Analysis of stormwater runoff from impervious surfaces in downtown Minneapolis, MN

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Abstract

Urban stormwater runoff is a major concern for water quality. Impervious surfaces, especially in urban environments, can allow contaminated stormwater direct access to receiving waterbodies. Impervious surfaces make up nearly 90% of land cover in downtown Minneapolis, Minnesota. When rain falls or snow melts, pollutants quickly transfer from those surfaces into nearby waterways. A study of stormwater runoff from impervious surfaces in downtown Minneapolis, Minnesota USA was conducted to understand potential impacts of different types of impervious surfaces (i.e., streets, sidewalks, parking lots and rooftops). The results of this study could be used to inform urban stormwater management strategies, particularly when the makeup of the area is mostly impervious surfaces.

Between summer 2017 and spring 2018, a rainfall simulator was used to deliver water upon street, sidewalk, and parking lot sites, which removed differences in rainfall characteristics, and tested the role of varying surface types and seasonal differences. Characteristics of rooftop runoff were studied using natural rainfall and snowmelt event data collected year-round with automated samplers and rain gauges.

Results showed that the first flush of runoff contained higher pollutant concentrations compared to the whole rain event, and water quality differences for all of the surfaces were relatively minor for the summer and fall seasons. The greatest difference was observed with higher pollutant concentrations occurring in the spring for all sites, particularly on streets. Higher than expected concentrations of chloride in the winter occurred from roofs, though concentrations were overall much smaller than the ground sites in the spring. Street event mean concentrations (EMCs) were the highest across different stormwater constituents, including chloride, total phosphorus, and total suspended solids. For each stormwater constituent, when the average EMC value was used for calculating pollutant loading instead of individual surface type EMC values, street contributions were underestimated, and the other surface types were overestimated due to the higher pollutant concentrations from streets than other impervious surfaces.

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Introduction

Managing stormwater runoff can be challenging, especially in a highly built urban environment with fewer opportunities for direct stormwater infiltration that could capture rainfall and reduce pollutant inputs. However, stormwater management is more important than ever in a time of climate crisis in which more extreme weather can increase water pollution. Mississippi River water quality has been improving in Minnesota over the last century in part due to targeted point source pollution reduction from sources such as industrial and wastewater treatment facilities (Metropolitan Council, 2018). Nonpoint sources of pollution like stormwater runoff from cities and agriculture are more challenging to target and reduce quickly, but nonpoint source reduction is an important step in supporting healthy waterways.

In order to protect and improve vital water systems through effective stormwater runoff management in urban watersheds, it is necessary to understand the watershed's stormwater water quality runoff characteristics. A collaborative study between the Mississippi Watershed Management Organization and the Bioproducts and Biosystems Engineering department at the University of Minnesota was conducted to provide more information about the localized water quality of downtown Minneapolis.

The study's goal was to explore possible differences in stormwater runoff quality between various types of impervious surfaces to better inform watershed modeling strategies. A report was completed in 2018 with the results of this study (MWMO 2018). It provides the full dataset of all water quality analytes collected, detailed operating procedure for simulated rainfall data collection, a comparison of water quality results by site, and evidence for parameter estimation using the conductivity data and first bottle concentrations and event mean concentrations. The work presented in this paper expands upon the 2018 report with further data analysis of the total suspended solids (TSS), total phosphorus (TP), and chloride (Cl) results. Statistical analysis was performed to better understand the potential differences in runoff water quality concentrations between the four different impervious surface types and if seasonality was significant in this dataset.

One of the main questions that drove this study was: if impervious surface water quality concentrations were significantly different from one another, how would using unique surface type values impact watershed modeling? Typically, an average concentration is applied to the full impervious land area. To explore this question, pollutant loads were calculated for the impervious areas of downtown Minneapolis using both average concentrations for all surfaces as well as individual average surface type concentrations. These values were also compared to national and state commercial area TSS and TP concentrations (Cl had no suggested commercial area value).

Urban Stormwater Runoff

One of the biggest nonpoint source contributors to poor water quality from urban watersheds is runoff from impervious surfaces like roads, sidewalks, parking lots, and roofs. As the amount of impervious surfaces increases within a watershed, the amount of rainfall that is converted to direct runoff increases. Unlike natural ground cover areas in which 10% of rainfall goes to direct runoff, landscapes with over 75% impervious surface contribute 55% of rainfall to runoff (the rest goes to evapotranspiration and shallow and deep infiltration) (EPA n.d.). Impervious surfaces collect trash, sediment, fertilizers, pesticides, oils, metals, and organic matter that can easily be lifted off when it rains. As a result, large quantities of pollutants enter the storm sewer system and receiving waterbodies.

Excess pollutants in stormwater (such as total suspended solids, total phosphorus, and chloride) contribute to impairments of use and negatively impact aquatic life, drinking water, and recreation. Urban stormwater runoff contributes about 4.8% of total phosphorus inputs to Minnesota watersheds (Barr 2004). Beom et al (2021) found that chloride concentrations and loads observed in an urban watershed were significantly larger than those of a rural watershed. All three of these pollutants have been identified as contributors to water quality issues in the Twin Cities Metro Area (MPCA 2021). According to the Minnesota Pollution Control Agency's (MPCA) 2020 Impaired Waters list, 744 Minnesota waterbodies have been identified as impaired for TSS and turbidity, 410 impaired for TP, and 50 impaired for chloride. This list includes the section of the Mississippi River that receives runoff from downtown Minneapolis, which is currently impaired for suspended solids and nutrients.

Characteristics of Downtown Minneapolis

The downtown area of Minneapolis consists of almost 90% impervious surfaces (MWMO 2018). Figure 1 below shows the breakdown of the different surface types, with roofs and roads making up over half of all surface types. Most of the land use is commercial, a range of medium to very high-density residential, and institutional. Downtown Minneapolis experiences seasonal extremes and a range of precipitation with humid summers and snowy winters and high average temperature of 83°F in July to low average temperature of 9°F in January. Average precipitation is highest (greater than 3 inches) May through August (NOAA 2021).

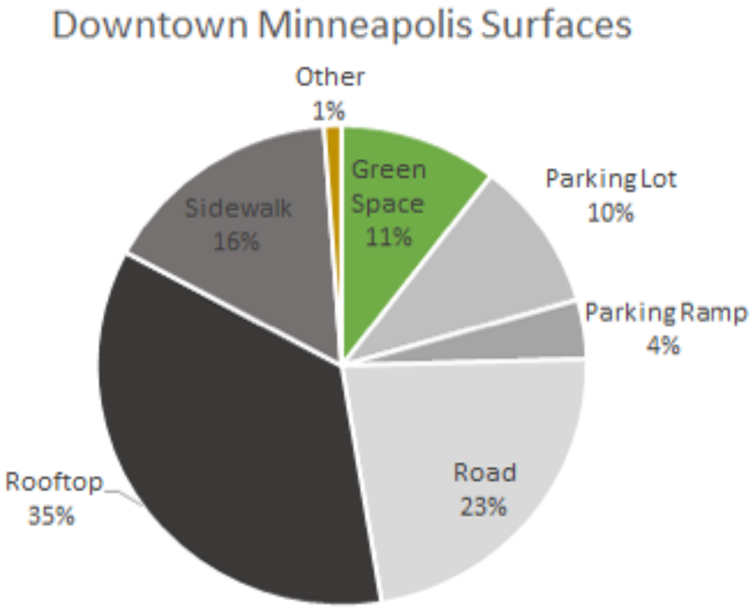

Figure 1. Breakdown of different types of surfaces in downtown Minneapolis.

Methods

Test Site Selection

Simulated rainfall events were conducted at streets, sidewalks, and parking lots, and natural rain event samples were collected at rooftop sites. Each type of impervious surface had three test sites throughout downtown Minneapolis. The selected test sites were chosen to represent a range in automobile and pedestrian traffic for downtown Minneapolis as well as a range of physical surface characteristics, such as construction material and age (see Table 1). Other selection factors included the testing site's proximity to a catch-basin in order to collect the sample runoff, and the ability to secure permits for the area to block the road and sidewalk. Sidewalk and street sites were paired for sampling convenience and roof test sites were selected based on the type of surface and willingness of building owners to participate in the project. All but one of the sampling locations were located in the southeast area of downtown Minneapolis.

Street and Sidewalk Sampling Sites

Rain simulations for the paired street and sidewalk were generally collected on the same day, which improved the efficiency of gathering data. The 3rd Ave South location has the heaviest automobile and pedestrian traffic (MnDOT's 2015 traffic data found an average daily traffic volume was 8,000 - 10,000 vehicles in this area). During the winter, it was observed that there is complete snow removal that occurs in this area. The South 8th street and sidewalk sampling site was located on South 8th Street adjacent to Elliot Park. During sampling events, a moderate amount of foot traffic along this corridor was observed as well as a moderate volume of automobile traffic. MnDOT's 2015 traffic data estimated an average daily traffic volume of 7,200 vehicles on this street. The 10th Ave South test site was located near the U.S. Bank Stadium at the intersection of 10th Ave South and South 6th Street adjacent to a parking garage. Fair to moderate automobile traffic was observed during sampling events and there was little to no pedestrian traffic, though it is presumed that pedestrian traffic increases dramatically during events at the stadium.

MnDOT's 2015 traffic data estimated an average annual daily traffic volume of 6,700 vehicles on nearby 11th Avenue South.

