text{o} - \text{C}_\text{f})\exp(-\kappa\,\text{V}) + \text{C}_\text{f}\right) dV}{V_{ro}} = \frac{C_o - C_f}{\kappa\, V_{ro}}\ (1 - \exp(-\kappa V_{ro})) + C_f \qquad 3$$

For a known runoff volume, the user needs to determine parameters C_o, C_f and κ to compute EMC. The next subsections discuss methods for determining these parameters. For this project, all of the methods are dependent on the relatively numerous conductivity data obtained by the YSI probe. This approach inherently assumes that the entrainment and transport of non-conductivity analytes are similar to those of conductivity. Some of the methods use the measured concentration of the first bottle (first flush) and the measured event mean concentration to determine the appropriate exponential parameters for non-conductivity values. The simplest method determines these parameters by only using the measured event mean concentration.

Parameter Estimation from Conductivity Probe

To use Eq. 2, a minimum of three observed data values of concentration and runoff volume are needed to determine the three parameters of C_o, C_f and κ. We will first determine these three parameters from the many conductivity values available from a conductivity probe. By using Solver in Excel, or equivalent optimization routines in other platforms, the parameters of $C_{c,o}$, $C_{c,f}$ and κ_c can be obtained from a known V by minimizing M defined as

$$\text{M} = \sum_{\text{i}=1}^{\cdot\cdot} (O_{ci} - C_{ci})^2 \qquad 4a$$

where O_{ci} is the observed conductivity and C_{ci} is the predicted conductivity given by Eq. 2. The subscript "c" is used to indicate a solution for conductivity values. For our runoff data, the solution to the parameters was obtained using Excel spreadsheets.

Once again, outcomes of this analysis are values for $C_{c,o}$, $C_{c,f}$ and κ_c for a given runoff event with measured conductivity and runoff volume data. From this data set, we can compute the ratio of final to initial concentration, which is

$$R_{cc} = \frac{C_{fc}}{C_{oc}} \qquad 4b$$

Parameter Estimation Using B1C and EMC

General Formulation

For many of the analytes, the first bottle and the event mean concentrations have been measured. We will use then notation of B1C for the concentration of the first bottle and V_{b1} for the corresponding cumulative runoff volume corresponding to the first bottle. To simplify the mathematical manipulations, we will define parameters of

$$K_1 = \exp(-\kappa\, V_{b1}) \qquad 5$$

$$K_m = \left(\frac{1}{\kappa\ V_{ro}}\right)(1 - \exp(-\kappa\, V_{ro})) \qquad 6$$

Using Eqs. 2 and 3, relationships corresponding to the known first bottle and event mean concentrations can then be written as

$$\mathrm{B1C} = K_1\, C_o + C_f\,(1 - K_1) \qquad 7$$

$$\mathrm{EMC} = K_m\, C_o + C_f\,(1 - K_m) \qquad 8$$

Parameters Using κ_c

We are now interested in solving for C_o and C_f for any analyte k. Since only B1C and EMC are known, this solution requires a condition for one or more of the parameters obtained from the analysis of the conductivity data. In this section, we assume that the decay coefficient obtained from conductivity data is applicable to other analytes, that is, κ_k=κ_c. Multiplying the B1C relationship by K_{mc}/K_{1c} and subtracting it from the EMC relationship, we can then solve for C_{fk} as

$$\mathrm{EMC_k} - K_{mc}\, \mathrm{B1C_k} / K_{1c} = C_{fk}\left((1 - K_{mc}) - K_{mc}(K_{1c} - 1)\right) \qquad 9$$

$$C_{fk} = \frac{\mathrm{EMC_k} - K_{mc}\, \mathrm{B1C_k} / K_{1c}}{(1 - K_{mc}) - K_{mc}(K_{1k} - 1)} \qquad 10$$

and solve for C_{ok} from Eq. 7 as

$$\mathrm{C_{ok}} = \frac{B1C_k - C_{fk}\,(1 - K_{1c})}{K_{1c}} \qquad 11$$

Parameters Using R_c

We can alternatively solve for κ_k, C_{ok} and C_{fk} by assuming that the ratio of the C_{fv} and C_{ov} obtained from the conductivity data is applicable to the analytes. Here we will further adjust the ratio from conductivity data to define R_c as

$$\mathrm{R_c} = \frac{\mathrm{C_{fk}}}{C_{ok}} = R_{cc}\left(\frac{B1C_c/EMC_c}{B1C_k/EMC_k}\right) \qquad 12a$$

In contrast to the solution of the previous section, the formulation here results in a nonlinear algebraic equation that needs to be solved using Excel solver or other iterative approach. For any analyte k, the ratio between these two concentrations is defined from Eqs. 7 and 8 as

$$\left(\frac{B1C}{EMC}\right)_{\mathrm{k}} = \frac{(\mathrm{C_{ok}} - \mathrm{C_{fk}})\mathrm{K_{1k}} + \mathrm{C_{fk}}}{(\mathrm{C_{ok}} - \mathrm{C_{fk}})\,K_{mk} + C_{fk}} = \frac{\mathrm{K_{1k}} + \dfrac{\mathrm{C_{fk}}}{\mathrm{C_{ok}} - \mathrm{C_{fk}}}}{K_{mk} + \dfrac{\mathrm{C_{f,k}}}{\mathrm{C_{o,k}} - \mathrm{C_{f,k}}}} = \frac{\exp(-\kappa_{\mathrm{k}}\,\mathrm{V_{b1}}) + \dfrac{\mathrm{R_c}}{1 - R_c}}{\dfrac{1 - \exp(-\kappa_k V_{ro})}{\kappa_k\,V_{ro}} + \dfrac{\mathrm{R_c}}{1 - R_c}} \qquad 12b$$

where an iterative solution can be used to determine κ_v. After κ_v is known, C_{ok} can be computed as

$$EMC_{\mathrm{k}} = (\mathrm{C_{ok}} - \mathrm{C_{fk}})\,K_{mk} + C_{fk} = \mathrm{C_{ok}}(1 - \mathrm{R_c})\,K_{mk} + C_{ok}R_c \qquad 13a$$

$$\mathrm{C_{ok}} = \frac{\mathrm{EMC_k}}{(1 - \mathrm{R}_c)\,K_{mk} + R_v} \quad and\ C_f = C_{ok}R_c \qquad 13b$$

The ratio of B1C and EMC must be greater than one. The right-hand side of Eq. 12 is greater than one if K_{mk} < K_{1k}. The largest possible value for K_{lk} is one that corresponds to V_{b1} =0. Greater insight into K_{mk} can be obtained by using the Taylor Series expansion for exponential function defined as

$$\mathrm{e^x} = 1 + \mathrm{x} + \frac{\mathrm{x}^2}{2!} + \frac{\mathrm{x}^3}{3!} + \cdots + \qquad 14$$

We can then evaluate K_{mk} as

$$K_{mk} = \frac{1 - \exp(-\kappa_k V_{ro})}{\kappa_k\,V_{ro}} = \frac{1 - \left(1 - \kappa_k\,V_{ro} + \dfrac{(\kappa_k\,V_{ro})^2}{2!} - \dfrac{(\kappa_k\,V_{ro})^3}{3!} + \cdots +\right)}{\kappa_k\,V_{ro}} = 1 - \frac{\kappa_k\,V_{ro}}{2!} + \frac{(\kappa_k\,V_{ro})^2}{3!} - \cdots + \qquad 15$$

which is generally less than one and is always less than one for $\kappa_k V_{ro} < 1$.

A robust solution can be obtained by using V_{b1} = 0 and neglect third-order terms in Taylor Series expansion for e^x. Eq. 12 can then be written as

$$\left(\frac{B1C}{EMC}\right)_{\mathrm{k}} = \frac{1+\frac{\mathrm{R_v}}{1-R_v}}{1-\frac{\kappa_k V_{ro}}{2}+\frac{\mathrm{R_v}}{1-R_v}} = \frac{1+\mathrm{K_r}}{1-\frac{\kappa_k V_{ro}}{2}+K_r} \qquad 16$$

which can be rearranged as

$$1-\frac{\kappa_k V_{ro}}{2}+K_r = \left(\frac{\mathrm{EMC_k}}{B1C_k}\right)(1+K_r) \qquad 17a$$

$$\kappa_{\mathrm{k}} = \left(\frac{2}{\mathrm{V_{ro}}}\right)\left(1-\frac{\mathrm{EMC_k}}{B1C_k}\right)(1+K_r) = \left(\frac{2}{\mathrm{V_{ro}}}\right)\left(1-\frac{\mathrm{EMC_k}}{B1C_k}\right)\left(1+\frac{\mathrm{R_c}}{1-R_c}\right) \qquad 17b$$

We also conclude that

$$C_o = B1C \text{ and } C_f = R_c\, C_o \qquad 18$$

Parameter Estimation EMC only

The event mean concentration is often the only measured concentration for a storm event. Consider a site that has a conductivity probe for which κ_v and R_v have been determined. We will assume that these values are applicable to other analytes, that is, κ_k=κ_c.and R_k=R_c. We can then define

$$\mathrm{K_m} = \left(\frac{1}{\kappa_c\ V_{ro}}\right)\left(1-\exp(-\kappa_c\, V_{ro})\right) \qquad 19$$

$$\mathrm{EMC_k} = K_m\, \mathrm{C_{ok}} + C_{fk}\,(1-K_m) = C_{ok}\left(K_m + R_c\,(1-K_m)\right) \qquad 20$$

We are then able to solve for C_o and C_f as

$$\mathrm{C_{ok}} = \frac{\mathrm{EMC_k}}{\mathrm{K_m}+R_c(1-K_m)} \quad \text{and} \quad C_{fk} = R_c\, C_{ok} \qquad 21$$

Results and Discussion

Streets, sidewalks, and parking lots

The following section describes the results found from the data collected over three seasons (summer, fall and spring) from three different surface uses (street, sidewalk and parking lot) with three different surfaces for each use. All data collected were adjusted for the source water sample values collected on each sampling day in order to get pollutant values from the surface. Contribution of analytes from rain water should therefore be added to reported values for a more precise estimate of concentrations resulting from natural rainfall events. For some samples, the subtraction of source water resulted in negative concentrations. These negative values only occur for small measured values and are likely caused by the accuracy of measuring such small values. *E. coli* results over the course of the study were consistently below the detection limit for streets, sidewalks and parking lots. Total phosphorus values were also frequently below the detection limit. Spring was the season with the highest yield in contaminant runoff, while summer and fall results were similar. Only a summary of the concentrations is given here. The complete data set is given in Appendices A and B.

An overview of the trends of EMCs with surface types is given by combining EMCs of seasons and sites to obtain average values for streets, sidewalks and parking lots. The overall average EMCs for chloride, TSS and COD are shown in Figure 13 and for much smaller concentrations for nickel, zinc, copper and lead are given in Figure 14. The largest potential concentrations are chloride and TSS for streets and sidewalks.

Greater insight into trends is obtained by considering seasonal impacts. Seasonal values for EMC and B1C of chloride, chromium, and TSS are given in Tables 1, 2 and 3. Other analytes are given in Appendix A. Event mean concentrations of chloride are fairly consistent and have small values for the summer and fall seasons. For example, the average chloride EMCs among three sites for the fall are 0.8 mg/L, 1.1 mg/L, and 0.6 mg/L streets, sidewalks and parking lots, respectively. However, the corresponding values for spring are 248 mg/L, 6 mg/L and 9 mg/L.

Graphical representations of seasonal trends of EMC and B1C for TSS and COD are given in Figures 15 and 16. These concentrations are averaged values for all sites for a given surface for each season. Water quality standard for TSS is also shown in Figure 15. Once again, the concentrations for the spring season are larger than those of the fall and summer. B1Cs are generally much greater than EMCs, indicating a first-flush process. The B1Cs are frequently greater than the water quality standard of TSS for all seasons, and the EMCs are greater than the standard for the spring season. More information on the measured analyte concentrations relative to their water quality standard are given in Appendix A.

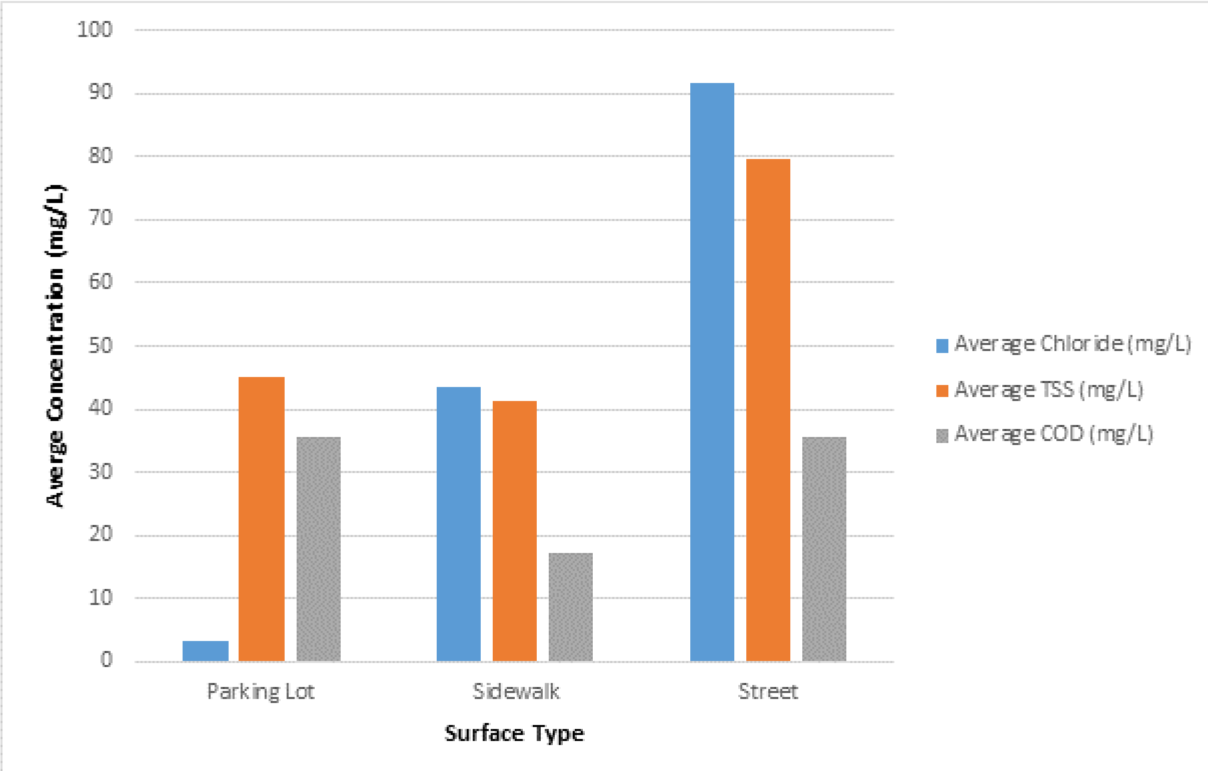


Figure 13. Average EMC for Cl, TSS and COD by Combining Data from Different Surfaces.

Table 1. Summary of Three Representative Analytes for Summer Season. B1C is the concentration of the 1st bottle and EMC is the event mean concentration.