Parking Lot Sampling Sites

Parking lot sampling sites were more challenging to secure for testing due to heavy daily use. MWMO and the University of Minnesota partnered with Augustana Health Care, Hope Community Church, and Hennepin County Health Services to use spaces in their parking lots. The Hope Community Church parking lot was the largest parking lot at one-quarter of a city block with approximately 50 parking spaces. 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. There was a moderate slope and the pavement appeared to be in older but overall good condition. The Portland Ave parking lot was made of concrete and was the smallest parking lot. This parking area is mainly used for contractor parking for the Hennepin County building and includes about 5 parking spots. A low amount of pedestrian traffic was observed during the sampling events, but it can be assumed that the area is regularly used as an employee and visitor entrance.

Rooftop Sampling Sites

The rooftop sampling sites included the City of Lakes building (309 2nd Avenue South), Mensing Hall of North Central University (2 10th Avenue South), and a garage roof at Hope Community Church (704 11th Avenue South, Minneapolis, MN 55415). Runoff characteristics were obtained from natural rainfall and snowmelt events.

The City of Lakes Building is a four-story building located at the southern corner of South 3rd Street and 2nd Avenue South in the Downtown West neighborhood. The roof testing location was on one of two smaller structures on the main roof. The roof is rectangular in shape (36 feet by 74.5 feet), paved with asphalt covered in a layer of gravel, and has a single downspout. Roof runoff drains through an indoor PVC pipe.

Hope Community Church East is located at the southwest corner of 7th Street and 11th Avenue South in the Elliot Park neighborhood. The monitored roof is a garage roof approximately 10 feet high and located in the southwest corner of the Hope Community Church East building. The roof is 10 feet by 30 feet trapezoidal prism and composed of a rubber membrane covered in a layer of gravel.

North Central University's Mensing Hall is located at the north corner of South 7th Street and 10th Avenue South in the Elliot Park neighborhood. The monitored roof area is a white EDPM membrane material approximately 20 feet by 60 feet and about 15 feet from the ground.

Table 1. Impervious surface sites and their surface material.

Surface Type	Location	Surface Material
Parking Lot	Hope Community Church	Asphalt, New
	Augustana	Asphalt, Old
	Portland Ave	Concrete
Street	3rd Ave S	Asphalt
	10th Ave S	Asphalt
	8th St S	Half concrete, half asphalt
Sidewalk	3rd Ave S	Concrete
	10th Ave S	Concrete
	8th St	Concrete
Roof	City of Lakes	Asphalt and gravel
	Hope Community Church	Rubber membrane and gravel
	Mensing Hall	White EDPM membrane

Data Collection and Sampling Procedures

Streets, Sidewalks and Parking Lots

Stormwater runoff samples were collected at three different sites per ground surface type for a total of nine ground test sites. To control for rainfall intensity, and test area, a rainfall simulator was used to collect samples from the street, sidewalk, and parking lot sites. Other studies that utilized rainfall simulators include Morin and Cluff (1980), which used a rotating disc nozzle simulator to measure infiltration rates in semi-arid watersheds; Beighley and Valdes (2009), which used a Norton Ladder nozzle simulator to determine the effectiveness of two common sediment control technologies on sloped surfaces; and Vaze and Chiew (2003), which used a rigged sprinkler rainfall simulator over small test plots to better understand pollutant wash-off processes in urban areas. Based on the needs of this study and intended test locations, a nozzle simulator like Beighley and Valdes (2009) was used. The rain simulator pumps water out of a tank which then travels through two nozzles above the desired test area. The nozzles move back and forth spraying water in a rain-like pattern at a constant rate, 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 8-foot tall rainfall simulator was centered over a framed 6 feet by 12 feet rectangular area. The rainfall intensity was set at a constant rate of 2.5 inches/hour for a duration of 45 minutes. According to the National Oceanic and Atmospheric Administration's Atlas 14 Volume 8, the return period for this type of event is approximately 2 years for Minneapolis, Minnesota (Perica et al, 2013). The equipment was lab-tested to ensure consistent rates prior to use in the field. To minimize material loss from rain events, sampling events occurred after at least 48 hours of dry weather.

Clean plastic sheets, putty, water bags, and long metal sheets were used to frame and seal the sample area. Runoff rate and volume data and grab samples from the test area were collected in a catch-basin when possible. Runoff water was guided to the collection point using the plastic sheets. When a catch-basin was not available near a testing location, a system of clean PVC pipes was used to move water to a clean plastic box marked in 1-liter increments. Wind screens were placed against the rainfall simulator when necessary to protect the artificial rainfall from being diverted away from the test area and ensure that the spatial depth over the plot was relatively uniform.

To run the simulation, a tank of tap water from the University of Minnesota's Saint Paul campus (otherwise referred to as "source water") was used. The rain simulator was first rinsed with source water while the sweep function was disarmed. Tank level and water characteristics (temperature, dissolved oxygen, pH, and conductivity) were recorded before and after each simulation. The water pressure was constantly monitored to ensure a stable rainfall intensity. After 45 minutes, the rainfall simulator was turned off. Runoff rate and volume from the simulation was measured until water stopped flowing into the runoff collection container.

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 runoff collection container. After each sample was collected, water quality measurements (water temperature, dissolved oxygen, conductivity, and pH) were taken on site using a multiparameter sonde. The filled one-liter bottles were composited into a larger sample bottle using an EMC spreadsheet to determine the appropriate volume from each bottle to obtain a flow-weighted sample.

The composited sample along with a sample of the source water were analyzed to determine concentrations of total suspended solids (TSS), chloride (Cl), chemical oxygen demand, *E. coli*, cadmium, chromium, copper, lead, nickel, magnesium, manganese, zinc, nitrate-N, total Kjeldahl nitrogen, total phosphorus (TP), ortho-phosphate, total organic carbon, calcium, iron, mercury, and potassium. Final concentrations were obtained by subtracting the source water values from the composite concentrations of the runoff. In addition to the composite sample, the remainder of the first sample bottle was also analyzed if the standard deviation of conductivity in the bottle was greater than two from the subsequent bottle.

Rooftop Sampling

Natural rainfall and snowmelt events were used to determine stormwater runoff characteristics from three test roofs. The following equipment was installed on each roof to collect data: an automated sampler, datalogger, rain gauge, and conductivity sensor.

The City of Lakes roof runoff monitoring design included a modified PVC pipe system to control the water flow regime as it traveled down the pipe. A rain gauge was installed on the roof and an area-velocity sensor was installed in the modified pipe which allowed for flow-paced samples. A conductivity sensor was also installed in the pipe system to collect continuous conductivity data.

The roof for Hope Community Church is roughly 10 feet above the ground and has one downspout. A tipping bucket rain gauge was installed on the roof and a PVC pipe with a p-trap was attached to the downspout and connected to a 275-gallon tank. Water depth measurements were measured using a pressure transducer data logger in the tank and samples and conductivity data were collected from the p-trap of the pipe. An automated sampler was housed in a cabinet next to the downspout and was programmed to collect runoff samples based on water depth change in the tank. The tank was emptied after each rainfall event.

Mensing Hall roof has at least three downspouts transporting water from the roof to the ground. Pool bags were strategically placed on the roof to establish a measured runoff area. A tipping bucket rain gauge was installed on the roof, a PVC pipe system was attached to the downspout that drained to a tank where a pressure transducer measured the water depth, and a p-trap was used for a conductivity probe and sample collection. A weatherproof cabinet was placed next to the tank to house an automated sampler and data logger. The automated sampler was triggered to collect samples by the tipping-bucket rain gauge.

Data Handling

Some sample results included symbols such as “>”, “<”, and “~” that needed to be removed before data analysis could be performed. MWMO’s data handling protocol was followed: If laboratory results were less than the detection limit, the value was divided by 2. If the value was greater than the reporting limit, 1 was added. If the sample value was approximate (~ symbol used), the symbol was removed.

Statistical Analysis

ANOVA statistical analysis was used to determine if the sites were significantly different from one another within surface type, between surface types, and seasons for chloride, total suspended solids, and total phosphorus. A natural logarithmic (ln) transformation was used to obtain a normalized distribution.

Calculating Loads

The Simple Method was used to calculate loads for TSS, TP, and Chloride (Schueler, 1987). The average EMCs from this study were compared to the Minnesota Pollution Control Agency Stormwater Manual’s recommended values for impervious surface (commercial areas) TSS and TP EMC values as well as Nationwide Urban Runoff Program (NURP)’s impervious surface values for TSS and TP (US EPA 1983).
The Simple Method is:

$L = 0.226 * R * C * A$
Where
L = annual load (lbs)
R = annual runoff (inches)
C = concentration (mg/L)
A = acres
0.226 = unit conversion factor
And
Annual runoff $(R) = P * Pj * Rv$
Where
P = annual rainfall (inches)
Pj = Fraction of annual rainfall events that produce runoff (usually 0.9)
Rv = runoff coefficient $= 0.05 + 0.9Ia$
Ia = Impervious fraction

Since the areas of interest in downtown Minneapolis consist of 100% impervious surface; where Ia = 1, which means Rv = 0.95. 0.9 was used for Pj. The Twin Cities Metropolitan Area (TCMA) average annual rainfall is 30.65 inches and was used to calculate annual runoff (R). The MPCA uses this value when calculating TSS and TP loads for the TCMA (MPCA 2021a). Annual runoff (R) = 30.65 inches * 0.9 * 0.95 = 26.205 inches. A breakdown of surface type by area was identified and mapped by MWMO staff using ArcGIS software.

Results

Between summer of 2017 and spring 2018, 27 runoff simulations were completed at the street, sidewalk, and parking lot test sites. Composite samples were collected during all simulations. First flush samples were collected as well but due to small sample volume, some water quality analyses were not performed on the first flush sample. Therefore, not every composite sample value has a corresponding first flush sample value. The number of samples at roof test sites varied based on success of sample collection and readiness of equipment. A total of 57 roof samples were collected. In the spring, 15 samples were collected from the City of Lakes and Hope Community Church roofs combined. 23 samples were collected in the summer from all three roofs. Eight samples were collected in the fall at Hope Community Church and City of Lakes combined, and 11 samples were collected in the winter at the City of Lakes roof.

Total Suspended Solids

First Flush and Event Mean Concentration

First flush process was evident in sample results from the street, sidewalk, and parking lot test sites. Every first bottle that was tested for TSS resulted in higher concentrations than the composite sample (Figure 2). For instance, the spring sampling at 10th Avenue South street test site had a first bottle TSS concentration of 2,449.5 mg/L and a composite sample TSS concentration of 231.50 mg/L. This pattern continued for all other samples in which the first bottle was analyzed for TSS and compared to the composite sample.

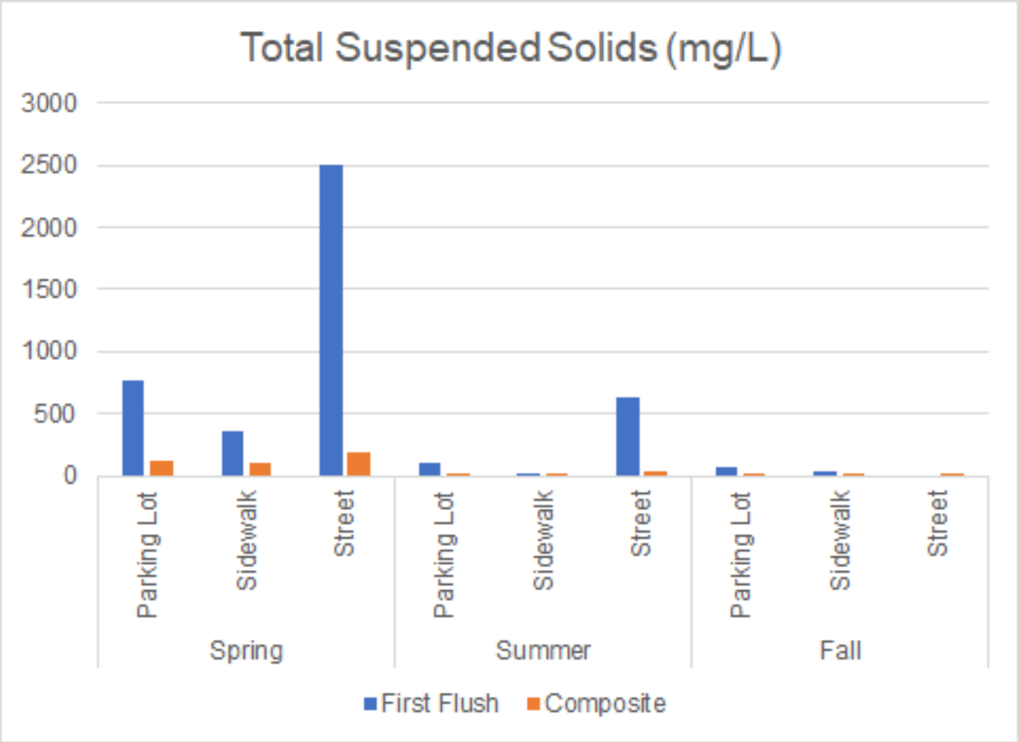

Figure 2. TSS first flush and composite samples; compared by season.

The highest average TSS concentrations occurred in the spring season for parking lots, sidewalks, and streets (124.5 mg/L, 95.6 mg/L, and 194.7 mg/L respectively). Total suspended solid concentrations from the roof test sites had an average of 29.31 mg/L and the seasonal results did not vary significantly from the average, with a range of 28.07 mg/L (summer) to 30.57 mg/L (fall). Streets had the highest average EMC (79.56 mg/L), followed by parking lots (45.11 mg/L), sidewalks (35.23 mg/L), and roofs (29.31 mg/L). The Minnesota TSS standard (30 mg/L) for the Mississippi River between Upper Saint Anthony Falls and the Saint Croix River was exceeded by all ground sites in the spring and by the roof sites in the winter (Figure 3).

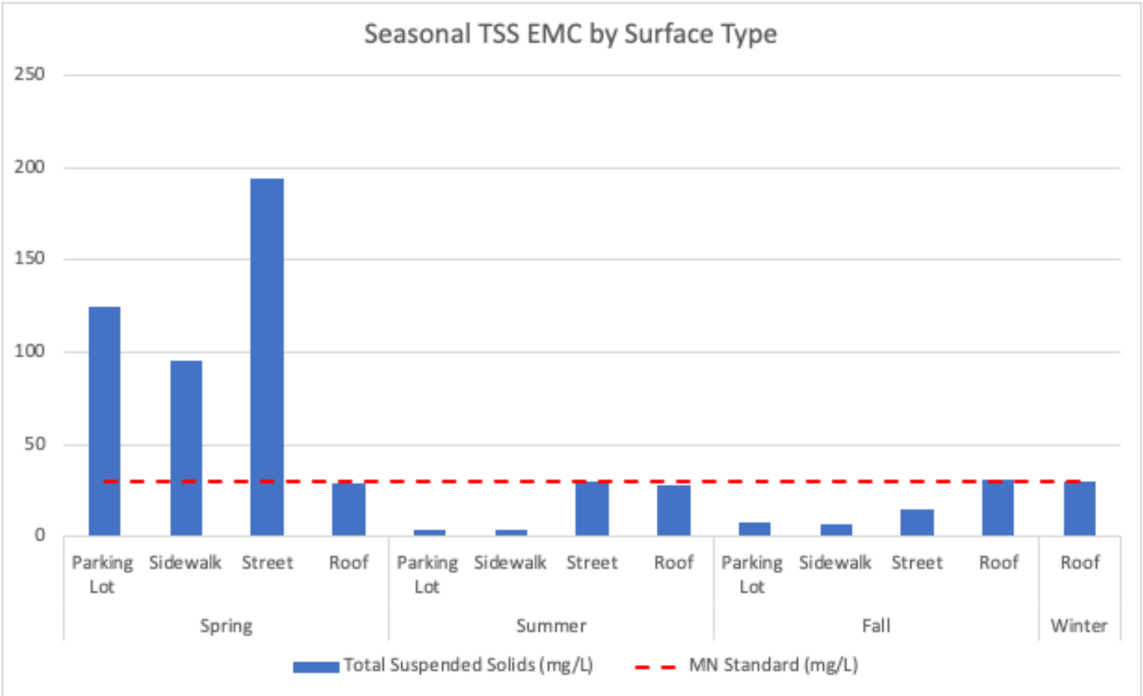

Figure 3. TSS EMC values separated by season and compared to the MN standard for the Mississippi River (30 mg/L).

Table 2. TSS average values in mg/L by season and surface type.

Season	Parking Lot	Sidewalk	Street	Roof
Spring	124.50	95.63	194.67	29.20
Summer	3.33	3.57	29.67	28.07
Fall	7.50	6.50	14.33	30.57
Winter				29.40
Average	**45.11**	**35.23**	**79.56**	**29.31**
Overall average	**47.30**			

Table 3. TSS composite and first flush results by season, surface type, and site.

Season	Surface Type	Site	Sample Type	Total Suspended Solids (mg/L)
Summer	Sidewalk	3rd Ave S	Composite	2.20
		10th Ave S	First flush	15.50
		10th Ave S	Composite	0.00

		South 8th St	Composite	8.50
	Street	3rd Ave S	Composite	11.00
		South 8th St	First flush	639.00
		South 8th St	Composite	65.00
		10th Ave S	Composite	13.00
	Parking Lot	Augustana	First flush	91.00
		Augustana	Composite	2.00
		Hope Community Church	First flush	31.00
		Hope Community Church	Composite	1.00
		Portland Ave	First flush	167.50
		Portland Ave	Composite	7.50
Fall	Sidewalk	3rd Ave S	Composite	10.50
		10th Ave S	Composite	3.50
		South 8th St	First flush	41.50
		South 8th St	Composite	5.50
	Street	3rd Ave S	Composite	18.50
		10th Ave S	Composite	16.50
		South 8th St	Composite	8.00
	Parking Lot	Augustana	First flush	77.50
		Augustana	Composite	7.50
		Hope Community Church	Composite	3.50
		Portland Ave	Composite	11.50
Spring	Sidewalk	3rd Ave S	Composite	87.50
		10th Ave S	First flush	356.50
		10th Ave S	Composite	38.50
		South 8th St	Composite	210.00
	Street	3rd Ave S	Composite	112.50
		10th Ave S	First flush	2,499.50
		10th Ave S	Composite	231.50
		South 8th St	Composite	240.00
	Parking Lot	Augustana	First flush	768.50
		Augustana	Composite	149.50
		Hope Community Church	Composite	72.50
		Portland Ave	Composite	151.50

Table 4. Roof sample results by season and site.