Site	Chloride		Chromium		TSS	
	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)
S 8th St Street	-	0.8	-	0.0041	639	65
S 8th St Sidewalk	6.2	0.8	0.0042	0.0004	-	8.5
3rd Ave S Street	0.7	2.6	0.0052	0.0007	-	11
3rd Ave S Sidewalk	7.5	1.8	0.0024	0.0002	-	2.2
10th Ave S Sidewalk	5.4	0.8	0.0012	0.0001	15.5	0
10th Ave S Street	-	1	-	0.0009	-	13
Portland Parking Lot	2.5	0.7	0.0056	0.0002	167.5	7.5
HCC Parking Lot	2.3	0.1	0.0013	0.0001	31	1
Augustana Parking Lot	1	0.7	0.0009	0.0001	91	2

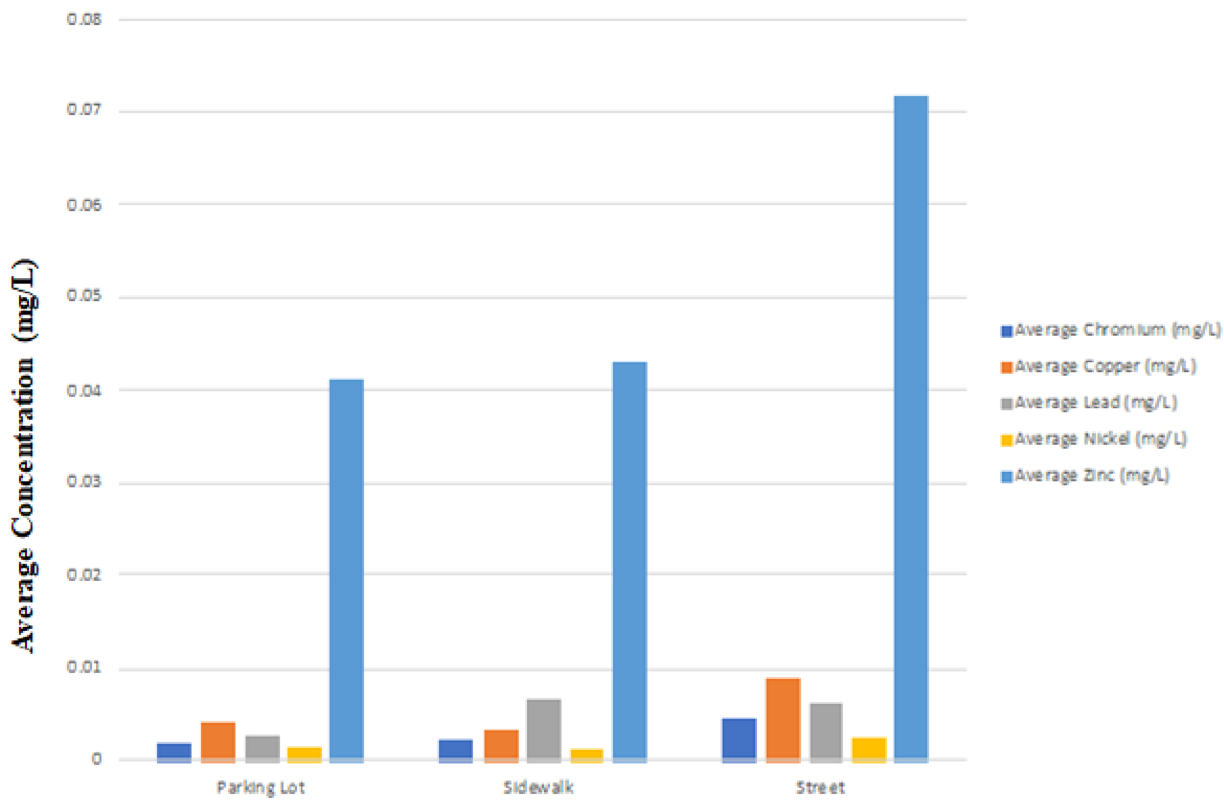


Figure 14. Average EMC for Cr, Cu, Pb, Ni, and Zn by Combining Data from Different Surfaces

Table 2. Summary of Three Representative Analytes for Fall Season. B1C is the concentration of the 1st bottle and EMC is the event mean concentration.

Site	Chloride		Chromium		TSS	
	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)
S 8th St Street	1.2	0.7	0.0033	0.0005	-	8
S 8th St Sidewalk	2.8	1	0.0028	0.0005	41.5	5.5
3rd Ave S Street	2.4	0.8	0.0084	0.0012	-	18.5
3rd Ave S Sidewalk	7.9	1.2	0.0067	0.0006	-	10.5
10th Ave S Street	2.6	0.9	0.0049	0.0007	-	16.5
10th Ave S Sidewalk	8.8	1	0.0049	0.0002	-	3.5
Portland Parking Lot	2.3	0.6	0.0047	0.0006	-	11.5
HCC Parking Lot	-	0.5	-	0.0002	-	3.5
Augustana Parking Lot	0.5	0.7	0.0017	0.0004	77.5	7.5

Table 3. Summary of three representative analytes for Spring season. B1C is the concentration of the 1st bottle and EMC is the event mean concentration.

Site	Chloride		Chromium		TSS	
	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)	B1C (mg/L)	EMC (mg/L)
S 8th St Street		704.1	0.08219	0.01379	-	240
S 8th St Sidewalk	598.7	410.6	0.05739	0.00879	-	210
3rd Ave S Street	863.8	88.4	-	0.00949	-	112.5
3rd Ave S Sidewalk	174.1	14.1	-	0.00699	-	87.5
10th Ave S Street	122	27.1	0.05839	0.00979	2499.5	231.5
10th Ave S Sidewalk	14.1	2.6	0.00728	0.00298	108.5	46.5
	20.1	2	0.02119	0.00259	356.5	38.5
Portland Parking Lot	162.5	14.6	0.06366	0.00786	-	151.5
HCC Parking Lot	19.3	3.4	0.01542	0.00282	-	72.5
Augustana Parking Lot	34.6	8.7	0.02862	0.00552	768.5	149.5

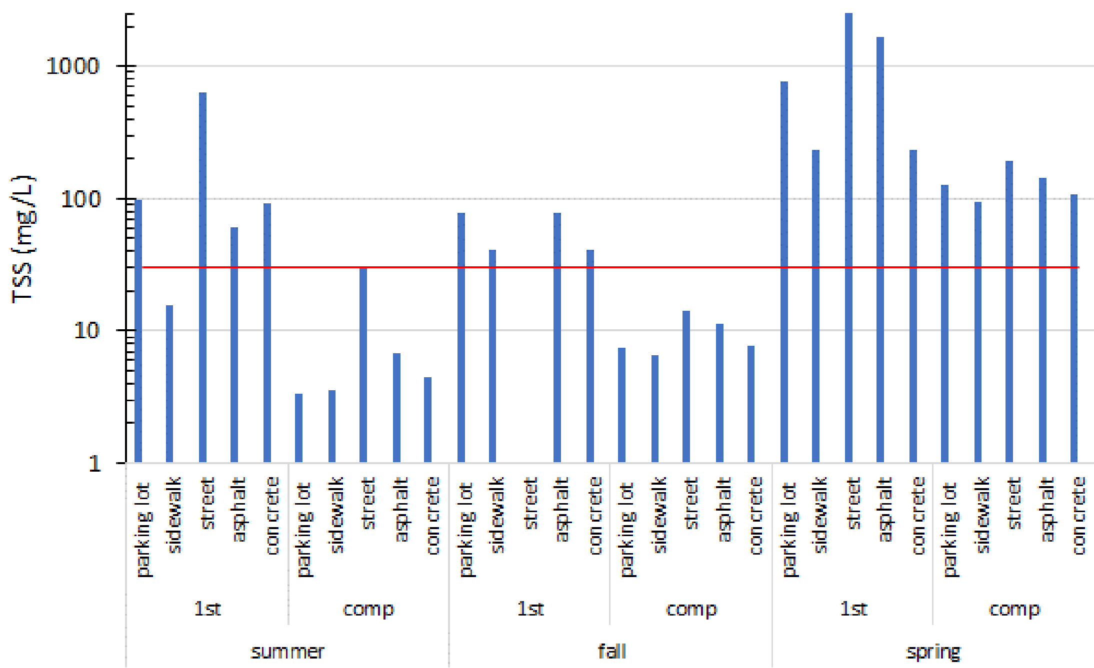


Figure 15. First Bottle (1st) and Event Mean (comp) TSS Concentrations for each season.

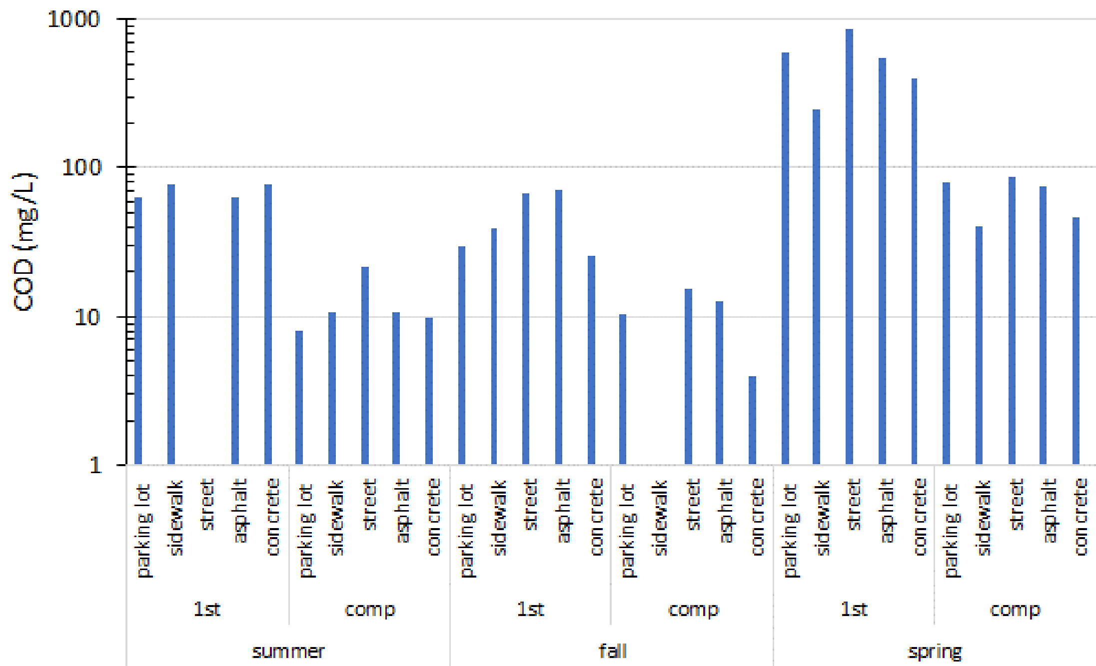


Figure 16. First Bottle (1st) and Event Mean (comp) COD Concentrations for Each Season

Roofs

Tabular concentration values from roofs are given in Appendix A. These values are summarized by using the average values for summer, fall and spring seasons in Figures 17 through 22. Selected analytes for comparison are chloride, total Kjeldahl nitrogen, total suspended solids, total phosphorus, E. coli and chemical oxygen demand. In contrast to the rain simulator events, measured values for roofs can have different storm characteristics. For example, roof runoff data from Mensing Hall was only collected during the summer of 2018. Because of these different storm characteristics, assessment of the impact of roof type on measured concentrations is more difficult.

In general, chloride concentrations from the roofs are small for summer, fall and spring seasons. Their EMCs for summer and fall are similar in magnitude to those of the ground sites. For the spring season, ground site concentrations are generally much larger than those measured for the roofs. The EMCs of TSS and TP from the roofs exceeded Minnesota water quality standards for some of the runoff events. In contrast to the ground sites, detectable *E. coli* concentrations were observed for the roofs. The COD concentrations tend to be larger for roofs than the summer and fall data of ground sites.

An approach to evaluate the possible differences in the response of roof type is to compare the slopes of regression surfaces obtained for each roof. This approach was examined by plotting the measured EMCs for each roof as a function of precipitation depth. The results are shown in Figure 23. No noticeable trend between EMC and depth is apparent. However for similar precipitation depth, the TSS and TP for COL roof appears larger than those of HCC.

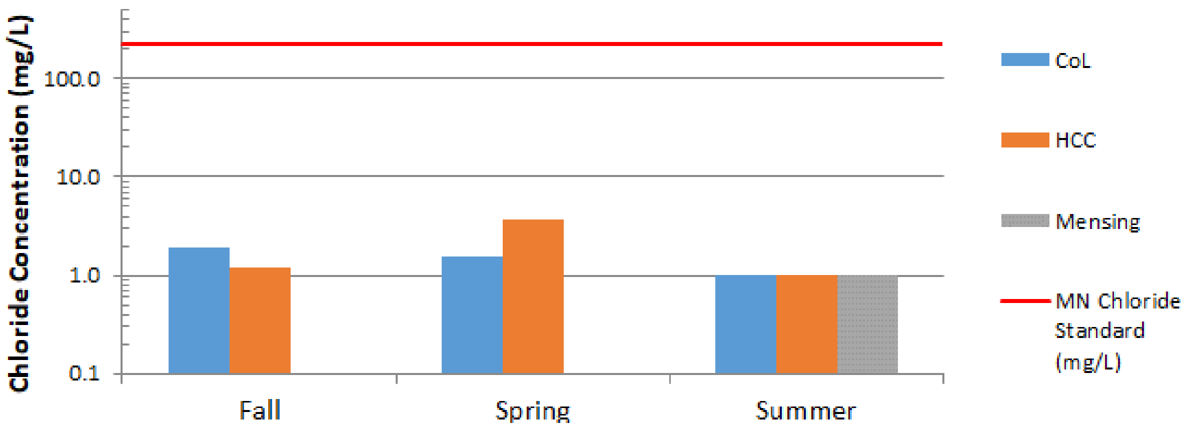


Figure 17. Average Chloride EMCs for Roofs by Season.

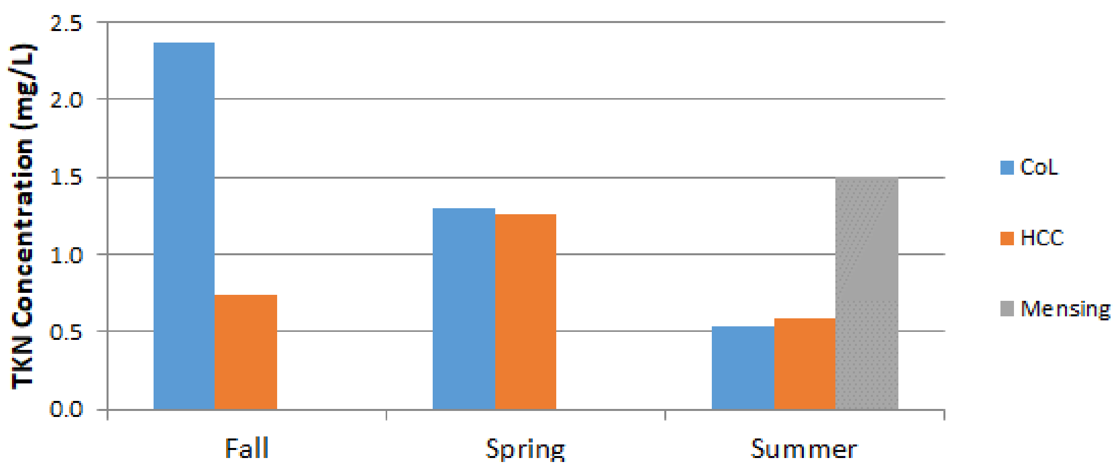


Figure 18. Average TKN EMCs for Roofs by Seasons.