Season	Date	Site	Total Suspended Solids (mg/L)
Fall	9/20/2017	Hope Community Church	7
	10/2/2017	Hope Community Church	3
	10/2/2017	City of Lakes	25
	10/2/2017	Hope Community Church	2
	10/6/2017	Hope Community Church	2
	10/21/2017	City of Lakes	22
	10/21/2017	Hope Community Church	2
	11/4/2017	City of Lakes	158
Winter	1/10/2018	City of Lakes	58
	1/10/2018	City of Lakes	115
	1/26/2018	City of Lakes	15
	2/25/2018	City of Lakes	19
	2/25/2018	City of Lakes	12
	2/25/2018	City of Lakes	20
	2/27/2018	City of Lakes	13
	3/1/2018	City of Lakes	14
	3/3/2018	City of Lakes	13
	3/4/2018	City of Lakes	15
Spring	3/26/2018	City of Lakes	16
	4/4/2018	City of Lakes	14
	4/5/2018	City of Lakes	14
	4/9/2018	City of Lakes	54
	4/15/2018	City of Lakes	137
	5/24/2018	Hope Community Church	21
	5/24/2018	City of Lakes	51
	5/29/2018	City of Lakes	16
	6/2/2018	City of Lakes	10
	6/9/2018	City of Lakes	9
	6/16/2018	City of Lakes	54
	6/16/2018	Hope Community Church	5
	6/17/2018	City of Lakes	19
	6/18/2018	City of Lakes	9
	6/19/2018	City of Lakes	9

Summer	6/26/2018	City of Lakes	8
	6/26/2018	Hope Community Church	1
	6/26/2018	Mensing Hall	4
	7/1/2018	City of Lakes	5
	7/1/2018	Hope Community Church	1
	7/1/2018	Mensing Hall	1
	7/12/2018	Hope Community Church	11
	7/12/2018	City of Lakes	25
	7/12/2018	Mensing Hall	10
	7/28/2018	Mensing Hall	215
	6/26/2018	Mensing Hall	4
	7/1/2018	Mensing Hall	1
	7/12/2018	Mensing Hall	10
	7/28/2018	Mensing Hall	215
	8/3/2018	Mensing Hall	11
	8/24/2018	Mensing Hall	12
	9/4/2018	Mensing Hall	5
	9/17/2018	Mensing Hall	18
	9/18/2018	Mensing Hall	19
	9/20/2018	Mensing Hall	7

Statistical Analysis

ANOVA two-factor with replication statistical analysis was performed to test if the water quality results from the different types of surfaces were statistically different and if water quality results were statistically different due to seasonality. The data were transformed by the natural log plus one to normalize the data and to adjust for data values of zero. TSS had a P-value of 0.385 for interaction between surface type and season, a P-value of 0.00000005 for season, and a P-value of 0.0058 for surface type. With P-values <0.05, it can be assumed that there is a significant difference between seasons and a significant difference between surface type. However, with the interaction P-value >0.05, it cannot be ruled out that there is interaction between surface type and season. Statistical analysis of the TSS data showed that there were significant differences in season and surface type.

TSS Load

Loading calculations were performed on the dataset using the Simple Method to compare how using unique TSS concentration values might differ from using an overall average value for impervious surfaces, as well as how these results compare to MPCA's recommended TSS value for commercial areas (75 mg/L) and NURP's suggested concentration value (54.5 mg/L). Using the unique impervious surface values collected from this study, it was found that streets contribute the most to TSS loading in downtown Minneapolis impervious surface runoff, followed by rooftops, sidewalks, and parking lots. Using the average of all of the impervious surfaces (47.3 mg/L) like one might when modeling an area with an unspecified amount of each type of surface, rooftops would contribute the most to TSS load, followed by streets, sidewalks, and parking lots.

Using the impervious surface average value of 47.3 mg/L resulted in a smaller amount of estimated TSS load than the MPCA recommended value for commercial areas as well as the NURP TSS value. With all surface types combined, individual surface EMC had the smallest total load (153,185 lbs), followed by the average (157,806 lbs), NURP (181,820 lbs), and the MPCA concentration (250,212 lbs). See Table 5 and Figure 4 for a side by side comparison of each surface type.

When the average impervious surface value was used to calculate parking lot TSS loading, it was 105% higher than the load obtained by using the parking lot EMC. The average impervious surface value also resulted in a load that was 59% of the load resulting from the street EMC. For rooftops, the average impervious surface value load was 161% greater than the rooftop EMC load. The average impervious surface value also resulted in a load value 134% greater than the sidewalk EMC load result.

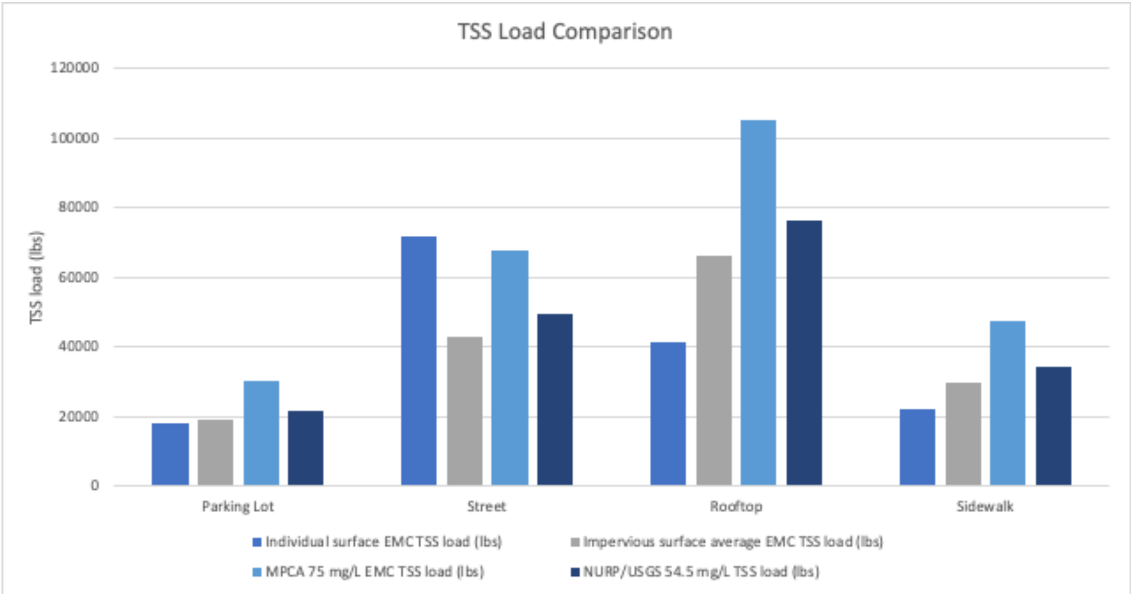

Figure 4. A comparison of calculated TSS loads by surface type and the differences in load results based on possible options for event mean concentration.

Streets contributed the most to the overall total load from the four different surfaces (42%) when individual EMC value was used to calculate load, otherwise it had a 27% contribution in other scenarios. Rooftops had a 27% contribution when the rooftop EMC was used and 42% in the other average value situations due to a larger contributing area. Sidewalks had a 15% contribution when the sidewalk EMC value was used and 19% otherwise. The total pollutant load calculated had an average value 3% greater than the total pollutant load calculated using the individual value (overestimated slightly).

Table 5. TSS load calculation results by surface type.

Surface type	**Acres**	**Individual surface EMC TSS load (lbs)**	**Impervious surface average EMC TSS load (lbs)**	**MPCA 75 mg/L EMC TSS load (lbs)**	**NURP/USGS 54.5 mg/L TSS load (lbs)**
Parking Lot	67.48	18,029.55	18,905.12	29975.23	21782.00
Street	152.37	71,789.64	42,684.42	67678.78	49179.92
Rooftop	236.64	41,078.15	66,292.23	105110.42	76380.24
Sidewalk	106.82	22,287.58	29,924.58	47447.26	34478.34
Total	**563.3**	**153184.92**	**157806.35**	**250211.69**	**181820.49**

Total Phosphorus

First Flush and Event Mean Concentration

First flush process was evident in the total phosphorus concentrations of the first bottle compared to the composite sample at every test site in which total phosphorus was analyzed. All first bottle results were higher than composite sample results (Figure 5). For example, the spring sample at 10th Avenue South had a first bottle EMC of 0.29 mg/L and a composite sample EMC of 0.03 mg/L. The season with the highest concentrations was spring. The average EMC of street sites was 0.16 mg/L, parking lot sites was 0.13 mg/L, sidewalk sites average EMC was 0.12 mg/L, and roof sites had an average EMC of 0.11 mg/L. Roof results by season did not vary significantly, ranging between 0.11 mg/L in the spring to 0.05 mg/L in the winter. The average EMC for each surface type was 0.09 mg/L (streets), 0.08 mg/L (roofs), 0.06 mg/L (sidewalks), and 0.05 mg/L (parking lots). The overall average TP EMC of all impervious surfaces is 0.07 mg/L. See tables 6 and 7 below for all TP EMC data.

For 15 samples (all composite), total phosphorus results were below the detection limit for analysis (0.02 mg/L). Four were parking lot samples (one in summer and all three fall composite samples), three were sidewalk samples (one in the summer and two in the fall), and eight were roof samples (three in the fall, four in the summer, and one in the winter).

In the spring, average TP EMC exceeded the MN Standard for Class 2B water (0.10 mg/L) (Figure 6). Summer values were at or below the standard, and fall values were quite low.

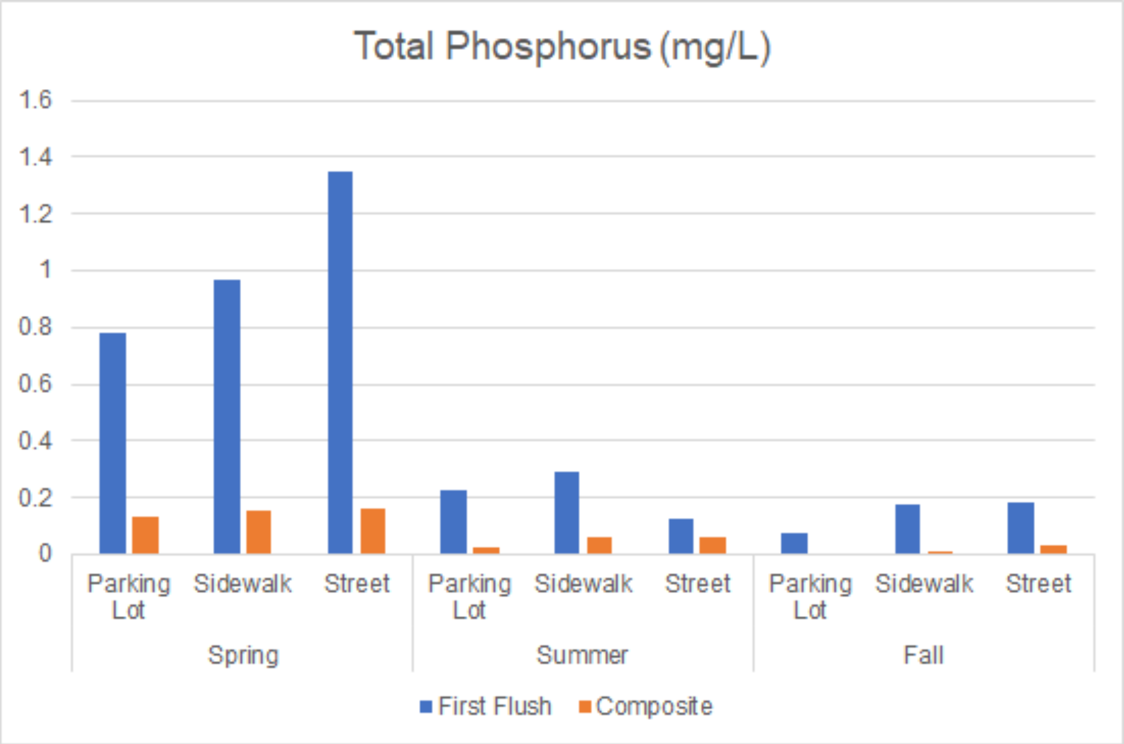

Figure 5. TP first flush and composite sample results at each ground surface type by season.

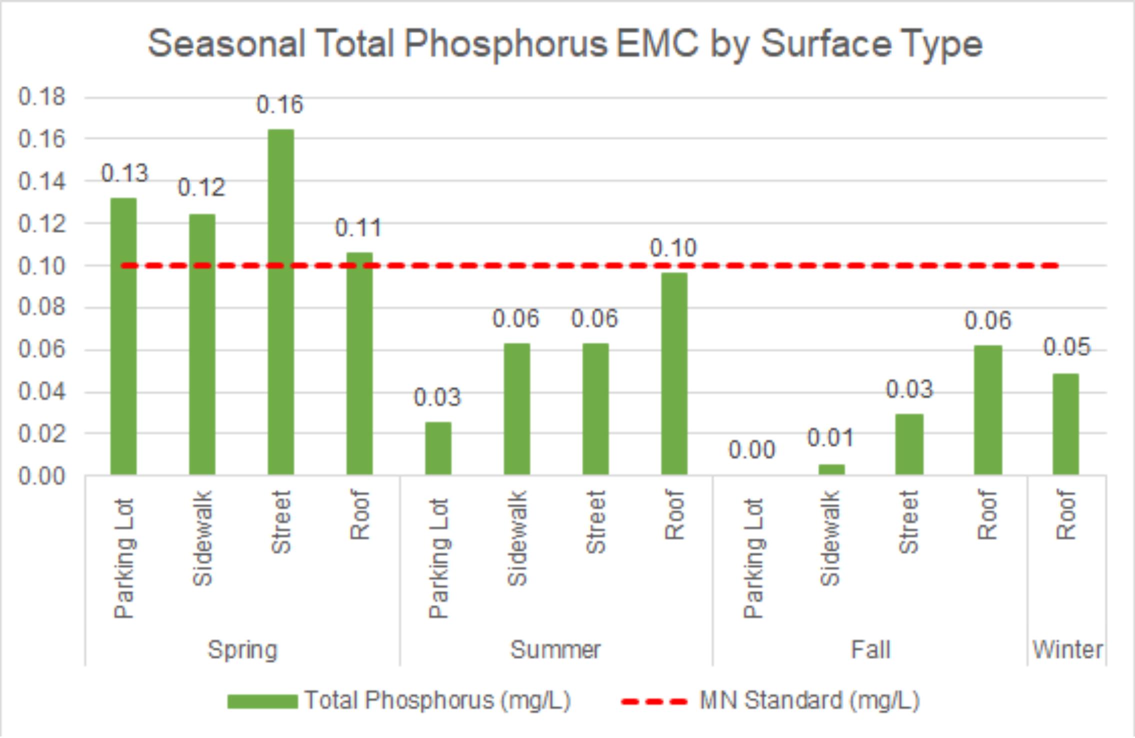

Figure 6. Average seasonal TP results at all four surface types compared to the MN water quality standard for TP for the Mississippi River in the TCMA (0.10 mg/L).

Table 6. First flush and composite sample results by season, surface type, and sampling location.

Season	Surface Type	Site	Sample Type	Total Phosphorus (mg/L)
Summer	Sidewalk	3rd Ave S	First flush	0.08
		3rd Ave S	Composite	0.03
		10th Ave S	First flush	0.07
		10th Ave S	Composite	0.00
		South 8th St	First flush	0.71
		South 8th St	Composite	0.16
	Street	3rd Ave S	First flush	0.13
		3rd Ave S	Composite	0.04
		South 8th St	Composite	0.12
		10th Ave S	Composite	0.03
	Parking Lot	Augustana	First flush	0.41
		Augustana	Composite	0.04
		Hope Community Church	First flush	0.09
		Hope Community Church	Composite	0.00
		Portland Ave	First flush	0.18
		Portland Ave	Composite	0.03
Fall	Sidewalk	3rd Ave S	First flush	0.13
		3rd Ave S	Composite	0.00
		10th Ave S	First flush	0.15
		10th Ave S	Composite	0.00
		South 8th St	First flush	0.24
		South 8th St	Composite	0.02
	Street	3rd Ave S	First flush	0.23
		3rd Ave S	Composite	0.05
		10th Ave S	First flush	0.18
		10th Ave S	Composite	0.02
		South 8th St	First flush	0.13
		South 8th St	Composite	0.02
	Parking Lot	Augustana	First flush	0.09
		Augustana	Composite	0.00
		Hope Community Church	Composite	0.00
		Portland Ave	First flush	0.06

		Portland Ave	Composite	0.00
Spring	Sidewalk	3rd Ave S	First flush	0.75
		3rd Ave S	Composite	0.07
		10th Ave S	First flush	0.29
		10th Ave S	Composite	0.03
		South 8th St	First flush	1.86
		South 8th St	Composite	0.36
	Street	3rd Ave S	First flush	0.67
		3rd Ave S	Composite	0.08
		10th Ave S	First flush	1.91
		10th Ave S	Composite	0.17
		South 8th St	First flush	1.47
		South 8th St	Composite	0.24
	Parking Lot	Augustana	First flush	0.79
		Augustana	Composite	0.12
		Hope Community Church	First flush	0.38
		Hope Community Church	Composite	0.06
		Portland Ave	First flush	1.18
		Portland Ave	Composite	0.21

Table 7. Roof sample results by season and site.

Season	Date	Site	Total Phosphorus (mg/L)
Fall	9/20/2017	Hope Community Church	0.02
	10/2/2017	Hope Community Church	0.01
	10/2/2017	City of Lakes	0.06
	10/2/2017	Hope Community Church	0.01
	10/6/2017	Hope Community Church	0.01
	10/21/2017	City of Lakes	0.07
	10/21/2017	Hope Community Church	0.05
	11/4/2017	City of Lakes	0.18
	12/19/2017	City of Lakes	0.11
Winter	1/10/2018	City of Lakes	0.11
	1/10/2018	City of Lakes	0.17
	1/26/2018	City of Lakes	0.03
	2/25/2018	City of Lakes	0.04

	2/25/2018	City of Lakes	0.03
	2/25/2018	City of Lakes	0.04
	2/27/2018	City of Lakes	0.03
	3/1/2018	City of Lakes	0.03
	3/3/2018	City of Lakes	0.01
	3/4/2018	City of Lakes	0.03
	3/8/2018	City of Lakes	0.02
Spring	3/26/2018	City of Lakes	0.12
	4/4/2018	City of Lakes	0.04
	4/5/2018	City of Lakes	0.04
	4/9/2018	City of Lakes	0.08
	4/15/2018	City of Lakes	0.16
	5/24/2018	Hope Community Church	0.09
	5/24/2018	City of Lakes	0.16
	5/29/2018	City of Lakes	0.08
	6/2/2018	City of Lakes	0.08
	6/9/2018	City of Lakes	0.07
	6/16/2018	City of Lakes	0.16
	6/16/2018	Hope Community Church	0.07
	6/17/2018	City of Lakes	0.36
	6/18/2018	City of Lakes	0.04
	6/19/2018	City of Lakes	0.05
Summer	6/26/2018	City of Lakes	0.03
	6/26/2018	Hope Community Church	0.01
	6/26/2018	Mensing Hall	0.08
	7/1/2018	City of Lakes	0.03
	7/1/2018	Hope Community Church	0.01
	7/1/2018	Mensing Hall	0.01
	7/12/2018	Hope Community Church	0.02
	7/12/2018	City of Lakes	0.11
	7/12/2018	Mensing Hall	0.23
	7/28/2018	Mensing Hall	0.41
	6/26/2018	Mensing Hall	0.08
	7/1/2018	Mensing Hall	0.01
	7/12/2018	Mensing Hall	0.23
	7/28/2018	Mensing Hall	0.41

	8/3/2018	Mensing Hall	0.03
	8/24/2018	Mensing Hall	0.05
	9/4/2018	Mensing Hall	0.03

Statistical Analysis

ANOVA two-factor with replication statistical analysis was performed to test if the water quality results from the different types of surfaces were statistically different and if water quality results were statistically different due to seasonality. The data were transformed by the natural log plus one to normalize the data and to adjust for data values of zero. TP had a P-value of 0.997 for interaction between surface type and season, a P-value of 0.003 for season, and a P-value of 0.63 for surface type. With an interaction P-value of 0.997, it can be assumed that there is significant interaction between seasons and surface type. The season P-value is <0.05, which could mean that TP by season is significantly different but cannot be concluded as such due to the interaction P-value. The P-value for surface type is >0.05, which means that the null hypothesis cannot be ruled out and surface types are not significantly different from one another.