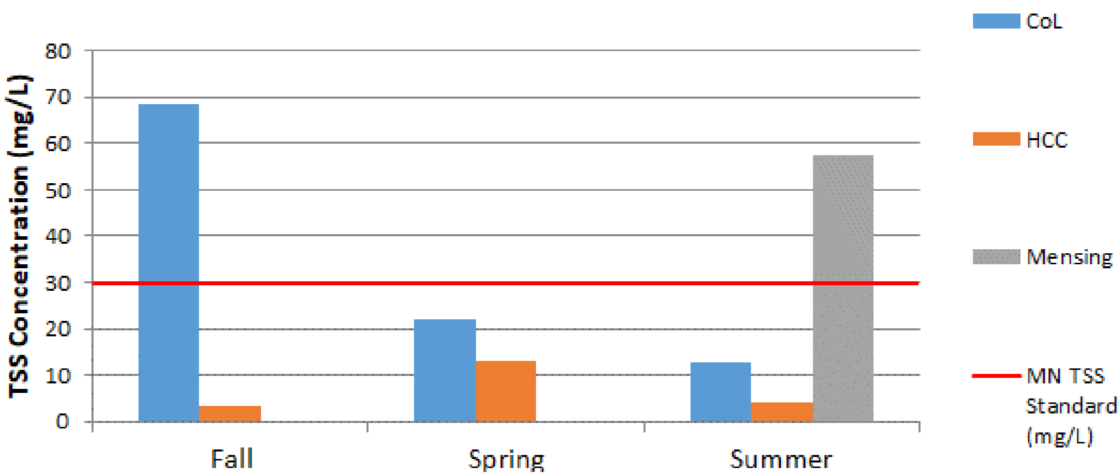


Figure 19. Average TSS EMCs for Roofs by Season.

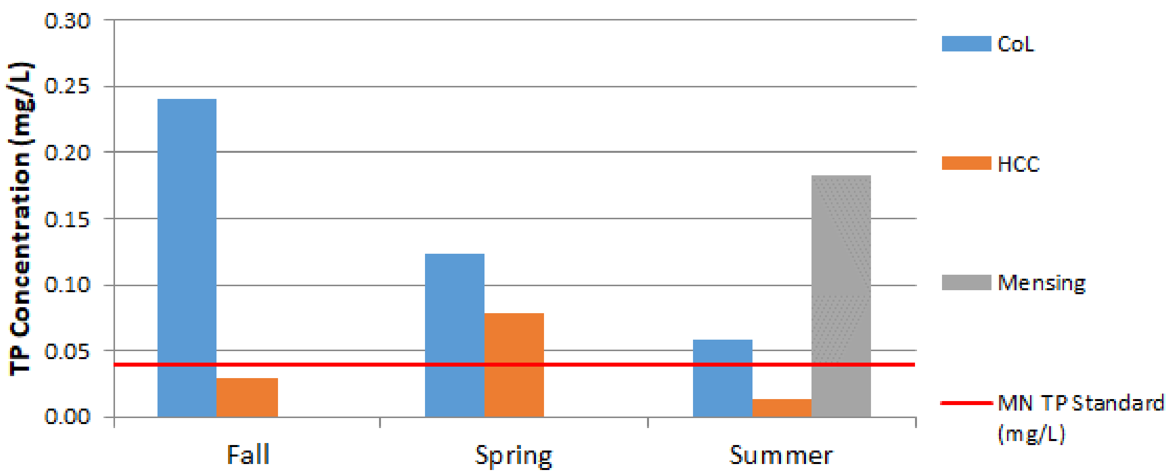


Figure 20. Average TP EMCs for Roofs by Season.

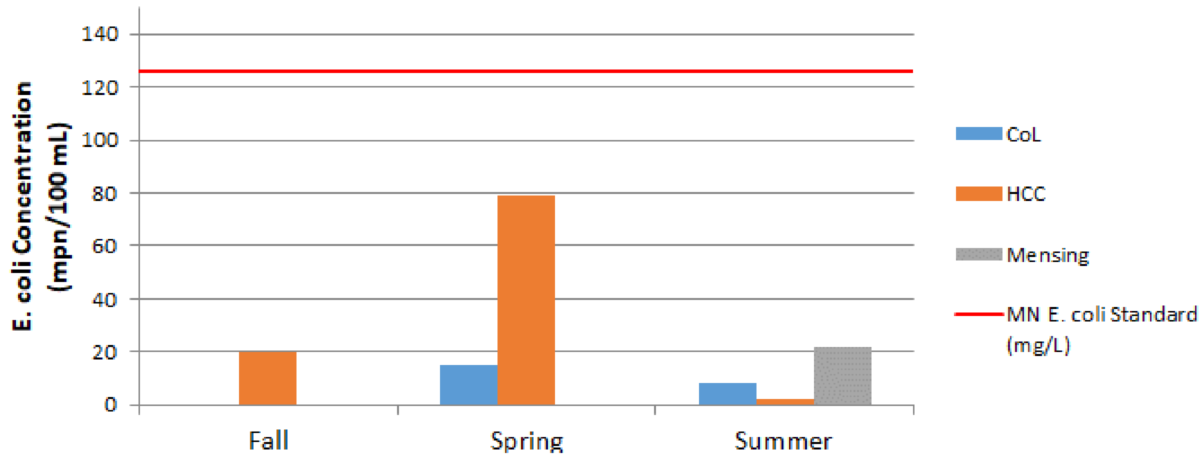


Figure 21. Average E. coli EMCs for Roofs by Season.

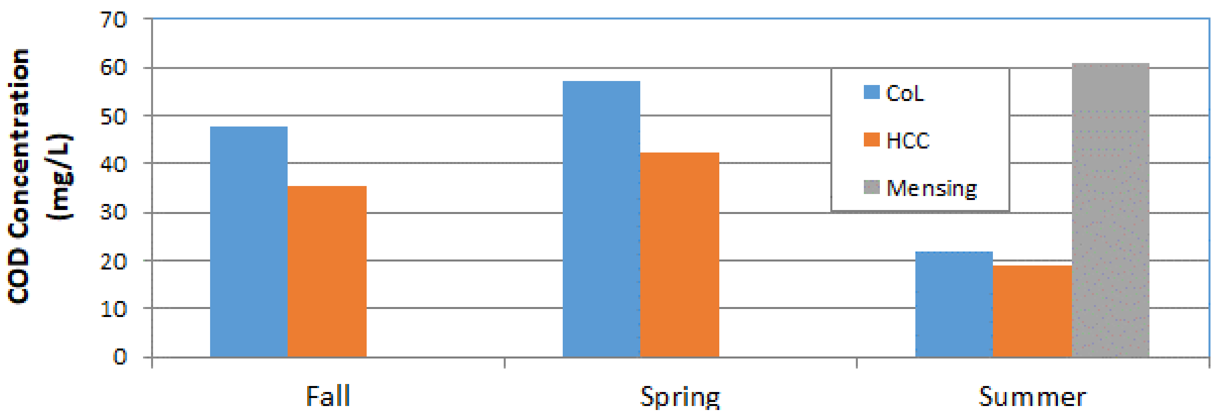


Figure 22. Average CODs for Roofs by Season.

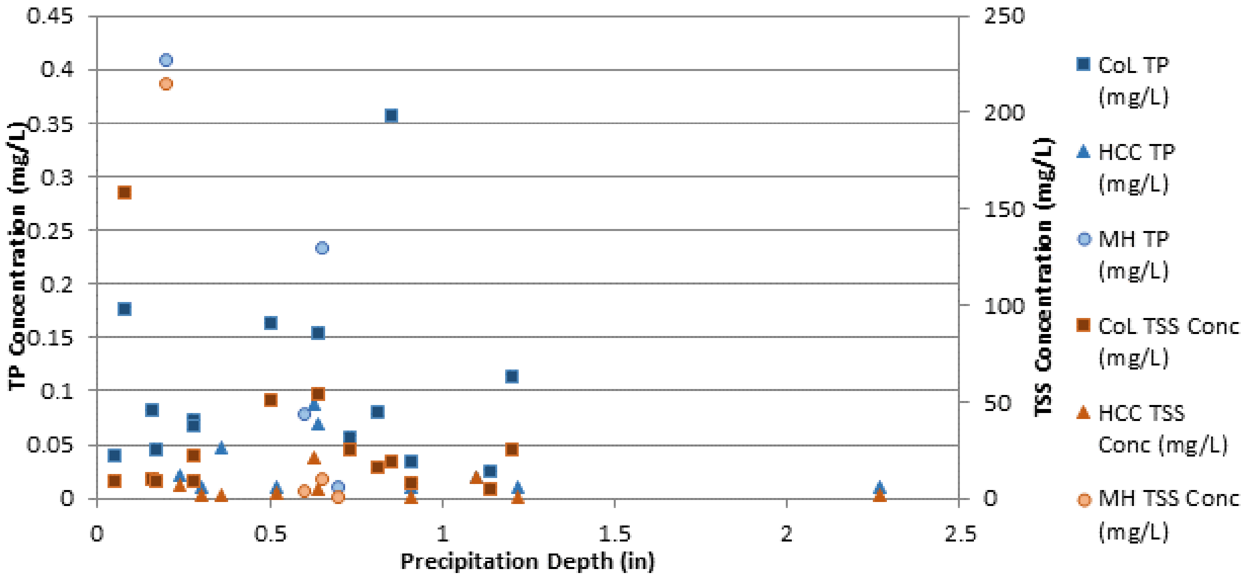


Figure 23. Trends in TSS and TP EMCs of Roofs with Precipitation Depth.

Winter season

Snowmelts are generally challenging to measure because freezing and thawing cycles can create problems on the operation of sensors and data acquisition systems. However, the data collection system for COL site was inside the building, negating any potential freeze thaw issues. Several snowmelt events from this roof were measured during winter of 2017-2018. The most interesting trends were in the chloride concentrations. These trends are shown in Figure 24. Each chloride concentration value corresponds to a composite sample collected for a snowmelt event.

As shown in Figure 24, there were several snow events for the winter season and corresponding snow removal and/or salt application activities. Snowmelt events can occur when the average daily temperature is less than 32°F because of solar radiation, heat loss from the building and other processes. Measured concentrations of chloride exceeded 60 mg/L for three of the events. These large concentrations are particularly interesting because the average chloride concentrations for non-winter events were less than 10 mg/L.

Composite concentrations were obtained from grab samples for two snowmelt events. One of the events sampled runoff at the 8th Street site on February 14, 2018 and the other event sampled runoff at the 3rd Avenue site on February 28, 2018. Composite concentrations for different analytes are shown in Table 4. Chloride and TSS concentrations are generally larger than those measured from the rain simulator runs. Chloride concentrations are much larger. The largest chloride EMC observed from the simulator runs was 704 mg/L; whereas the chloride concentrations for the snowmelt events were 26,331 mg/L and 2,996 mg/L for the first and second events, respectively.

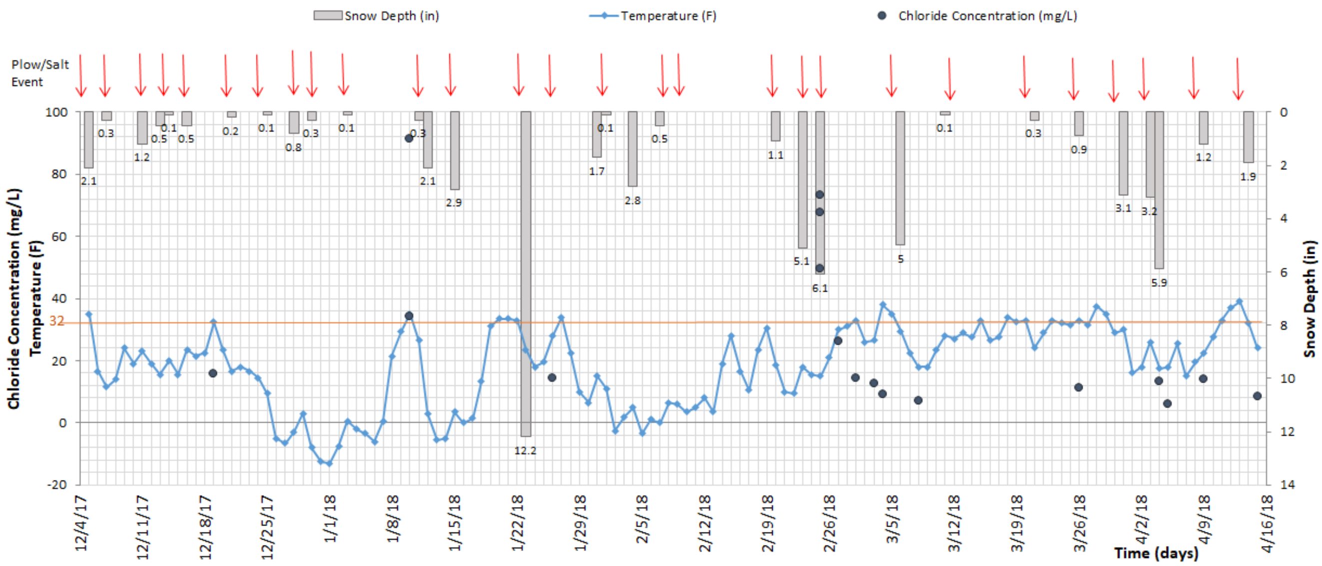


Figure 24. Cl concentrations, snow depth, average temperature and plow/salt event at COL Roof.

Table 4. Concentrations of Analytes for Two Snowmelt Events.

Analyte	Units	8th Street Feb 14	3rd Ave Feb 28
Cl	mg/L	26331.8	2996.7
COD	mg/L	860	
E. coli	mpn/100 ml		38
Cd	mg/L	0.002	~0.00055
Cr	mg/L	0.0339	0.0217
Cu	mg/L	0.1	0.0816
Pb	mg/L	0.0561	0.0268
Ni	mg/L	0.02	0.0144
Zn	mg/L	0.56	0.388
TKN	mg/L	18	2.9
TP	mg/L	1.3	0.491
TSS	mg/L	652	288

Runoff dependent EMC

Selected rain simulator events were used to evaluate the parameters for the runoff dependent EMC given by Eq. 3. Three parameters, C_o, C_f and κ, are needed to use this relationship. As previously discussed, we proposed that one or more of these parameters can be determined from the frequently recorded conductivity data. However, the runoff conductivity values obtained by subtracting the conductivity of the source water from these measured values were sometimes negative. These results were likely a consequence of a different temperature of the source water than that of the sample bottles. Specific conductance (SC) was therefore used instead of conductivity. Only a few of the simulator events recorded both conductivity and specific conductance. The number of possible events to evaluate the parameters for Eq. 3 was greatly reduced. It was beyond the scope of the project to manually adjust conductivity for temperature. Extra care is needed for this project because of the small conductivity values.

Measured SCs for Portland Parking Lot collected for the spring season are shown in Figure 25. The upper curve corresponds to SCs measured in the sample bottles and the lower corresponds to the estimated SCs obtained by subtracting the source water SC from these values. The adjusted SC at nearly steady conditions is very small relative to the source water SC. A small change in the SC of source water results in a relatively large percent change in the steady-state SC. Also shown in Figure 25 are the three parameters for each set of data obtained using Eq. 4a. The exponential decay function was able to accurately represent both sets of data.