Total Phosphorus Load

Using the unique impervious surface EMC values, rooftops contribute the most to TP loading from the four types of impervious surfaces, followed by streets, sidewalks, and parking lots. When all four of the impervious surfaces are averaged together, the order remains the same. Loads calculated using individual surface type EMCs had a larger total load (247.5 lbs) than loads calculated with the impervious surface average of 0.07 mg/L (233.11 lbs) (see Table 8).

Parking lots contributed the least to TP loads overall, with individual surface type values showing 8% contribution to impervious surface loading and 12% when impervious surface average value was used. Rooftops contributed the most overall, with 44% for individual surface type values and 42% when impervious surface average was used. Streets were second with 31% individual value and 27% contribution with average values. Sidewalks were third with 16% individual value contribution and 19%

contribution with average values. When the average impervious surface TP value is used, the TP loading is smaller than the load using the individual surface values by 6%. MPCA's value overestimates pollutant load contribution compared to the individual value calculation by 170%.

The MPCA's recommended EMC value of 0.2 mg/L was also used to compare load estimates from the four different surface types. The Nationwide Urban Runoff Program (1983) summarized data from 28 studies in the United States which resulted in a median TP concentration of 0.2 mg/L, the same value the MPCA recommends. Using the MPCA's recommended EMC value of 0.2 mg/L resulted in the same order (rooftop highest, followed by street, sidewalk, and parking lot) but with much higher amounts. Loads calculated using the impervious surface average EMC had the smallest total load compared to the total load calculated with the individual impervious surface EMCs as well as the load calculated with the MPCA recommended value (see Table 8 and Figure 7 below).

Table 8. Loads calculated using different EMCs for impervious surfaces.

Surface type	Acres	Individual surface EMC TP load (lbs)	Impervious surface average EMC TP load (lbs)	MPCA 0.2 mg/L EMC TP load (lbs)
Parking Lot	67.48	20.92	27.93	79.93
Street	152.37	76.80	63.05	180.48
Rooftop	236.64	109.18	97.93	280.29
Sidewalk	106.82	40.58	44.20	126.53
Total	**563.3**	**247.48**	**233.11**	**667.23**

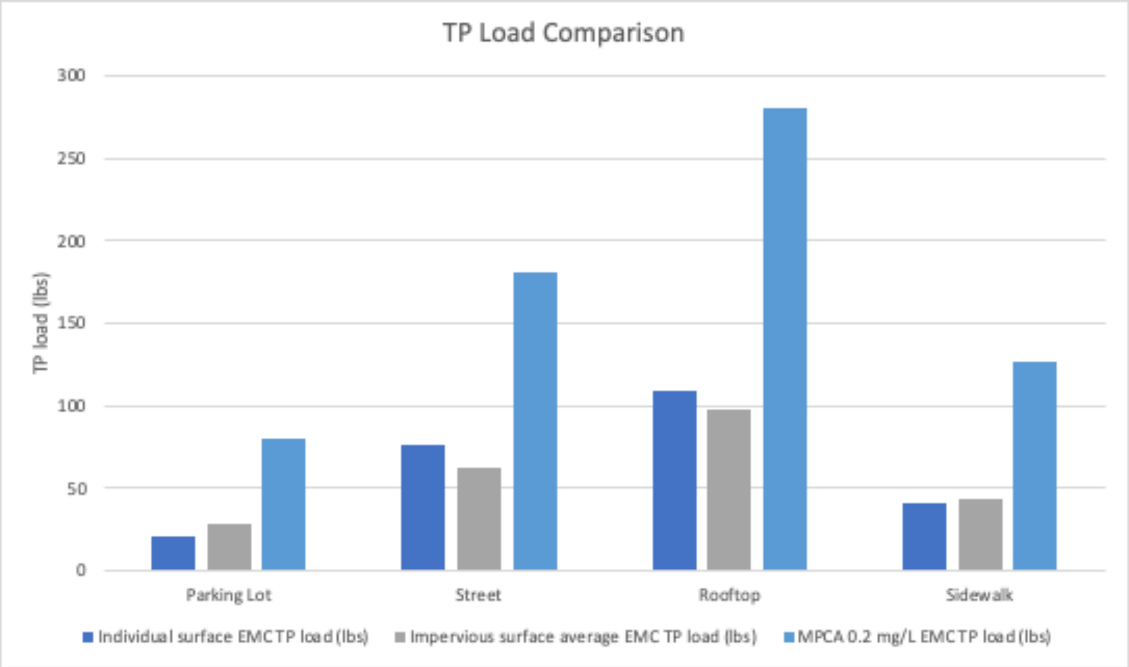

Figure 7. Graphical comparison of TP loads based on different EMC use.

Chloride

First Flush and Event Mean Concentration

First flush process was evident for almost all of the first bottles when compared to the associated composite sample (Figure 8). All but two first bottles had chloride concentrations higher than the composite sample. In the spring, the street rain simulation at 8th Street South had a first bottle chloride concentration of 118.7 mg/L and a composite sample chloride concentration of 704 mg/L and in the fall, and a fall parking lot rain simulation at Augustana had a first bottle chloride concentration of 0.5 mg/L and a composite sample chloride concentration of 0.7 mg/L. There were 7 of 9 fall roof samples, 7 of 15 spring roof samples, and all 17 summer roof samples that had chloride concentrations below the detection limit of 2 mg/L. Due to elevated chloride concentrations in the source water, no street, sidewalk, or parking lot samples had results below the detection limit and due to the source water adjustment some results were below 2 mg/L.

Spring season saw the highest average chloride concentrations, with streets having an average chloride concentration of 273.85 mg/L, parking lots with 8.90 mg/L, sidewalks with 5.17 mg/L, and roofs with 4.86 mg/L. In the winter, the City of Lakes roof site had an average concentration of 36.43 mg/L which was the highest of any season for roof sites. Overall, street test sites had the highest average concentration (91.83 mg/L), followed by roofs (11.32 mg/L), parking lots (3.33 mg/L), and sidewalks (2.46 mg/L). Fall and summer had similar low concentrations at all test sites. See Tables 9 and 10 for all sample results. Figure 8 shows the distinct results of the spring season compared to the summer and fall composite and first flush samples. The MN Standard for chloride (230 mg/L) was exceeded by the average spring street concentration (Figure 9).

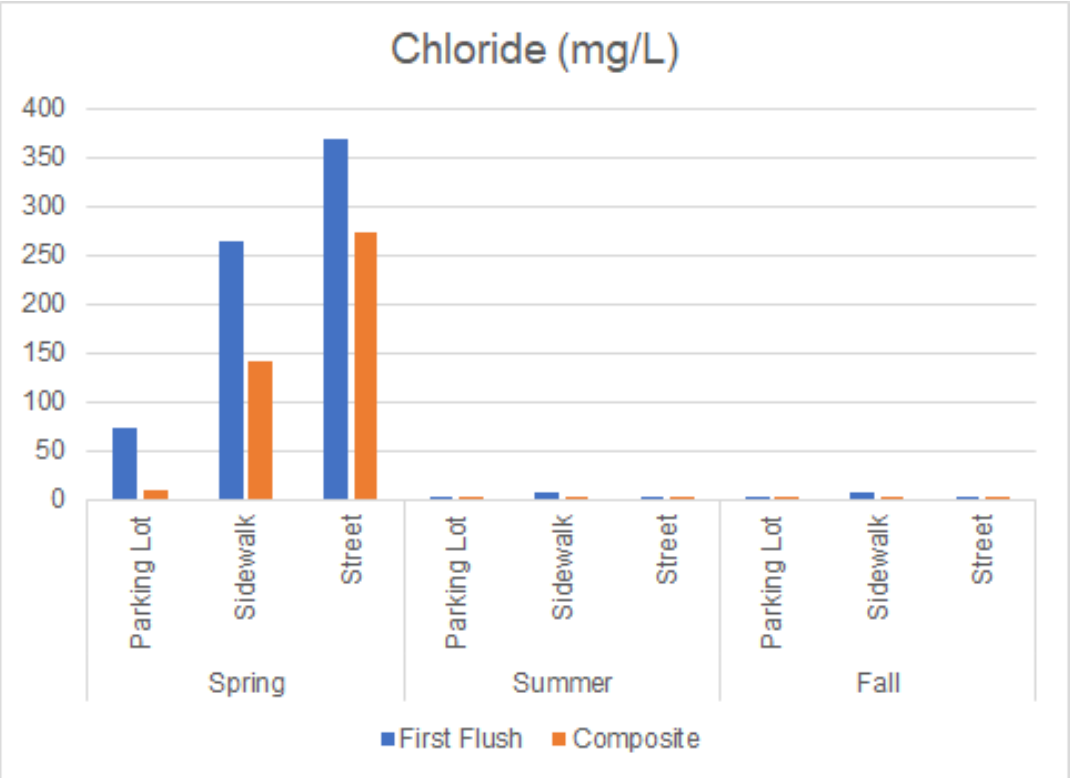

Figure 8. Seasonal first flush and composite sample chloride results of the three different ground impervious surfaces.

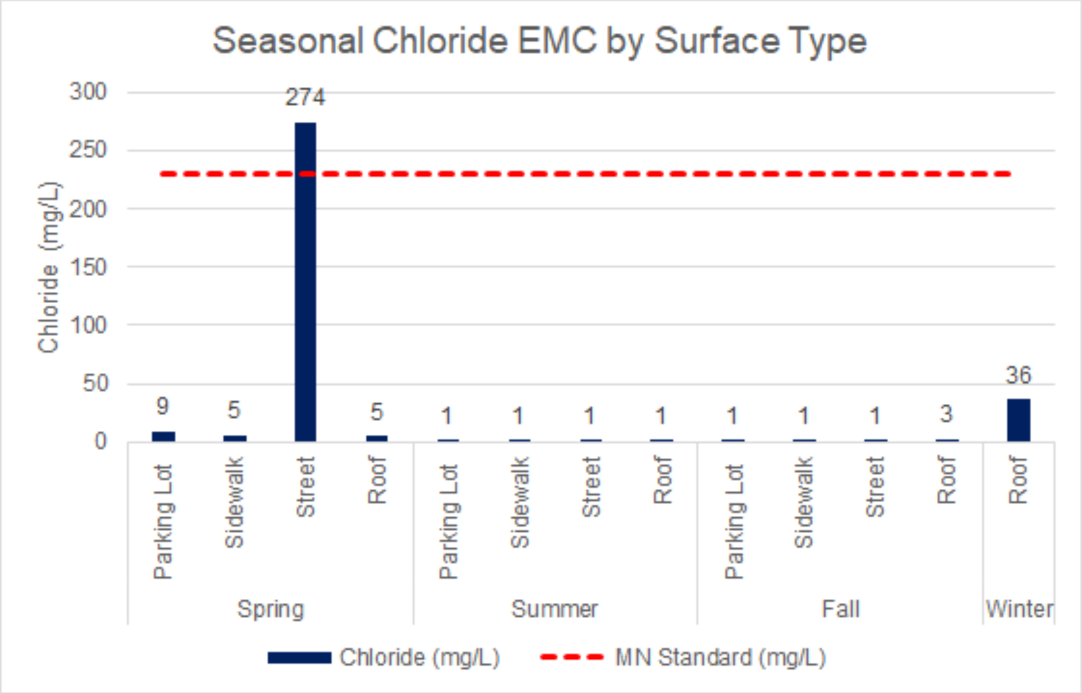

Figure 9. Average seasonal composite sample results by surface type compared to Minnesota state chloride standard (230 mg/L).

Table 9. First flush and composite sample chloride results by season, surface type, and site.

Season	Surface Type	Site	Sample Type	Chloride (mg/L)
Summer	Sidewalk	3rd Ave S	First flush	7.53
		3rd Ave S	Composite	1.83
		10th Ave S	First flush	5.40
		10th Ave S	Composite	0.80
		South 8th St	First flush	6.20
		South 8th St	Composite	0.80
	Street	3rd Ave S	First flush	2.60
		3rd Ave S	Composite	0.70
		South 8th St	Composite	0.80
		10th Ave S	Composite	1.00
	Parking Lot	Augustana	First flush	1.00
		Augustana	Composite	0.70
		Hope Community Church	First flush	2.30
		Hope Community Church	Composite	0.10
		Portland Ave	First flush	2.50

		Portland Ave	Composite	0.70
Fall	Sidewalk	3rd Ave S	First flush	7.90
		3rd Ave S	Composite	1.20
		10th Ave S	First flush	8.80
		10th Ave S	Composite	1.00
		South 8th St	First flush	2.80
		South 8th St	Composite	1.00
	Street	3rd Ave S	First flush	2.40
		3rd Ave S	Composite	0.80
		10th Ave S	First flush	2.60
		10th Ave S	Composite	0.90
		South 8th St	First flush	1.20
		South 8th St	Composite	0.70
	Parking Lot	Augustana	First flush	0.50
		Augustana	Composite	0.70
		Hope Community Church	Composite	0.50
		Portland Ave	First flush	2.30
		Portland Ave	Composite	0.60
Spring	Sidewalk	3rd Ave S	First flush	174.10
		3rd Ave S	Composite	14.10
		10th Ave S	First flush	20.10
		10th Ave S	Composite	2.00
		South 8th St	First flush	598.70
		South 8th St	Composite	410.60
	Street	3rd Ave S	First flush	863.80
		3rd Ave S	Composite	88.40
		10th Ave S	First flush	122.00
		10th Ave S	Composite	27.10
		South 8th St	First flush	118.70
		South 8th St	Composite	704.10
	Parking Lot	Augustana	First flush	34.60
		Augustana	Composite	8.70
		Hope Community Church	First flush	19.30
		Hope Community Church	Composite	3.40
		Portland Ave	First flush	162.50
		Portland Ave	Composite	14.60

Table 10. Roof sample results by season and roof test site.

Season	Date	Site	Chloride (mg/L)
Fall	9/20/2017	Hope Community Church	1.0
	10/2/2017	Hope Community Church	1.0
	10/2/2017	City of Lakes	1.0
	10/2/2017	Hope Community Church	1.0
	10/6/2017	Hope Community Church	1.0
	10/21/2017	City of Lakes	1.0
	10/21/2017	Hope Community Church	1.0
	11/4/2017	City of Lakes	2.0
	12/19/2017	City of Lakes	15.9
Winter	1/10/2018	City of Lakes	91.3
	1/10/2018	City of Lakes	34.2
	1/26/2018	City of Lakes	14.5
	2/25/2018	City of Lakes	73.4
	2/25/2018	City of Lakes	67.7
	2/25/2018	City of Lakes	49.6
	2/27/2018	City of Lakes	26.4
	3/1/2018	City of Lakes	14.5
	3/3/2018	City of Lakes	12.8
	3/4/2018	City of Lakes	9.2
	3/8/2018	City of Lakes	7.1
Spring	3/26/2018	City of Lakes	11.4
	4/4/2018	City of Lakes	13.2
	4/5/2018	City of Lakes	6.1
	4/9/2018	City of Lakes	13.9
	4/15/2018	City of Lakes	8.6
	5/24/2018	Hope Community Church	5.1
	5/24/2018	City of Lakes	3.7
	5/29/2018	City of Lakes	1.0
	6/2/2018	City of Lakes	1.0
	6/9/2018	City of Lakes	2.5
	6/16/2018	City of Lakes	1.0
	6/16/2018	Hope Community Church	2.4
	6/17/2018	City of Lakes	1.0

	6/18/2018	City of Lakes	1.0
	6/19/2018	City of Lakes	1.0
Summer	6/26/2018	City of Lakes	1.0
	6/26/2018	Hope Community Church	1.0
	6/26/2018	Mensing Hall	1.0
	7/1/2018	City of Lakes	1.0
	7/1/2018	Hope Community Church	1.0
	7/1/2018	Mensing Hall	1.0
	7/12/2018	Hope Community Church	1.0
	7/12/2018	City of Lakes	1.0
	7/12/2018	Mensing Hall	1.0
	7/28/2018	Mensing Hall	1.0
	6/26/2018	Mensing Hall	1.0
	7/1/2018	Mensing Hall	1.0
	7/12/2018	Mensing Hall	1.0
	7/28/2018	Mensing Hall	1.0
	8/3/2018	Mensing Hall	1.0
	8/24/2018	Mensing Hall	1.0
	9/4/2018	Mensing Hall	1.0

Statistical Analysis

ANOVA two-factor with replication statistical analysis was performed to test if the water quality results from the different types of surfaces were statistically different and if water quality results were statistically different due to seasonality. The data were transformed by the natural log to normalize the data. Chloride had a P-value of 0.006 for interaction between surface type and season, a P-value of 0.00000017 for season, and a P-value of 0.01 for surface type. With P-values <0.05, it can be assumed that there is a significant difference between seasons and a significant difference between surface type and there is no interaction between seasons and surface type.

Chloride Load

Chloride loads were calculated using individual surface EMCs as well as the overall average EMC for impervious surfaces (27.23 mg/L). No recommended EMC value was found for chloride, so loading results from individual surface EMCs and loading results using the average of these values were compared. The following results can be found in detail in Table 11 and Figure 10 below. Use of the parking lot EMC resulted in a much smaller chloride load than when the average value was used; the average value resulted in an 817% greater load. The calculated load with the average chloride EMC was 30% of the load calculated with the street EMC value. Use of the average impervious surface EMC resulted in a load that was 241% greater than the rooftop EMC calculated load. The sidewalk EMC value is much lower than the impervious surface average value so when the average value was used for loading calculations, it was 1108% greater than the sidewalk EMC chloride load. These calculations showed that in downtown Minneapolis, roads contribute the most chloride, followed by rooftops, sidewalks, and parking lots.

Table 11. Loads calculated by individual surface type EMC and impervious surface average EMC (27.23 mg/L).