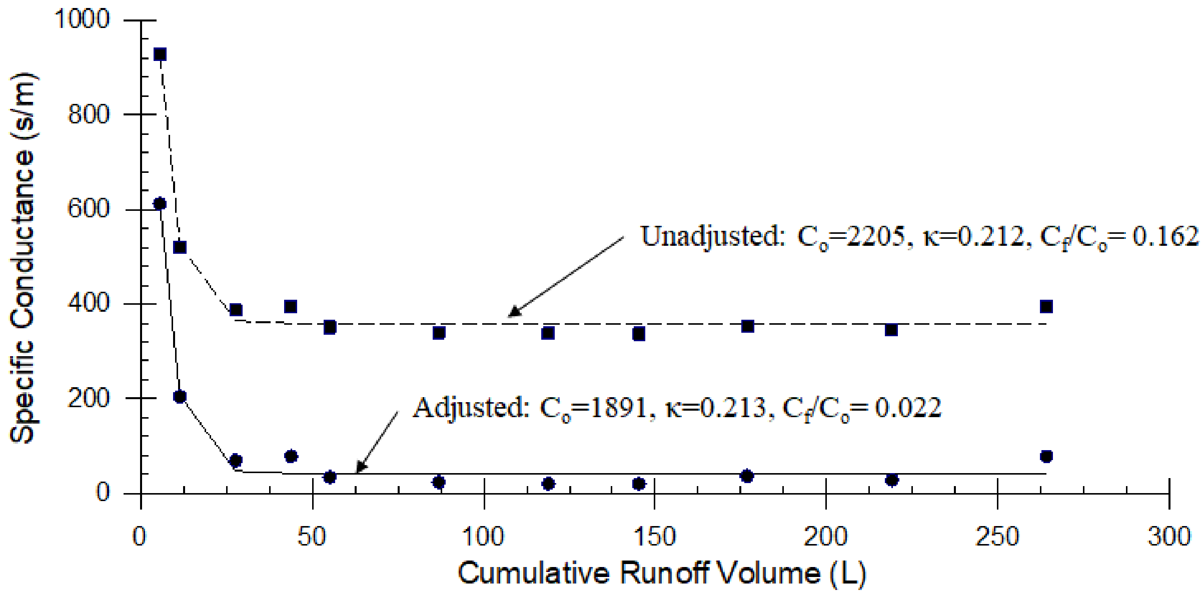


Figure 25. Specific Conductances for Portland Parking Lot Measured on March 23, 2008.

Four different methods were previously discussed to estimate, C_o, C_f and κ. These methods use κ and/or the ratio of C_f/C_o. As shown in Figure 25, the decay coefficients, κ, vary little with the adjustment of SC; whereas the C_f/C_o ratios vary substantially for the two data sets. Since rigorous adjustment of the original conductivity data with temperature was beyond the scope of the project, we decided to use only the decay coefficient to estimate the exponential parameters for the other analytes. This decision limits us to only one method for determining C_f and C_o. These parameters are obtained by using Equations 10 and 11. Parameters determined by these equations ensure that the B1C and EMC obtained from the exponential functions are equal to the measured values.

Estimates of κ, C_o and C_f for four events are shown in Table 5. The decay coefficient varied substantially for the different events. The concentration response for the largest decay coefficient is shown in Figure 25. The C_o and C_f are dependent on the observed B1C and EMC.

Table 5. Exponential Parameters for Select Sites and Analytes. Units are κ, C_o, and C_f are L^{-1} and mg/L.

Sites/ Season	Fitted Parm	Analytes								
		Cl	TKN	TP	Cu	Ni	Pb	Cr	Cd	Zn
8th St Spring	κ		0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
	C_o		6.283	2.000	0.235	0.059	0.186	0.112	0.001	1.620
	C_f		0.722	0.114	0.011	0.003	0.008	0.007	0	0.078
8th Walk Fall	κ	0.845	0.845	0.845		0.845	0.845	0.845		0.845
	C_o	9.152	5.594	1.016		0.006	0.017	0.011		0.384
	C_f	0.925	0.162	0.009		0	0	0		0.011
Port Lot Fall	κ	0.067	0.067				0.067	0.067		
	C_o	3.153	0.550				0.011	0.007		
	C_f	0.428	0.070				0	0		
Port Lot Spring	κ	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213
	C_o	516.22	14.677	3.503	0.636	0.139	0.207	0.197	0.006	5.539
	C_f	5.327	0.166	0.146	0.011	0.003	0.004	0.004	0	0.077

Natural rainfall events

To supplement the rain simulator data, a unique instrumentation system was installed at the 10th Avenue site in August of 2018. Several natural rainfall events were collected with this system. Complete analysis of this data set was not possible within the time constraints of the project. However, preliminary results were useful in providing insight into whether the response from natural rainfall events was similar to those obtained from the simulator. The concentrations obtained from the ISCO samples will likely not change with additional analysis. The flow rates are approximations to the actual inflow rates. To obtain the correct flow rates, the data needs to be adjusted to account for storage within the collection system. These adjustments will likely have a minor impact on the final flow rates. The unit for the conductivity probe corresponds to bits recorded by the data acquisition system. The conductivity probe needs to be calibrated to convert the recorded number of bits into units of s m^{-1}. In addition, the influent conductivity needs to be adjusted for the dilution impact of water in the collection system. This impact may be important because of the frequent sampling of conductivity values.

The runoff response is given for storm events on August 27 and September 4 of 2018. The runoff hydrographs are shown in Figure 26. The first storm has a single, relatively large peak flow rate. The runoff hydrograph for the second storm is more complex with a runoff volume more than seven times larger than the first storm. The uncalibrated conductivity recorded at the site and the chloride concentrations collected with the ISCO sampler are shown in Figure 27. Changes in these values with cumulative runoff volume are generally similar to exponential decline obtained from rain simulator trends shown in Figure 25. The irregularity of the conductivity data may partially be a consequence of the dilution impact of the collection system and adjustment needed for different temperatures. Changes in total Kjeldahl nitrogen (TKN) and total phosphorus (TP) concentrations are shown in Figure 28. These changes are also similar to the exponential decline used to vary EMC with runoff volume. Measured TP is near the detection limit after a runoff volume of approximately 800 gal for both storms.

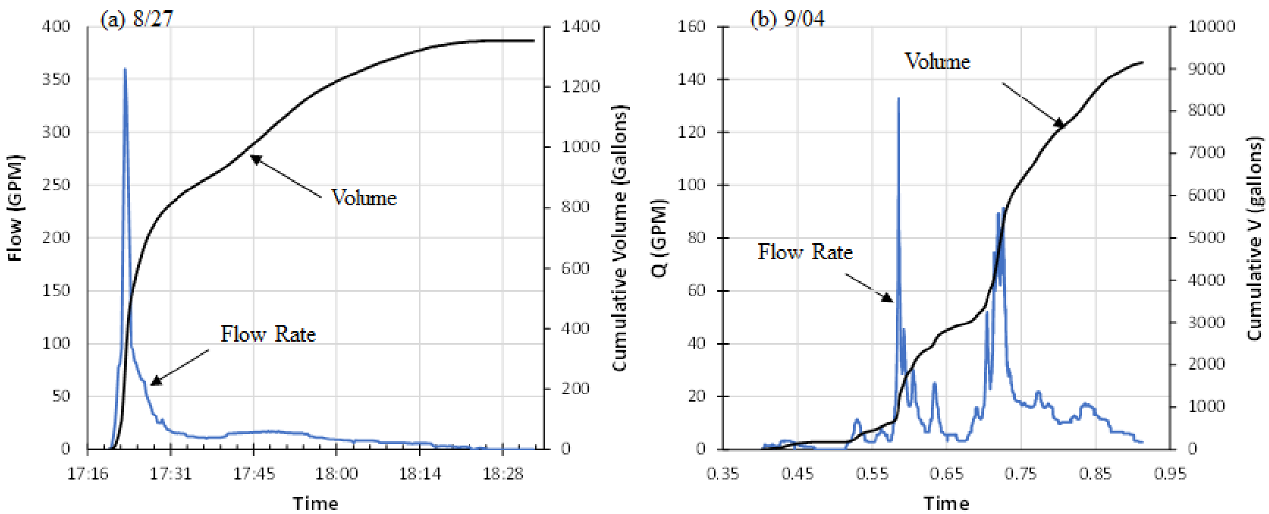


Figure 26. Flow Rates and Cumulative Runoff Volumes for Storms on 8/27/2018 and 9/04/2018. Flow rates have not been adjusted for storage within the collection system.

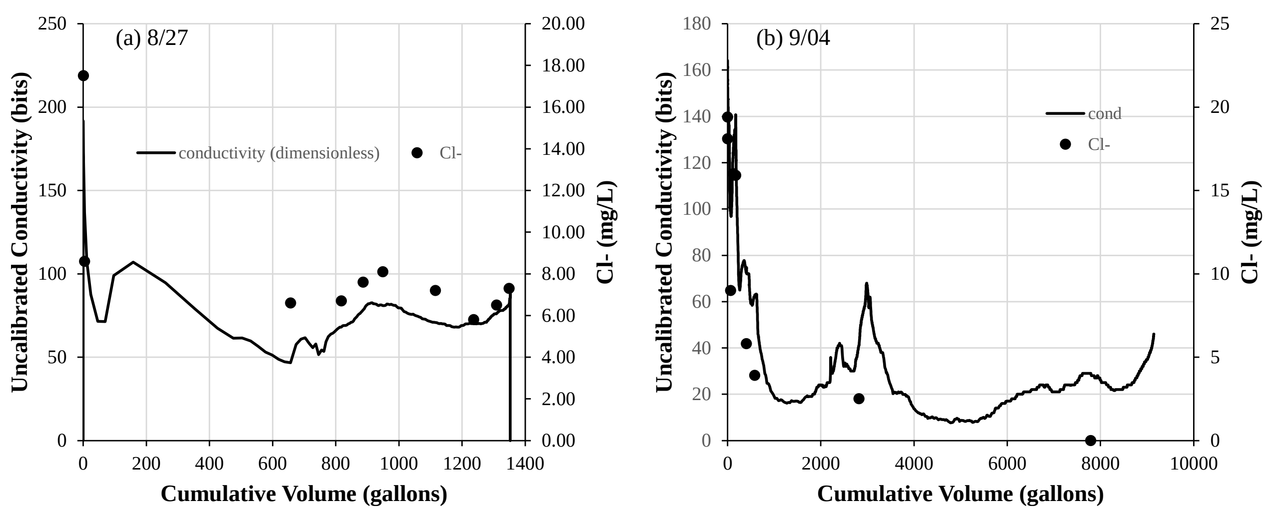


Figure 27. Uncalibrated Conductivity and Chloride concentrations for storms on 8/27/2018 and 9/04/2018. Conductivity values have not been adjusted for dilution impacts of the collection system

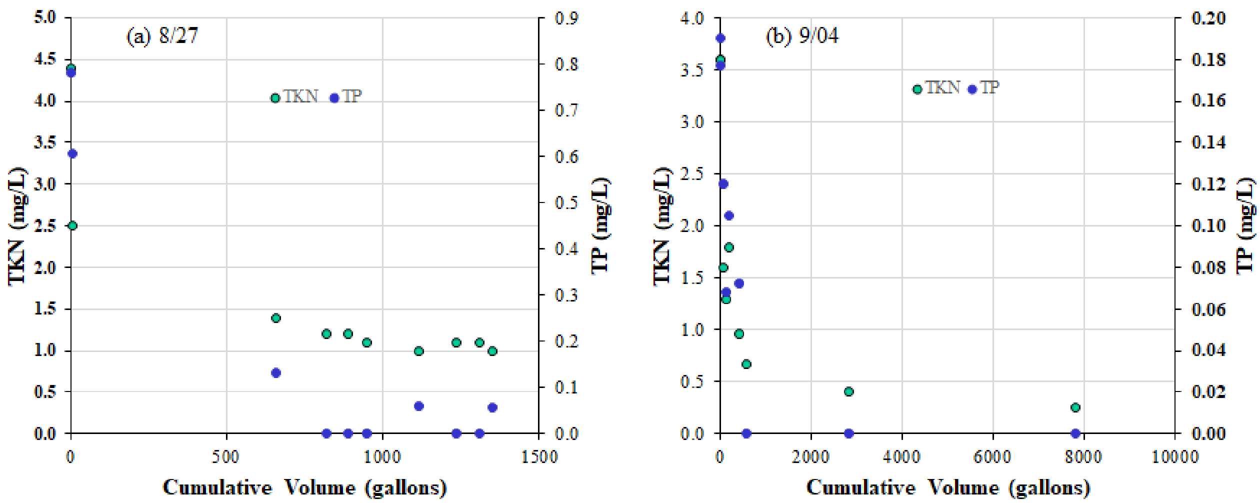


Figure 28. TKN and Total Phosphorus Concentrations for Storms on 8/27/2018 and 9/04/2018.

Concluding Comments

The primary focus of the project was to determine appropriate EMCs resulting from rainfall events for different impervious surfaces in downtown Minneapolis. The study used a rain simulator for streets, sidewalks, and parking lots for summer, fall, and spring conditions. Differences in EMCs with ground surface types for the summer and fall seasons were relatively minor. The greatest difference was observed with the spring season. It is also interesting that the sidewalk located next to a park generally had larger analyte concentrations. EMCs from roofs were obtained using natural rainfall events. The *E. coli* concentrations were detectable for the roofs, and their COD concentrations were larger for the summer and spring seasons than those of the ground sites. Additional work is needed to investigate the statistical significance of the observed trends for both rain simulator and natural rainfall events.

The first-flush process was evaluated by analyzing the concentrations in the first collected sample bottle and by measuring the conductivity at different times during the runoff events. B1Cs were generally much larger than EMCs. An exponential decay function was used to represent the first-flush process of a decrease in concentration with runoff volume. The project mathematically derived the EMC for this exponential function. This relationship allows EMC to vary with runoff volume. The parameters of the exponential function were determined using the conductivity data and the measured B1Cs and EMCs. The project also collected data from several natural rainfall events using a unique instrumentation system. Preliminary analysis suggests an exponential decay in concentrations similar to those obtained from the rain simulator.

Additional work is needed to gain a better understanding of the relative role of atmospheric deposition, vehicle and pedestrian traffic and other potential sources of contaminants onto impervious surfaces. This information would be especially useful in determining how pollutant loads change based on the number of days between large rainfall events. A test area could be cleaned by spraying it with water under relatively high pressure. Sections could then be selected and protected from natural rainfall events. The vehicle and pedestrian traffic would be measured for the test area. The simulator, using similar procedures to those of this project, could then be used to collect runoff data for different sections corresponding to a different number of days after cleaning the test area. It is recommended that such a project consider using natural rain as the source water for the simulator. The collected rain water would need to be stored in relatively large inert storage tanks.

Relatively large concentrations found in the limited snowmelt data suggest that more efforts are needed to estimate pollutant concentrations for this process. It is important that the monitoring system used to collect this type of data is reliable under freeze/thaw conditions. The unique instrumentation system of this project is capable of operating under these conditions.

Noteworthy advances have been made in the development of sensor and electronics for data acquisition that provide a nearly continuous recording of runoff characteristics. Those of particular interest in urban studies are conductivity and optical sensors. The hardware to measure, store and download data from these types of sensors can be obtained at very reasonable costs. Although the use of these data sets has great potential to determine EMCs at a much lower cost, more work is needed to implement them in field applications. Considerable amount of relatively large-sized materials was observed in the collection of natural rainfall events. This material is difficult to gather using the current sampling equipment. The design of a new instrumentation system should also include devices to measure this component of contaminant loading.

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Appendix A. Tabular Concentration Data

Table 1. Event mean concentrations of summer data for each ground simulation site.

EMC for Summer Data										
		Street			Sidewalk			Parking Lot		
		3rd Ave	8th St	10th Av	3rd Ave	8th St	10th Ave	Port	HCC	Aug
Analyte	Units	8/23[2]	8/2	8/30	7/27	8/1	7/28	8/24	8/30	8/24
TSS	mg/L	11	65	13	2.2	8.5	0	7.5	1	2
Cl	mg/L	0.7	0.8	1.0	1.8	0.8	0.8	0.7	0.1	0.7
COD	mg/L	10	42	13	10	13	9	7	9	
E. coli	MPN/100mL	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
Cd	mg/L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	mg/L	0.0007	0.0041	0.0009	0.0002	0.0004	0.0001	0.0002	0.0001	0.0001
Cu	mg/L	0.0028	0.0037	0.0004						0.0009
Pb	mg/L	0.0005	0.0133	0.0011	0.0004	0.0045	0.0003	0.0007	0.0003	0.0004
Ni	mg/L	0.0006	0.0022	0.0006	0.0002	0.0003	0.0001	0.0005	0.0004	0.0003
Zn	mg/L	0.0161	0.0385	0.0214	0.0082	0.0058	0.0042	-0.0022	0.0048	0.0062
TKN[1]	mg/L	0.1	0.5	0.0		0.4			0.1	0.3
TP	mg/L	0.042	0.121	0.025	0.033	0.155	0.000	0.034	0.000	0.042
OP	mg/L	0.000	0.018	0.000		0.053	0.005	0.005	0.008	0.006
DP	mg/L									
Mg	mg/L							0.1		
Mn	mg/L	0.0068						0.0076		
Na	mg/L							0.4		
NO_3-N	mg/L									
NO_2e	mg/L									
Oil/Gr	mg/L							0.0		
TOC	mg/L	1.2						0.2		
Turb	NTRU	7.5						2		
Ca	mg/L							0.7		
Fe	mg/L							0.11		
Hg	µg/L							0.016		
K	mg/L							0.2		

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen, OP= Ortho Phosphate, DP=Dissolved Phosphorous, Turb = Turbidity, Oil/Gr=Oil and Grease. [2]Date of run.

Table 2. Event mean concentrations for fall sampling at each ground test site.

EMC for Fall Data										
		Street			Sidewalk			Parking Lot		
		3rd Ave	8th St	10th Av	3rd Ave	8th St	10th Ave	Port	HCC	Aug
Analyte[1]	Units	10/19[2]	10/13	10/20	10/19	10/26	10/20	10/18	10/25	10/26
TSS	mg/L	18.5	8	16.5	10.5	5.5	3.5	11.5	3.5	7.5
Cl	mg/L	0.8	0.7	0.9	1.2	1.0	1.0	0.6	0.5	0.7
COD	mg/L	14	13	19	8		5	13	7	11
E. coli	MPN/100mL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cd	mg/L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	mg/L	0.0012	0.0005	0.0007	0.0006	0.0005	0.0002	0.0006	0.0002	0.0004
Cu	mg/L	0.0011		0.0007						0.0005
Pb	mg/L	0.0012	0.0009	0.0015	0.0013	0.0004	0.0004	0.0008	0.0003	0.0006
Ni	mg/L	0.0006	0.0004	0.0008	0.0003	0.0001	0.0003	-0.0003	0.0005	0.0003
Zn	mg/L	0.0258	0.0270	0.0451	0.0319	0.0138	0.0110	0.0117	-0.0138	0.0145
TKN	mg/L	0.1	0.1	0.3	0.0	0.2	0.1	0.1	0.1	0.2
TP	mg/L	0.046	0.016	0.024	0.000	0.016	0.000	0.000	0.000	0.000
OP	mg/L	0.008			0.005					
DP	mg/L									
Mg	mg/L	0.6			0.2			0.3		
Mn	mg/L	0.0180			0.0104			0.0108		
Na	mg/L	0.9			2.0			1.1		
NO_3-N	mg/L									
NO_2-N	mg/L									
Oil/Gr	mg/L	-0.70			-1.10			-0.35		
TOC	mg/L	1.3			0.7					
Turb	NTRU	8.5			5.5			6		
Ca	mg/L	2.7			1			3.9		
Fe	mg/L	0.41			0.19			0.14		
Hg	µg/L	0.004			0.004			0.009		
K	mg/L	0.2			0.8			0.3		

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen, OP= Ortho Phosphate, DP=Dissolved Phosphorous, Turb = Turbidity, Oil/Gr=Oil and Grease. [2]Date of run

Table 3. Event mean concentrations of spring samples from each ground test site. See analyte units in table 2.

EMC for Spring Data										
	Street			Sidewalk				Parking Lot		
	3rd Ave	8th St	10th Av	3rd Ave	8th St	10th Ave		Port	HCC	Aug
Analytes	4/20[2]	4/27	4/25	4/20	4/27	3/29	4/25	3/23	4/26	4/26
TSS	112.5	240	231.5	87.5	210	46.5	38.5	151.5	72.5	149.5
Cl	88.4	704.1	27.1	14.1	410.6[3]	2.6	2	14.6	3.4	8.7
COD	54	120		33	67	20		67	72	100
E. coli	0	0.5	0	0	0	0	0	0	0	0
Cd	0	0.00012	0	0.00013	0.0001	0	0	0.00017	0	0
Cr	0.00949	0.01379	0.00979	0.00699	0.00879	0.00298	0.00259	0.00786	0.00282	0.00552
Cu	0.023	0.0263	0.0235	0.0181	0.0115	0.0076	0.006	0.0227	0.0084	0.0122
Pb	0.00679	0.02004	0.01006	0.00929	0.04154	0.00445	0.00336	0.00755	0.0045	0.009
Ni	0.00447	0.00715	0.00504	0.00357	0.00495	0.00189	0.00154	0.00534	0.00326	0.00416
Zn	0.1374	0.1826	0.1511	0.1534	0.0783	0.0717	0.0523	0.1775	0.0756	0.0966
TKN[1]	0.57	1.12	0.76	0.27	1.62	0.24	0.16	0.43	0.81	0.81
TP	0.081	0.243	0.168	0.071	0.356	0.038	0.033	0.213	0.06	0.122
OP	0.01			0.019						
DP		0.01			0.068					
Mg	3.5			1.9				3.6		
Mn	0.09785			0.07935				0.13235		
Na	57.5			11.8				12.1		
NO_3-N										
NO_2-N	0		0	0			0			
Oil/Gr								0		
TOC										
Turb	57			52				79.5		
Ca	8.8			5.5				11.7		
Fe	3.68			3.08				4.17		
Hg	0.037			0.005						
K	0.6			1.1				1.1		

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen, OP= Ortho Phosphate, DP=Dissolved Phosphorous, Turb = Turbidity, Oil/Gr=Oil and Grease. [2]Date of run. [3]Value is inconsistent with conductivity data.

Table 4. 1st bottle concentrations at each ground sampling site during summer season.

B1C for Summer Data									
		Street		Sidewalk			Parking Lot		
		3rd Ave	8th St	3rd Ave	8th St	10th Ave	Port	HCC	Aug
Analytes	Units	8/23[2]	8/2	7/27	8/1	7/28	8/24	8/30	8/24
TSS	mg/L		639			15.5	167.5	31	91
Cl	mg/L	2.6		7.5	6.2	5.4	2.5	2.3	1.0
COD	mg/L				136	18		64	
E. coli	MPN/100mL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.5
Cd	mg/L	0.0000		0.0001	0.0002	0.0000	0.0001	0.0000	0.0000
Cr	mg/L	0.0052		0.0024	0.0042	0.0012	0.0056	0.0013	0.0009
Cu	mg/L	0.0249		0.0027	0.0098	0.0037	0.0166	0.0033	0.0066
Pb	mg/L	0.0053		0.0038	0.0148	0.0019	0.0091	0.0014	0.0022
Ni	mg/L	0.0038		0.0015	0.0031	0.0025	0.0048	0.0024	0.0013
Zn	mg/L	0.1294		0.0752	0.1224	0.0485	0.4005	0.0442	0.0407
TKN[1]	mg/L	0.9		0.4	3.8	0.3	0.7	1.4	1.9
TP	mg/L	0.128		0.082	0.707	0.074	0.177	0.090	0.410
OP	mg/L	0.017				0.019	0.017	0.075	0.028
DP	mg/L								

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen, OP= Ortho Phosphate, DP=Dissolved Phosphorous,
[2]Date of run.

Table 5. 1st bottle concentrations for fall samples at each ground sampling site.

B1C for Fall Data										
		Street			Sidewalk			Parking Lot		
		3rd Ave	8th St	10th Av	3rd Ave	8th St	10th Ave	Port	HCC	Aug
Analyte[1]	Units	10/19[2]	10/13	10/20	10/19	10/26	10/20	10/18	10/26	10/19
TSS	mg/L					41.5			77.5	
Cl	mg/L	2.4	1.2	2.6	7.9	2.8	8.8	2.3	0.5	2.4
COD	mg/L		64	150		64	65		75	
E. coli	MPN/100mL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cd	mg/L	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	mg/L	0.0084	0.0033	0.0049	0.0067	0.0028	0.0049	0.0047	0.0017	0.0084
Cu	mg/L	0.0384	0.0102	0.0258	0.0194	0.0116	0.0091	0.0140	0.0084	0.0384
Pb	mg/L	0.0110	0.0047	0.0091	0.0101	0.0042	0.0045	0.0076	0.0031	0.0110
Ni	mg/L	0.0069	0.0023	0.0035	0.0035	0.0015	0.0022	0.0027	0.0020	0.0069
Zn	mg/L	0.4055	0.0886	0.2711	0.3585	0.0962	0.1811	0.3027	0.0694	0.4055
TKN	mg/L	2.1	0.7	1.9	1.1	1.4	1.1	0.4	1.3	2.1
TP	mg/L	0.228	0.132	0.181	0.131	0.239	0.148	0.055	0.090	0.228
OP	mg/L									
DP	mg/L									

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen, OP= Ortho Phosphate, DP=Dissolved Phosphorous, Turb = Turbidity, Oil/Gr=Oil and Grease. [2]Date of run

Table 6. 1st bottle concentrations for ground sampling sites in the spring season. See table 5 for analyte units.

B1C for Spring Data										
	Street			Sidewalk				Parking Lot		
	3rd Ave	8th St	10th Av	3rd Ave	8th St	10th Ave		Port	HCC	Aug
Analytes	4/20[2]	4/27	4/25	4/20	4/27	3/29	4/25	3/23	4/26	4/26
TSS			2499.5			108.5	356.5			768.5
Cl	863.8	118.7[3]	122	174.1	598.7	14.1	20.1	162.5	19.3	34.6
COD		869			425	75		686	419	687
E. coli	0	0	0	0	0	0	0	0	0	0
Cd		0.0009	0.00063		0.001	0	0.0004	0.0018	0.00024	0.00043
Cr		0.08219	0.05839		0.05739	0.00728	0.02119	0.06366	0.01542	0.02862
Cu		0.1723	0.1512		0.0838	0.0188	0.0536	0.2033	0.0491	0.0793
Pb		0.13574	0.06526		0.25674	0.01005	0.02606	0.06615	0.0261	0.0495
Ni		0.04315	0.03104		0.03165	0.00409	0.01244	0.04464	0.01706	0.02436
Zn		1.1866	1.0671		0.5476	0.1603	0.3991	1.7575	0.4234	0.6254
TKN[1]	2.87	4.72	5.56	2.87	6.22	0.78	1.66	4.63	3.11	5.51
TP	0.668	1.47	1.91	0.749	1.86	0.109	0.293	1.179	0.376	0.793
OP	0.007			0.023						
DP		0.12			0.265					

[1]Definition of symbols: TKN = Total Kjeldahl Nitrogen , OP= Ortho Phosphate, DP=Dissolved Phosphorous, Turb = Turbidity, Oil/Gr=Oil and Grease. [2]Date of run, [3]Value inconsistent with conductivity data.

Table 7. Analyte concentrations from City of Lakes roof runoff.

Sampled Date	Ca mg/L	Cl mg/L	COD mg/L	E. coli	Hg ug/L	Cr mg/L	Cu mg/L	Pb mg/L	Ni mg/L	Zn mg/L
10/2/17		<2.0	27			0.0013	0.0113	0.0113	0.0011	0.0256
10/21/17		<2.0	36			0.0012	0.0108	0.008	0.00091	0.0322
11/4/17		2	80			0.0048	0.0278	0.0484	0.0041	0.17
12/4/17[1]		3.8		6						
12/19/17		15.9	46	6		0.0043	0.0269	0.0449	0.0025	0.191
1/10/18		91.3	68			0.0026	0.0174	0.0329	0.0019	0.138
1/10/18		34.2	84			0.005	0.0317	0.0448	0.003	0.181
1/26/18		14.5	~10			0.0009	0.0059	0.0069	<0.0006	0.0275
2/25/18		73.4	35			0.0013	0.0074	0.0125	~0.00074	0.107
2/25/18		67.7	24			0.00097	0.0059	0.009	~0.00087	0.0469
2/25/18		49.6		6		0.0016	0.0088	0.0147	~0.00090	0.0601
2/27/18		26.4	28			0.00083	0.0059	0.0076	<0.0006	0.0358
3/1/18		14.5	28	1		0.001	0.0076	0.0163	~0.00060	0.0468
3/3/18		12.8	24			0.0013	0.0064	0.0075	<0.0012	<0.020
3/4/18		9.2	25	<1		0.0012	0.0079	0.0097	<0.0012	<0.020
3/8/18		7.1	19	<1		0.00071	0.0066	0.0081	0.00094	0.0795
3/26/18		11.4	19			0.0014	0.0098	0.0117	0.00082	0.0764
4/4/18		13.2	22			0.0011	0.0079	0.0065	0.00064	0.0722
4/5/18		6.1	15	<1		0.0011	0.0057	0.0077	0.00091	0.0282
4/9/18		13.9	28			0.002	0.0135	0.0198	0.0012	0.101
4/15/18		8.6	58			0.0061	0.0279	0.0739	0.0032	0.268
5/24/18		3.7	70	15		0.0027	0.0177	0.0244	0.0019	0.0557
5/29/18		<2.0				0.00068	0.016	0.0066	0.00072	0.0246
6/2/18		<2.0	56			0.0011	0.0174	0.0103	0.00088	0.041
6/9/18		2.5	39			0.00076	0.0133	0.0067	0.00095	0.028
6/16/18		<2.0	96			0.0023	0.017	0.0304	0.0016	0.0816
6/17/18		<2.0	77			0.0017	0.0166	0.0125	0.0012	0.0356
6/18/18		<2.0	15			0.00075	0.0051	0.0031	~0.00042	0.0154
6/19/18		<2.0	47			0.00059	0.0127	0.003	~0.00056	0.0128
6/26/18	4.3	<2.0	23	8	~0.007	0.00049	0.0052	0.0036	~0.00044	0.0151
7/1/18	3.7	<2.0	~9		0.072	0.00032	0.0042	0.0011	<0.0003	<0.010
7/12/18		<2.0	34			0.0011	0.006	0.0088	0.00073	0.0224

[1]Grab sample and not an event mean concentration.

Table 8. City of Lakes roof runoff data, continued.

Sampled Date	Mg mg/L	Mn mg/L	Na mg/L	NO_3--N mg/L	NO_2-N mg/L	TKN mg/L	TP mg/L	Oil/Gr mg/L	OP mg/L	DP mg/L	Turb NTRU	TSS mg/L
10/2/17						0.66	0.057					25
10/21/17						0.71	0.073					22
11/4/17						2.4	0.176					158
12/4/17[1]						5.7	0.655					
12/19/17						1.6	0.11					
1/10/18						2	0.108					58
1/10/18						2.4	0.169					115
1/26/18						0.45	~0.025					15
2/25/18						0.78	~0.043					19
2/25/18						0.8	~0.032					12
2/25/18						0.68	~0.040					20
2/27/18						0.47	~0.025					13
3/1/18						0.46	~0.031					14
3/3/18						0.44	<0.020					13
3/4/18						0.63	~0.030					15
3/8/18						0.43	~0.022					
3/26/18						0.59	0.118					16
4/4/18						0.84	~0.038					14
4/5/18						0.39	~0.039					14
4/9/18						0.92	0.08					54
4/15/18						1.3	0.158					137
5/24/18				3.05	0.26	2.1	0.164		0.025	~0.043		51
5/29/18						1.1	0.08					16
6/2/18						1.3	0.082					10
6/9/18						1.3	0.067					9
6/16/18						1.6	0.155					54
6/17/18						1.5	0.358					19
6/18/18						0.8	~0.040					9
6/19/18						0.73	~0.045					9
6/26/18	~0.88	0.0191	~0.70			0.53	~0.034	<7	0.018		6	8
7/1/18	~0.64	0.0091	~0.69			0.26	~0.025	<7			3	5
7/12/18				0.36	0.03	0.82	0.114		0.015	~0.031		25

[1]Grab sample and not an event mean concentration

Table 9. Roof runoff concentrations from Hope Community Church.

Sampled Date	Ca mg/L	Cl mg/L	COD mg/L	E. coli	Hg ug/L	Cr mg/L	Cu mg/L	Pb mg/L	Ni mg/L	Zn mg/L
9/20/17		<2.0	50			0.00035	0.0087	0.00059	0.00091	0.0347
9/26/17[1]		2.2	77			0.0014	0.113	0.0035	0.0021	0.304
10/2/17		<2.0	23			0.00073	0.0045	0.00058	~0.00053	0.0137
10/2/17		<2.0	~12	20		0.00022	0.0029	~0.00031	~0.00035	0.0067
10/6/17		<2.0	21			~0.00010	0.007	~0.00044	0.00064	0.02
10/21/17		<2.0	30			0.00033	0.0066	~0.00022	~0.00051	0.0233
5/24/18		5.1	58	79		0.00082	0.0132	0.0017	0.0011	0.0606
6/16/18		2.4	27			0.00018	0.0091	~0.00039	0.00081	0.0321
6/26/18	7.8	<2.0	26	2	~0.006	~0.00012	0.0066	~0.00024	~0.00059	0.0105
7/1/18	5.6	<2.0	~9		0.259	~0.00013	0.0054	~0.00020	~0.00043	<0.010

[1]Grab sample and not an event mean concentration

Table 10. Roof runoff concentrations from Hope Community Church, continued.

Sampled Date	Mg mg/L	Mn mg/L	Na mg/L	NO_3--N mg/L	NO_2-N mg/L	TKN mg/L	TP mg/L	Oil/Gr mg/L	OP mg/L	DP mg/L	Turb NTRU	TSS mg/L
9/20/17						1.1	~0.022					7
9/26/17[1]						1.6	0.074					
10/2/17						0.39	<0.020					3
10/2/17						0.39	<0.020					~2
10/6/17						0.38	<0.020			<0.020		~2
10/21/17						0.61	~0.047					~2
5/24/18				0.86	0.05	1.7	0.088		~0.006	<0.020		21
6/16/18						0.83	0.069					5
6/26/18	1.3	0.0134	~0.77			0.67	<0.020	<7	~0.007		2	~1
7/1/18	~0.91	0.0048	~0.65			0.27	<0.020	<8			<1	<1

[1]Grab sample and not an event mean concentration

Table 11. Roof runoff concentrations from Mensing Hall.

Sampled Date	Ca mg/L	Cl mg/L	COD mg/L	E. coli	Hg ug/L	Cr mg/L	Cu mg/L	Pb mg/L	Ni mg/L	Zn mg/L
6/26/18	1.3	<2.0	22	22	<0.004	0.00022	0.0061	0.00083	<0.0003	0.0616
7/1/18		<2.0	<5			0.00021	0.0029	~0.00034	<0.0003	0.0348
7/12/18		<2.0	30			0.00046	0.0097	0.001	~0.00042	0.0765
7/28/18		<2.0	228							
8/3/18			21							

Table 12. Roof runoff concentrations from Mensing Hall, continued.

Sampled Date	Mg mg/L	Mn mg/L	Na mg/L	NO_3--N mg/L	NO_2-N mg/L	TKN mg/L	TP mg/L	Oil/Gr mg/L	OP mg/L	DP mg/L	Turb NTRU	TSS mg/L
6/26/18	~0.46	0.012	~0.27			0.64	0.079	<7	0.035		3	~4
7/1/18						0.17	<0.020					~1
7/12/18				0.41	<0.03	2.3	0.234		<0.005	~0.021		10
7/28/18						2.9	0.408					215
8/3/18												

Appendix B. Graphical Representation of Concentration Data

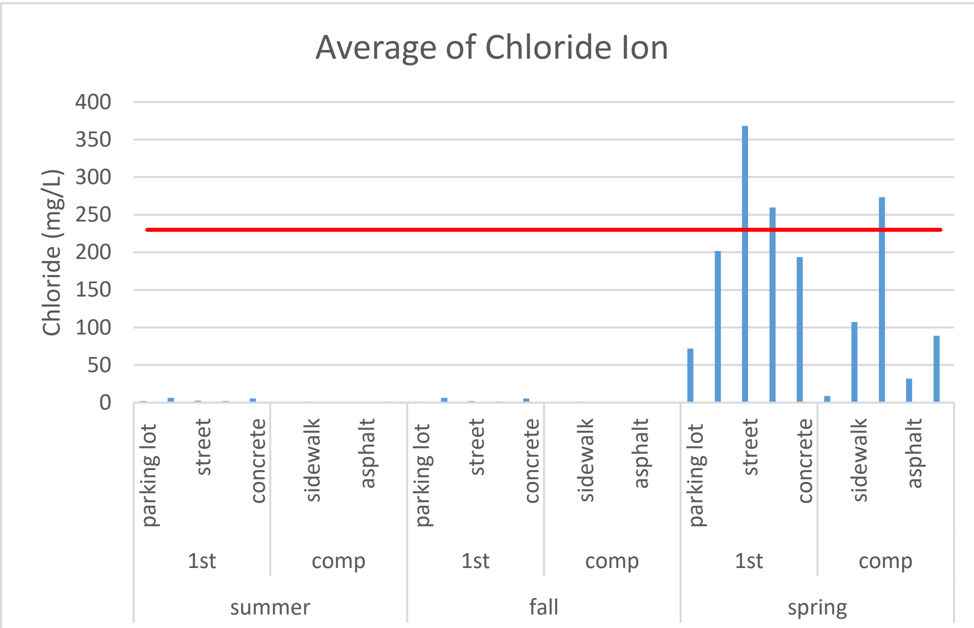

Figure 2. Average chloride ion concentrations of 1st bottle and composite samples for each surface type and season.

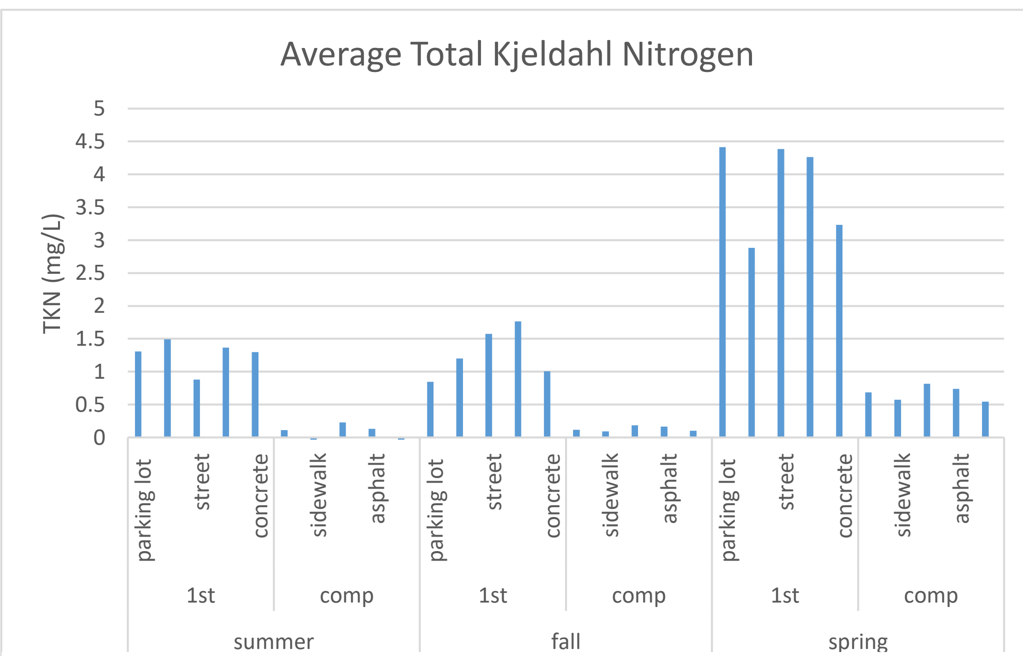

Figure 1. Average Total Kjeldahl Nitrogen concentrations of 1st bottle and composite samples for each surface type and season.

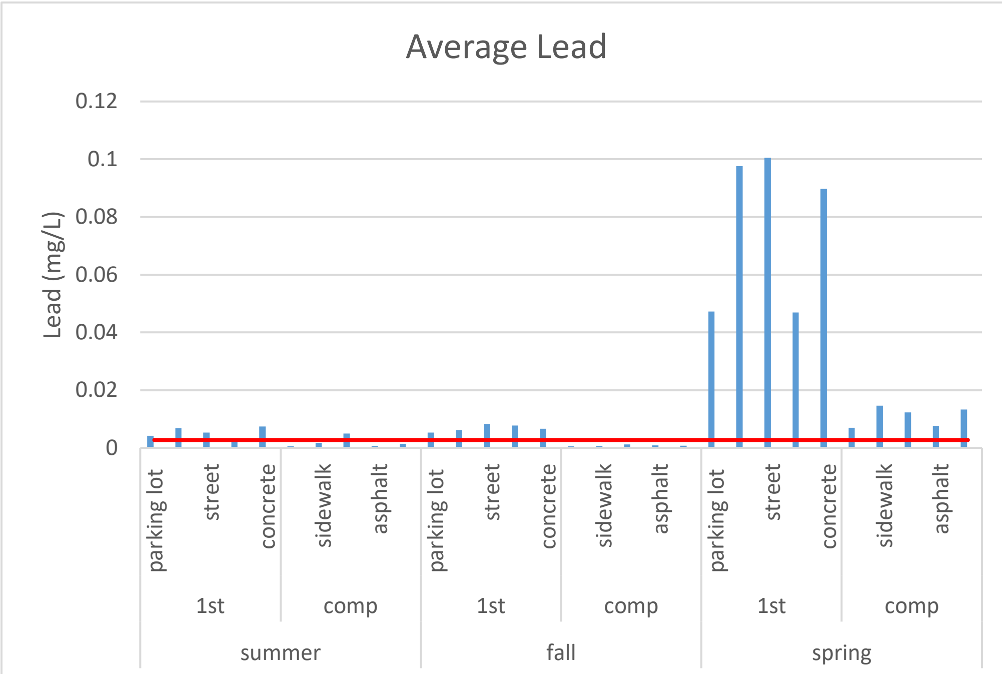

Figure 4. Average lead concentrations of 1st bottle and composite samples for each surface type and season.

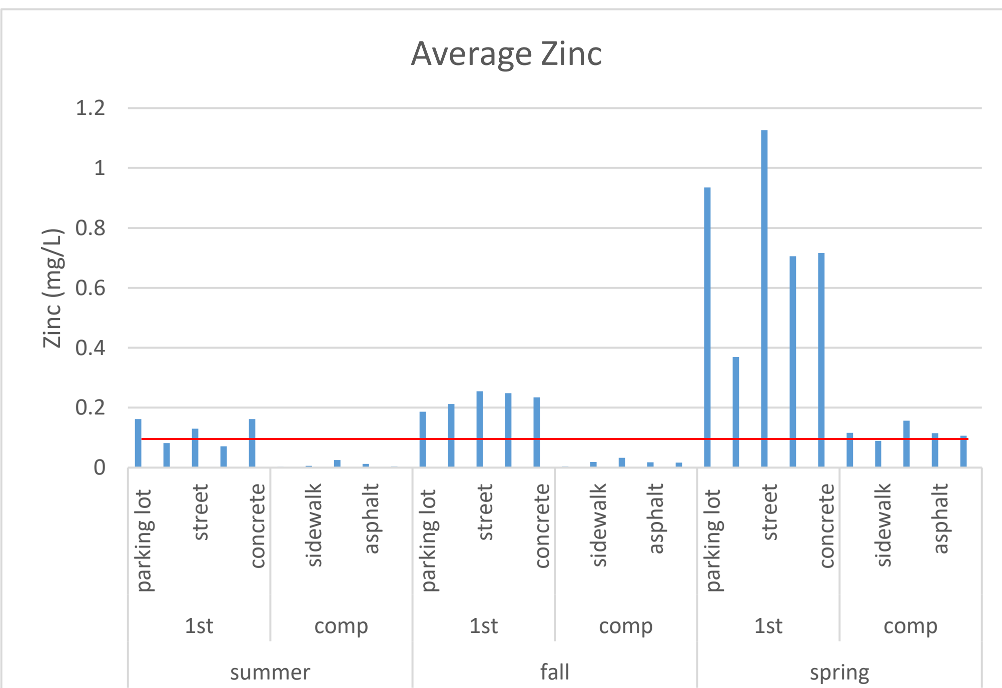

Figure 3. Average zinc concentrations of 1st bottle and composite samples for each surface type and season.

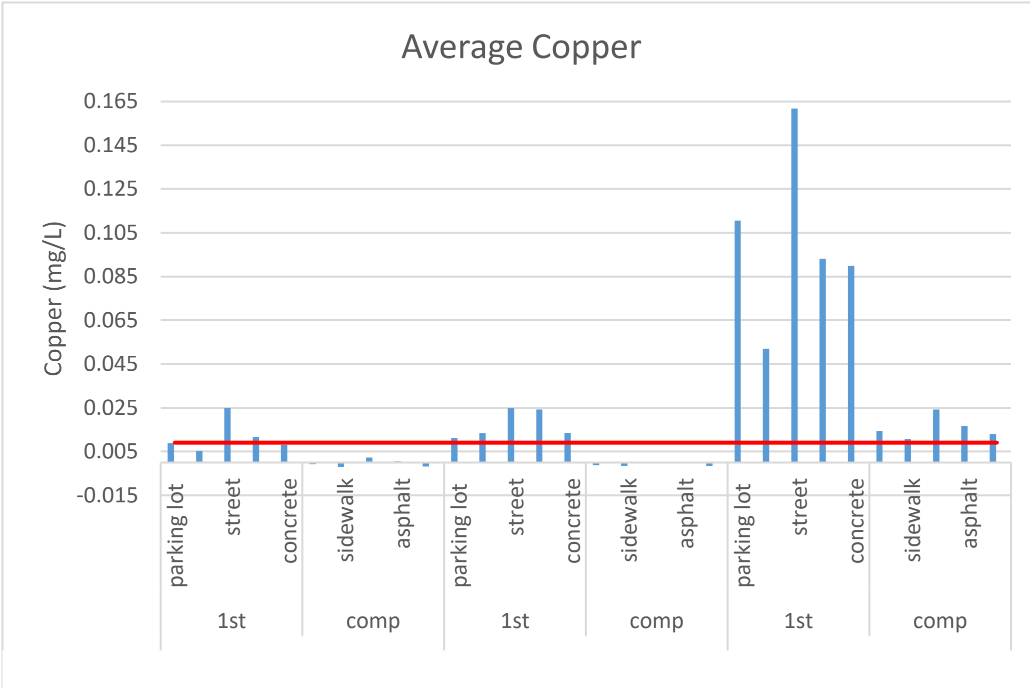

Figure 6. Average copper concentrations of 1st bottle and composite samples for each surface type and season.

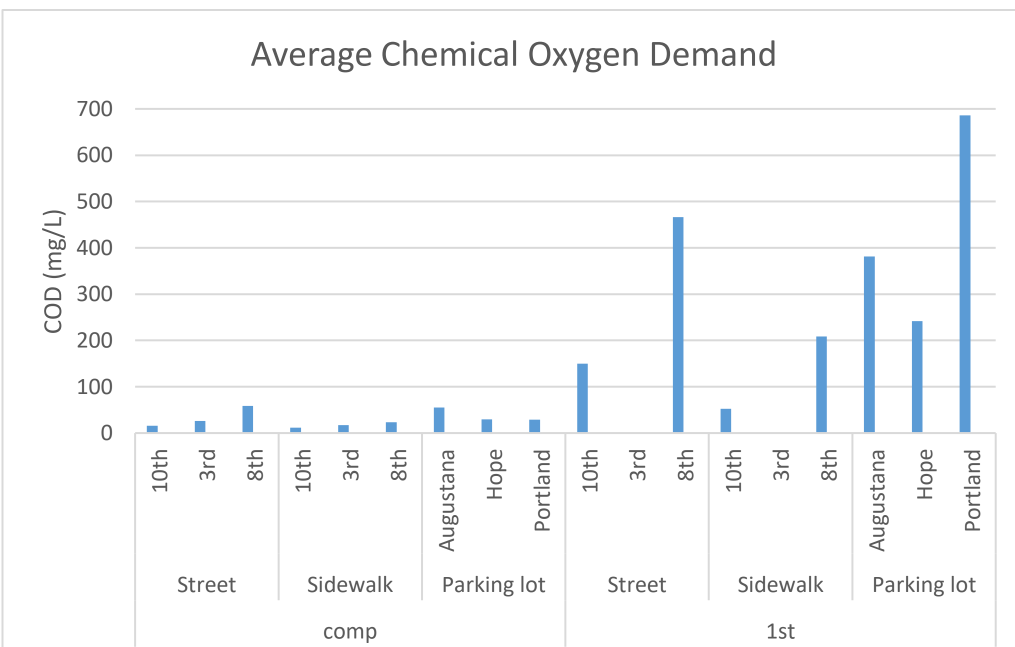

Figure 5. Average chemical oxygen demand concentrations of 1st bottle and composite samples for each surface type and sampling site.

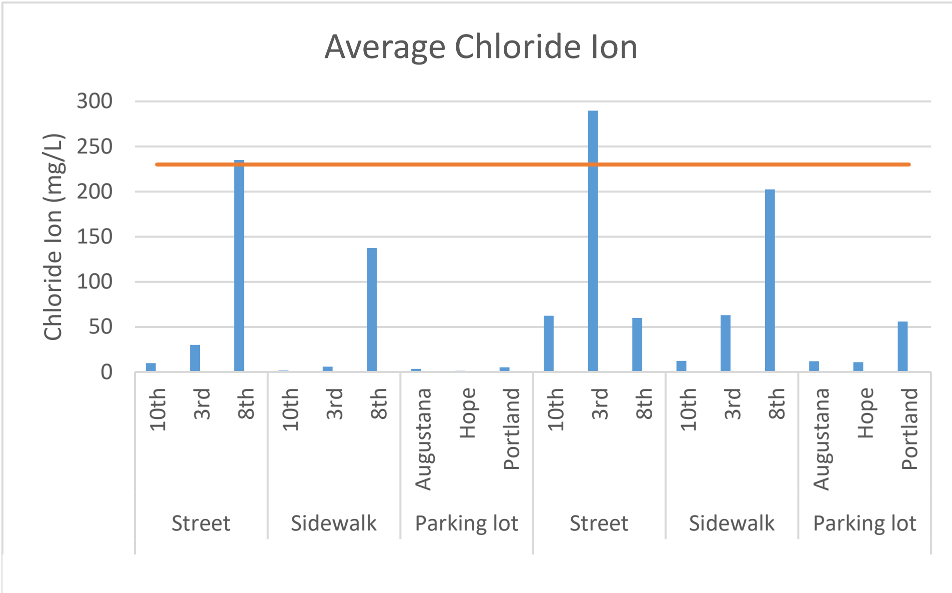

Figure 7. Average chloride ion concentrations of 1st bottle and composite samples for each surface type and sampling site.

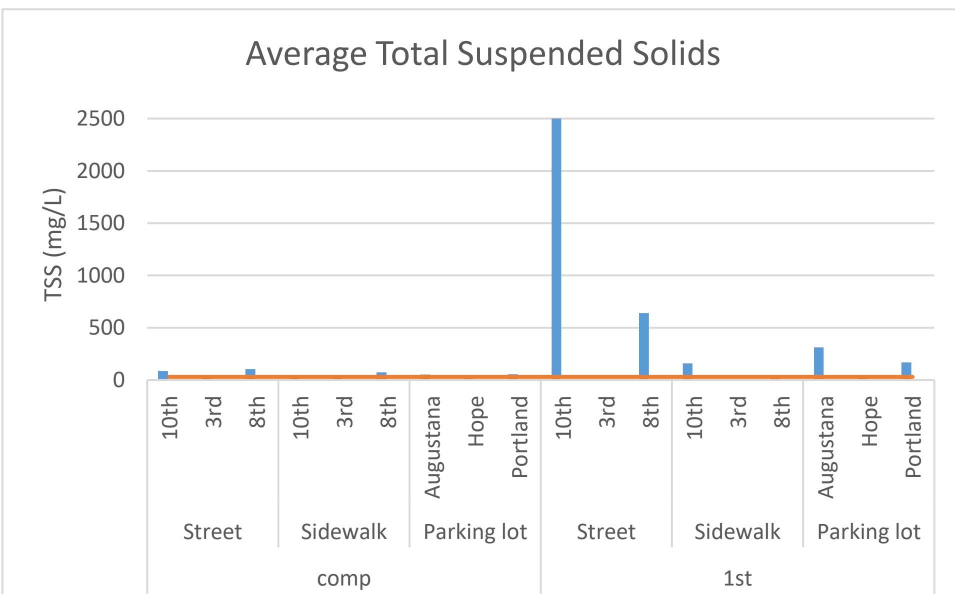

Figure 8. Average total suspended solids concentrations of 1st bottle and composite samples for each surface type and sampling site.

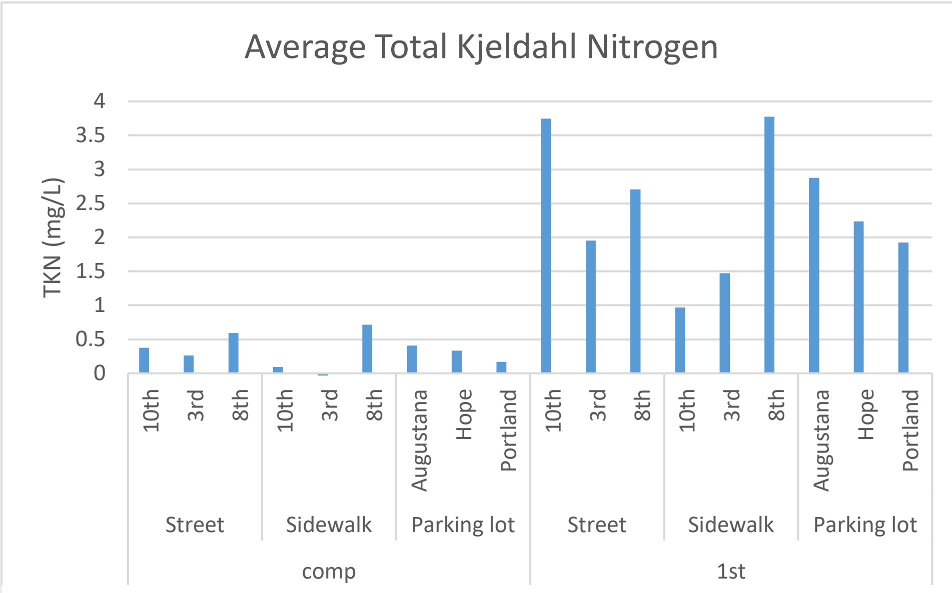

Figure 9. Average Total Kjeldahl Nitrogen concentrations of 1st bottle and composite samples for each surface type and sampling site.

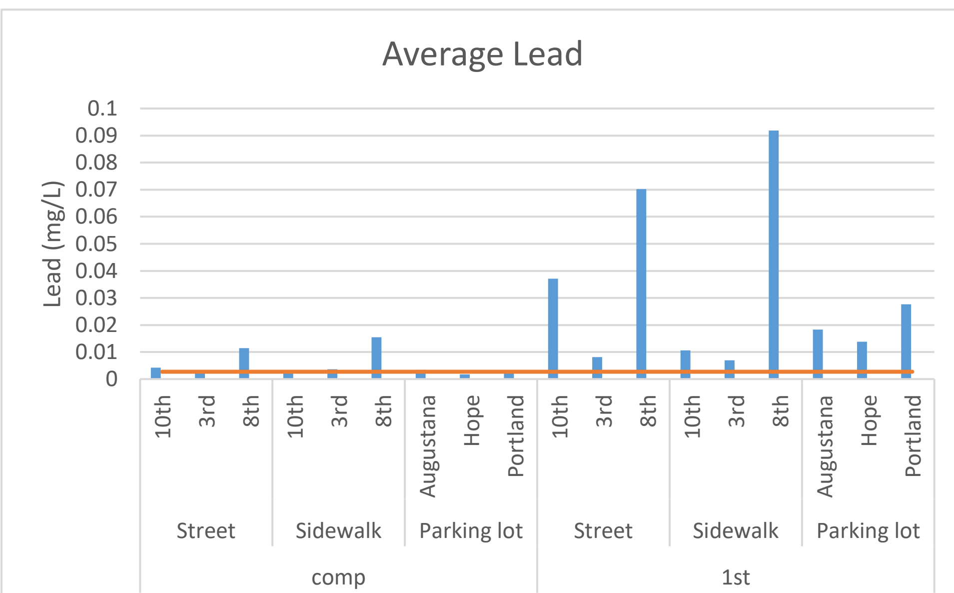

Figure 10. Average lead concentrations of 1st bottle and composite samples for each surface type and sampling site.

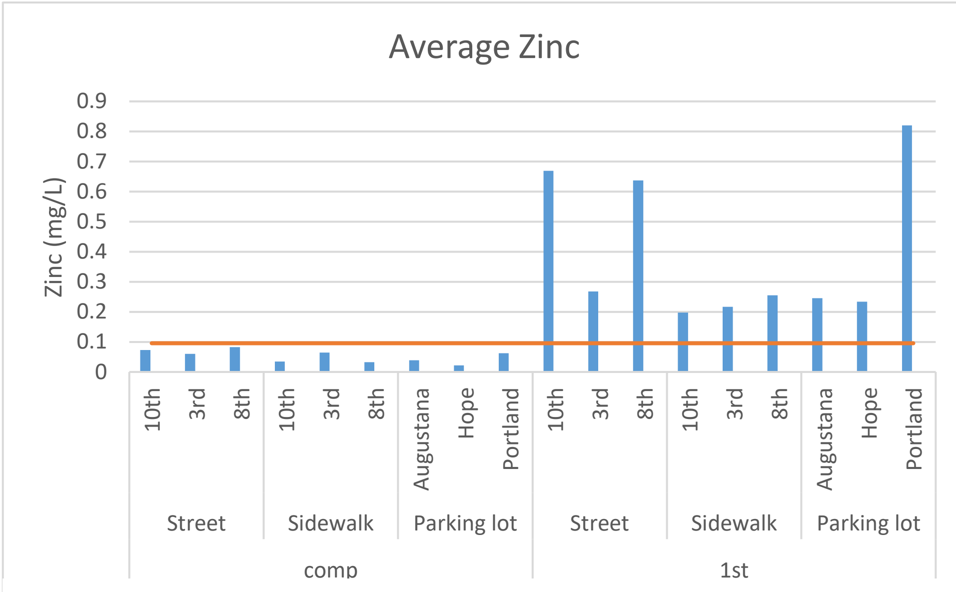

Figure 11. Average zinc concentrations of 1st bottle and composite samples for each surface type and sampling site.

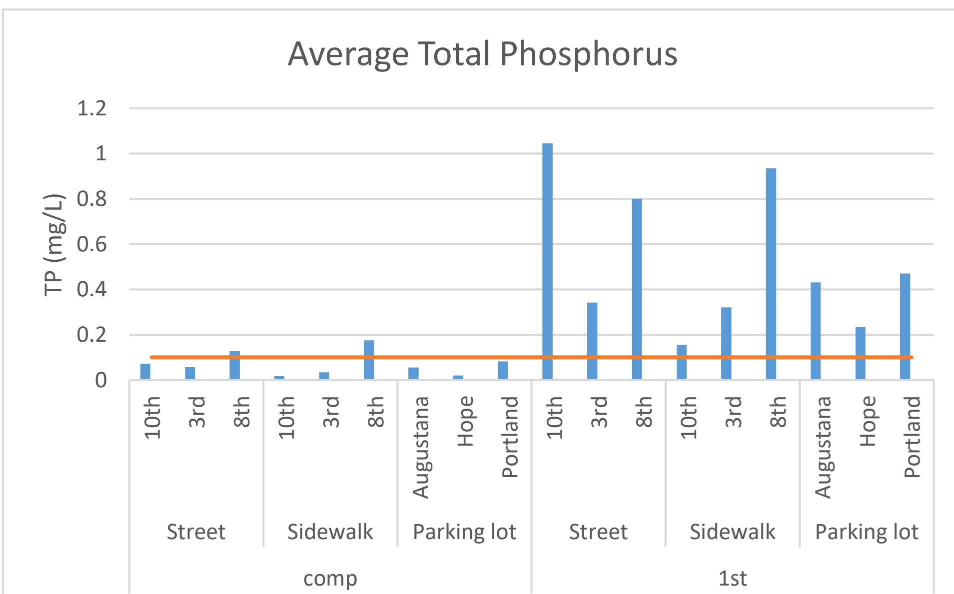

Figure 12. Average total phosphorus concentrations of 1st bottle and composite samples for each surface type and sampling site.

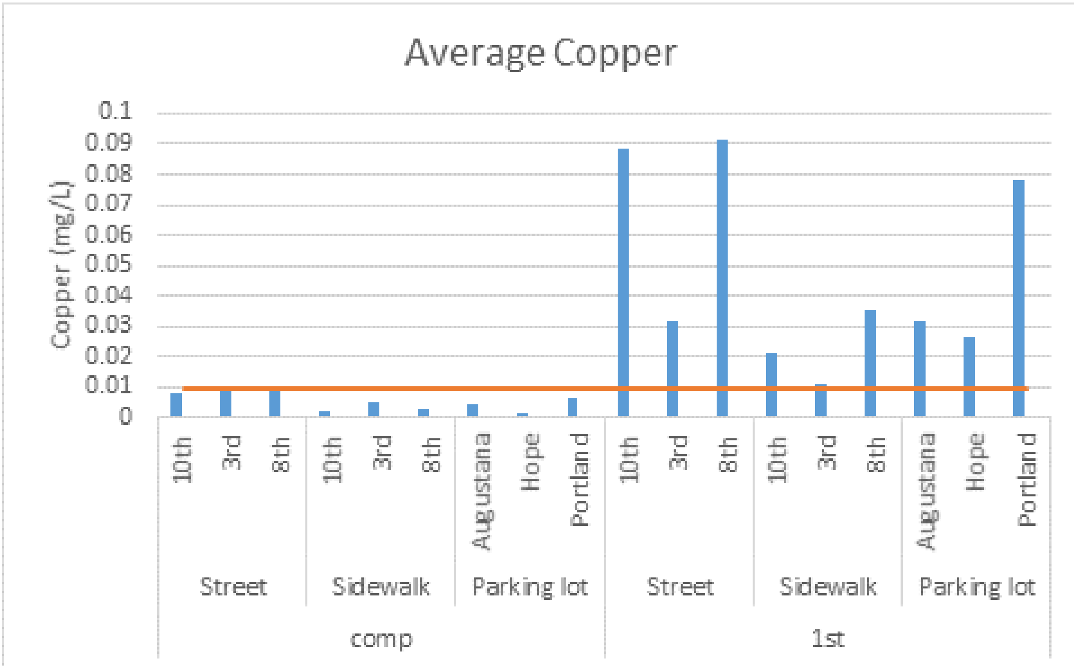

Figure 13. Average copper concentrations of 1st bottle and composite samples for each surface type and sampling site.

Appendix C. Detail Operating Procedures for Rain simulator Tests

This appendix details information about preparing for each rain simulation season, loading the trucks for each rain event, executing each rain event, cleaning the simulator between rain events, and storing the rain simulator between seasons. In addition, this guide includes information about each site and the permits necessary. Detailed checklists for rain simulator setup and sampling are both included as well.

Rain Simulation Procedures

Seasonal Preparation for Sampling

a. Create a daily schedule for the rain simulations including: which employees are available, how many MWMO employees are necessary, and which sites will be visited.
b. Organize and apply for permits for each site.
c. Check out vehicles for sampling days, and alert all BBE staff about vehicle use.
d. Gather all items using the checklists
e. Order any items that will be needed or may run out. All consumables are marked with an asterisk on the loading checklist.
f. Ensure that the generator and control box are working properly.
g. Check if the tanks are clean after sitting stagnant a few days before the simulation. Wash the tanks with vinegar or diluted bleach if they again if they are not clean.
h. Rinse the tanks and rain simulator.
    i. Rinse out both tanks thoroughly, making sure to clean the sides of the tank.
    ii. Put 30 gallons of water in one tank and run it through the simulator.
    iii. Make sure both tanks are empty.

Loading vehicles

i. Put the rack into the truck. This will take 2-3 people.
    i. If the trailer is being used the rack will be unnecessary.
j. Put the rain simulator onto the truck or trailer. This will take 3-4 people
k. Load the large items first, according to Figure 1. If the trailer is being used this figure can be disregarded.
l. Load all of the small items.
    i. Check consumables, which are marked by an asterick on the loading checklist.
    ii. Put other small items in any location, including the back seats and beds of the trucks.
m. Go through the checklist to ensure that all items are packed.
n. Use the straps to secure the rain simulator (2 straps), both tanks, and the windscreens
o. On the day of the simulation, one person must arrive 15 minutes before departure to fill one tank.
p. Check tank caps before driving!

Simulator Setup and Use

q. Put on safety vests!
r. Park the cars and set up cones around the work area. Put the men working signs on either end of the blocked off area.
s. Start by unloading items and putting them neatly in an area that is blocking the least amount of space possible.
t. While the items are being unloaded, the most experienced team member should mark out the rain simulator area with dimensions 6’6” x 12’6”, this will result in a finished area of 12 x 6
    i. Also mark where butyl tape, poly, and pool bags will go based on the site

u. Unload the rain simulator. This will take 3-4 people. Make sure the rain simulator is positioned in such a way that the longer side, the side without the motor box, is on the same side as the tank and snorkel.
v. Put the legs onto the rain simulator
    i. Have one person lift an end of the simulator while two people put the legs on
    ii. Do this for both sides
w. While the simulator is low, put on the PVC pipe, hoses, control box cord, and plumb bob for centering the simulator.
    i. PVC pipe should be secured with bungee cords. Use at least two on the side of the simulator with the snorkel.
    ii. Black hose connects directly to rain simulator and one of the orange-handled hose connections.
    iii. Plumb bob connects to middle of simulator.
    iv. Secure control box cord on the nearest leg.
    v. Use the green hose as a pump outlet..
    vi. Use small clear hose as return/pressure release hose. Always keep return open and open it first before opening the line to the black hose.
    vii. Use large clear hose as a suction/intake to the pump.
x. Raise the simulator up. This will take 4 people, two to hold the legs up and two to set it at 9 exposed holes or 8’ from the ground to the spray nozzle. This will be different for sidewalk test spots, where two legs will have 12 holes exposed to even out the simulator.
y. A team of people will be assigned the following tasks:
    i. Fill 6-7 pool bags using the small pump and the garden hose, ensuring no water contaminates the simulation area. The pool bags should be only half, or less than half, full, and any leaking pool bags should be discarded
    ii. Transfer the water from the tank in the truck or trailer to the tank placed on the ground by the simulators 4” discharge hose
    iii. Flush the simulator and take a sample. Attach the large snorkel to the end of the PVC pipe and place the end in a 5 gal bucket and turn the generator off when it is halfway full. This is when the source water sample should be taken.
z. A team of 2-3 people will be assigned the task of poly and butyl
    i. Measure out the amount of poly needed and cut the poly. It will take 2-3 people to keep the poly off the ground.
    ii. Sweep just inside of the chalk lines before putting butyl down. Technique: Do not sweep into or out of the sample space, but along the line. This step is critical for secure butyl application.
    iii. Start putting butyl tape down and rolling it to the pavement using heat gun if necessary.
    iv. Lay the poly down: position it first with metal L’s and stick it to the butyl tape once it is flat.
    v. Place the metal spout and stick it to the pavement using butyl tape. Use the poly tape to secure the poly sheet to the weir.
aa. Before starting the simulation complete the checklist:
    i. Ensure that everything is correctly connected and that the controller is off.
    ii. Let pump run/stabilize before simulating.
    iii. Check that everyone has an assigned job and that all jobs are covered.
    iv. Make sure someone has a timer ready.
bb. Starting the rain simulator
    i. Turn the controller on and make sure it lights up.
    ii. Turn the motor on and wait a few seconds to ensure it works properly.

iii. Make sure the pressure is at the marked line on the pressure gauge at 7 psi
iv. Ensure the control box is set to 5 and double sweep
v. Turn the sweep on and start the 45 minute timer at the same time

cc. Ending the rain simulation
i. Turn off the simulator and generator after 45 minutes
ii. Do not start taking apart the simulation area until the water has stopped flowing. This may be around 10 minutes after the simulation has ended.
iii. Start packing up for the next simulation.
iv. Drain all water if it is the last simulation of the day.
v. Pack up materials and the simulator according to the loading procedure.

Unloading Vehicles and Cleaning

dd. If there is another rain simulation the following day, nothing needs to be unpacked.
ee. Unpack all of the unneeded items and put them on the designated shelf.
ff. Set up the rain simulator without the generator and the control box.
gg. Mix 20 gallons of water with a gallon of vinegar in both tanks.
i. Splash the water and vinegar mixture onto the sides of the tank.
ii. Run one tank through the rain simulator and let it sit in the hoses. Leave the solution inside the simulator for 1-2 days.

hh. Before the next rain simulation rinse the vinegar out of the tanks and run water through it using the same method as described in the seasonal preparation for sampling section.
ii. Clean the pool bags if necessary.
i. Put hot soapy water in a bucket and scrub both sides of the pool bags.
ii. Hang them to dry. Make sure that all water is out of the pool bags before this!

Seasonal Storage

jj. Vinegar rinse the rain simulator and let it air dry for a few days.
kk. Put everything away in an orderly manner.

Sampling Operating Procedure

Before Sampling

a. Acid wash and air-dry HDPE Nalgene bottles.
b. Pack items on the material list. It is recommended to bring extra 1L Nalgenes in case of contamination or breakage.
c. If traveling alone, alert a colleague that you have left BAE.
d. Go to the rain simulation site.
e. Don a safety vest.
f. Obtain a printed parking obstruction permit from the U of M or MWMO staff who obtained the permit and place it on the dashboard of your vehicle.
g. Unload all materials near the collection site. The rain simulator set up team will bring a table where supplies can be placed during the experiment.
i. Water testing and collection gets the area around the table wet. Make sure you are far enough away from the collection point and any experiment conveyances so the experiment is not impacted.

Equipment Set Up

h. Record all initial data required in the Water Sampling Log before starting a rain simulation. *Note all data must be written in pen. If you make a mistake, cross it out with one slash. Do not obliterate data by scribbling it out or other means.*

    i. Location ID. Location ID is the location type. For all samples besides blanks, list the Location ID as either "street," "sidewalk," or "parking lot." For water blanks, list the Location ID as "Blank."

    i. For Sampling Point, write the site location. Sites names must be named exactly the same each time sampled for lab purposes. Sampling Points are:

        1. South 8th,
        2. 3rd Ave S,
        3. 10th Ave S,
        4. Portland Ave,
        5. Augustana Care,
        6. Hope Community Church, and
        7. Source Water (only to be used for "Blank" Location ID)

    ii. Ensure the Location ID and Sampling Point are written at the top of every page.

    iii. Write date and name of staff present at site (page 1).

    iv. Name of Recorder is the name of the person writing in the Water Sampling Log.

    v. Name of Sampler is the person collecting samples from the collection point.

    vi. Draw a site drawing.

    vii. Measure the dimensions of the area rain simulated on inside of the poly and butyl. Include significant figures (eg, on a 10ths inch measuring tape two decimal places should be recorded, such as 6.21 feet). Record the dimensions in the log (page 2).

    viii. Determine if the site is a "Core Parameter" site or a "Additional Parameter" site. All sites are "Core" except, 3rd Ave S street, 3rd Ave S sidewalk, and Portland Ave parking lot. "Core" sites require 2.5 L of water per composite sample. "Additional" sites require 4.5 L of water per composite sample.

ll. Obtain tank water information.

    i. Take an initial YSI reading of the tank water (page 3). Ask the set-up team when the water in the tank is ready to be sampled.

    ii. Fill a 4L Met Council Lab bottle. This requires working with the set-up team to momentarily turn on the pump so water can be collected from the hose. Label the bottle and place on ice in a cooler.

    iii. Record the initial volume of water in the tank (page 1).

mm. Label bottles 1-11 with colored masking tape and pen. Do not use permanent marker as it is water soluble.

nn. Identify staff for the following roles during the simulation:

    i. Recording flows and calling when sampling occurs.

    ii. Collecting water in bottles 1-11. Nitrile gloves must be worn.

    iii. Measuring bottles 1-11 with the YSI and recording data in the Water Sampling Log. This person also records the Rain Simulator and Runoff start and end times on page 1 of the Water Sampling Log. Nitrile gloves must be worn.

Rain Simulation

i. The following describes the normal flow of work during a rain simulation.

    i. The rain simulator is turned on by a member of the set-up team. The staff member running the YSI records the military start time of the rain simulation (page 1).

    ii. Water begins to flow down the conveyance. Once water exits the weir or pipe, the recorder writes the military start time of runoff (page 1).

iii. Water flows into the tray or bucket. The flow recorder and bucket tipper (or tray switcher) staff work together to determine when pre-determined volumes of water are collected (5, 10, and 15 L). These volumes are used to calculate flow rates throughout the experiment.
    1. At predetermined time intervals (page 4), samples are taken directly in a 1L Nalgene by the sampling staff.
    2. Samples can be taken 30 seconds before or after the designated time.
    3. When the flow recorder instructs the sampler to take a sample, the sampler states when they start and stop the sample, so the recorder can record these times (eg, "starting bottle 1" and "bottle 1 complete.").
        a. When taking a water quality sample in the Nalgene, only fill to the mouth of the bottle. Do not fill the headspace. Cap the bottle and bring over to the YSI recorder.
    4. The YSI recorder will rinse the YSI with deionized water, shake off the excess, measure the constituents (move the YSI gently up and down while measuring), and record measurements on page 3 for each bottle.
    5. After readings are taken, the bottle is recapped and placed on ice in a cooler.
    6. As the intervals in between each sample increase, this time can be used by the water collector to collect Sample Collection Start Times and Sample Collection End Times (page 3) from the flow recorder and enter data into the EMC Excel spreadsheet.

iv. Repeat steps 3a-f until the set-up team turns off the rain simulator at the end of the 45-minute run.
    1. The staff member running the YSI records the military end time of the rain simulation (page 1).
    2. Water will generally continue flowing to the collection point after the simulator is turned off. Continue to collect samples at the prescribed intervals and attempt to collect the last bottle, 11.
    3. The staff member running the YSI records the military end time runoff (page 1).

Post Rain Simulation

j. Obtain tank water information.
    i. Take an a final YSI reading of the tank water (page 3). Ask the set-up team when the water in the tank is ready to be sampled.
    ii. Observe final volume of water in the tank. Record the volume of water used (page 1) by subtracting the final volume from the initial volume.

k. Start compositing.
    i. Don nitrile gloves.
    ii. On page 3, check the "Core Parameter" boxes if at a "Core" site. Check both the "Core Parameter" boxes and "Additional Parameter" boxes if at an "Additional" site.
    iii. Enter data on the EMC and Conductivity spreadsheet.
        1. On the EMC tab, enter collection start and end times in minutes and seconds in columns A, B, D, and E. Enter the volume of sample collected in column H. Enter the total time of runoff in minutes and seconds in cells I21 and J21.
        2. On the Conductivity Composite tab enter the conductivity in column C. In column D, if a "Yes" appears this means this bottle is an outlier (generally bottle 1). If this happens, for any bottle, the volume of sample as determined by the EMC tab is added to the composite. Any remaining volume is added to a separate Metropolitan Council Lab bottle and sampled for as many analytes as

the volume will allow in this order of priority: chloride, *E. coli*, TKN and TP, total metals, chemical oxygen demand, and TSS.

3. Have someone who did not enter the data check to ensure all values were typed in correctly before compositing water samples.
4. If at a "Core" site add the volume in column N for each bottle into the composite bottle. Save the samples in the bottles until all compositing is complete in case a mistake is made. Label composite bottle.
5. If at an "Additional" site add the volume in column P into the composite bottle. Save the samples in the bottles until all compositing is complete in case a mistake is made. Label composite bottle.
6. Cap and shake the composite bottle. Pour out an *E. coli* sample into a Whirl Pak. If at an "Additional" site pour out three VOC bottles, careful to leave no air in the vials. Label containers.
7. If bottle 1 is an outlier, pour it into a separate brown, 2L bottle. Pour out and an *E. coli* sample into a Whirl Pak, if volume permits. Label bottle and pak.
8. Check that all samples have been collected. Pour out remaining sample water from the 1L Nalgene bottles.
9. Complete the Metropolitan Council Lab submittal form. See the attached example Metropolitan Council Lab submittal form. Ensure information on the form exactly matches labels. See the attached labeling guide.
10. Store bottles going to the lab on ice in a cooler.

Equipment Clean Up and Lab Delivery

l. Determine who will be dropping off samples at the lab. The lab address is attached.
    i. Ensure the person dropping off samples at the lab has all the samples on ice and Metropolitan Council Lab submittal form.
m. Clean up the project area and pack up vehicles.
n. Once at BAE, have used Nalgene bottles rinsed with tap water and air dried.
o. Dispose of any remaining deionized water in the squeeze bottle.

Data Entry

p. Obtain the spreadsheet from MWMO.
q. On the spreadsheet and sampling log (page 1) enter the weather data using information from the UMN St. Paul Climate Observatory.
r. In addition on the spreadsheet, enter the following:
    i. On the EMC tab enter the Runoff Flow Rates in columns Q, R, T, U, and X.
    ii. Enter the sample information from page 3 of the log to the Sample tab.

Enter the rain simulator ground dimensions on the Simulator Ground Dimensions tab.