Surface type	**Acres**	**Individual surface EMC Chloride load (lbs)**	**Impervious surface average EMC Chloride load (lbs)**
Parking Lot	67.48	1,332.23	10,884.97
Street	152.37	82,864.90	24,576.34
Rooftop	236.64	15,862.83	38,168.96
Sidewalk	106.82	1,555.45	17,229.62
Total	**563.3**	**101,615.42**	**90,859.89**

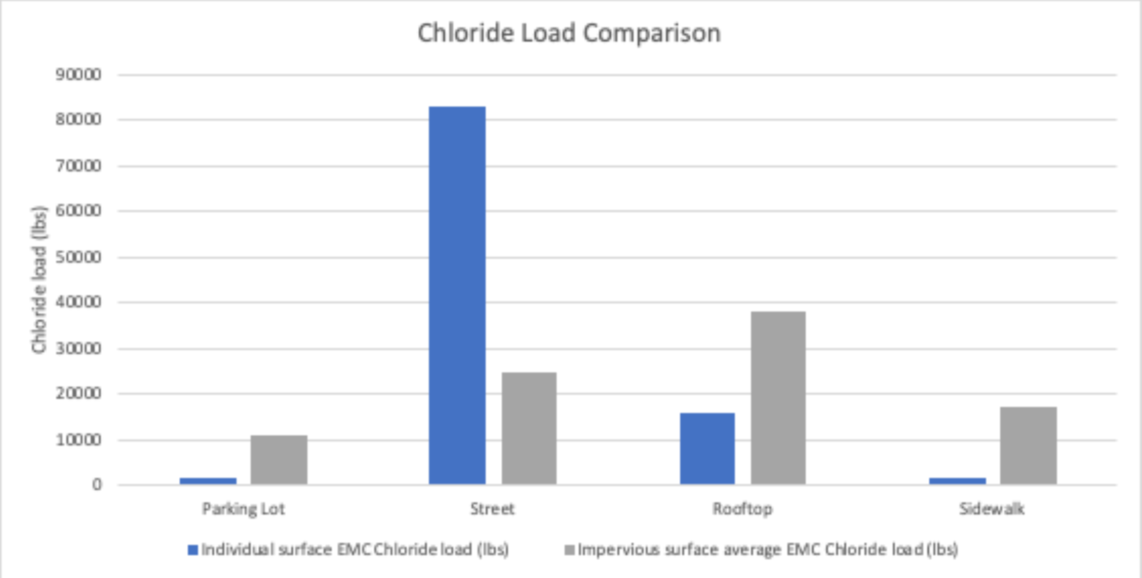

Figure 10. Calculated chloride loads by surface type.

The following results were found when comparing how each of the four impervious surface types contributed to overall chloride loading: When individual EMC values were applied, parking lots only contributed 1% to total Cl load. When the average EMC value was used, parking lots contributed 12% to overall load. Streets had an 82% contribution when street EMC value was used and 27% when the average impervious surface value was used. Roof results are also fairly different, with 16% contribution when the individual EMC values were used and 42% with average impervious surface value. Sidewalks contributed only 2% with individual EMC values and 19% with average impervious surface value. Streets clearly bring up the average impervious surface value which can skew actual contribution from these surfaces (see Figure 10). Altogether, the total chloride pollutant load using the average impervious surface value is smaller than the pollutant load using the individual EMC values by 11%.

Discussion

Simulated and natural rain events during this study found that total suspended solids, total phosphorus, and chloride were elevated in the spring season, and were particularly high at the street test sites. These findings are consistent with what Smith et al (2020) observed, which were seasonal differences in nutrient concentrations in residential stormwater runoff, and that springtime pollutant concentrations were higher across all sewersheds.

First Flush

A first flush effect was evident in simulated runoff events during which the majority of pollutant wash-off occurred in approximately the first five minutes. This is consistent with studies by Egodawatta et al. (2012) and Yufen et al. (2008) which found that TP and TSS concentrations in runoff of roofs, sidewalks, lawns and roads in urban areas had a first flush phenomenon. Beom et al. (2021) also found a strong first flush effect with chloride concentrations of urban stormwater runoff. This is important because intercepting the first flush of storm events can remove a majority of the pollutant load from entering a receiving water body. Li et al. (2015) suggest intercepting the first 40% of runoff volume could remove 55% of TSS load and 61% of TP load for all storm events.

Event Mean Concentrations

By season, spring had the highest TSS, TP, and Cl event mean concentrations for streets, sidewalks, and parking lots. Roof sites had the highest chloride EMC in the winter and TSS EMCs were not significantly different by season at the roof sites, though the average fall EMC was slightly higher. Total phosphorus average EMCs were highest in the spring for all four impervious surface types.

By surface type, streets had the highest average TSS, TP and Cl EMCs, followed by parking lots, sidewalks, and roofs. Streets also had the highest EMCs when comparing all seasonal averages. Average annual total phosphorus of each surface type did not vary significantly, ranging from 0.05 mg/L (parking lots) to 0.09 mg/L (streets). Meanwhile, average annual chloride ranged from 2.46 mg/L (sidewalk) to 91.38 mg/L (streets). Average annual TSS ranged from 29.31 mg/L (roofs) to 79.56 mg/L (streets). Table 12 below shows the average EMCs for Cl, TP, and TSS.

Table 12. Average surface type EMCs for Cl, TP, and TSS.

Surface	Chloride (mg/L)	Total Phosphorus (mg/L)	Total Suspended Solids (mg/L)
Parking Lot	3.33	0.05	45.11
Sidewalk	2.46	0.06	35.23
Street	91.83	0.09	79.56
Roof	11.32	0.08	29.31
Overall average	**27.23**	**0.07**	**47.30**

These results show that other factors such as traffic, litter or other debris, or soil from construction sites could play a role in pollutant loading on the ground and impervious surfaces. Whereas roof surfaces have little interaction with those particular inputs beyond atmospheric deposition and animal droppings, roof material could also contribute to pollutant loading. Since samples were able to be collected from the roofs in the wintertime, it was found that roofs had a non-negligible amount of chloride in its runoff, which could be from road salt dust settling on the roofs.

In the spring, streets exceeded the chloride MN Standard for Class 2B waters of 230 mg/L and all impervious surface types exceeded the total phosphorus MN Standard for Class 2B water (0.10 mg/L). Summer values were at or below the standard, and fall values were lower. Fall season TP concentrations were surprisingly low, as it was anticipated that leaf litter would increase the total phosphorus values, like what was found in Janke's (2017) study. Less tree cover and timing of sample collection could be some considerations for why this study had low TP values in the fall.

These results are supported by study conducted by Brezonik et al. (2001) in the Twin Cities Metropolitan Area in Minnesota which found that the median EMCs for 10 common constituents, including TSS and TP, tended to be higher in snowmelt runoff than in rainfall runoff, and significant seasonal differences were found in yields (kg/ha) and EMCs for most constituents.

Pollutant Loads

Parking lots across the board contributed the least to impervious surface TSS loading (12% in every scenario). Using the results of this study, roads account for over 80% of the chloride pollutant load and almost 50% TSS load. Roads contribute the most TSS though it is second to rooftops in surface area, followed by rooftops, sidewalks, and parking lots. The MPCA's value overestimates pollutant load compared to the individual surface value by 63%. NURP overestimates total pollutant load compared to the individual values by 19%. The EMC value from this study for streets was approximately the same as the recommended value for TSS but the other surface types had EMCs below the recommended value for modeling commercial land use areas.

In general, when the average impervious surface value was used for these three pollutants, streets were underestimated, and the other surface types were overestimated compared to results when the individual surface type EMC was used to calculate pollutant loads. TP and TSS EMCs from this study are well below the MPCA’s recommended value, which means that modeling with the recommended value would overestimate TP and TSS.

The results of this study show that different impervious surfaces contribute different concentrations of TP, TSS, and Cl and that seasons impact concentration amounts. This could be useful for models of areas with mostly impervious surfaces as they would be more accurate if they were calibrated by using impervious surface-specific event mean concentrations.

Limitations and Suggestions for Further Research

In future research, it would be worthwhile to investigate how traffic (car and pedestrian) and atmospheric deposition affect pollutant concentrations of different types of impervious surfaces in Downtown Minneapolis. Areas with significant atmospheric deposition can contain high concentrations of TSS, nutrients, and metals in stormwater runoff (EPA n.d.). Research by R.G. Brown in 1984 studied atmospheric deposition in the Twin Cities Metropolitan Area in three rural land areas and one urban land area, finding that atmospheric deposition of total phosphorus and chloride contributed approximately 6% to the runoff load of nonpoint source pollution; local inputs such as industrial, vehicular, and agricultural were found to influence the magnitude and rate of atmospheric deposition. With changing land use and increasing urbanization, another local or regional study could be conducted to update these findings.

A technical report by G.L. Oberts, Metropolitan Council, in 1982 found that the highest pollutant concentrations in urban stormwater runoff occurred from snowmelt in the late winter and spring. In Minnesota, snowmelt and early spring rainfall events account for approximately 65% of annual sediment, organic, nutrient loads, and practically all chloride loads. Bannerman et al. (1983) also found that the highest concentrations of TSS and Cl occurred in meltwater and early spring in Milwaukee, WI. Collecting consistent snowmelt samples from impervious surfaces beyond rooftops was also outside of the scope of this study but would be a good next step in understanding year-round runoff characteristics. In addition, further investigations could be performed of chloride levels and sources from roof snowmelt in downtown Minneapolis, as there were some winter roof samples with higher than expected chloride concentrations.

Some limitations for this study included accessing and sampling all three roofs for the same period of time. Due to equipment availability, roof access, and lack of winterization ability for two of the roofs, roof samples were collected at different times over the 2017-2018 study period. Rainfall simulations were also not feasible to conduct on rooftops in downtown Minneapolis so roof samples were not collected in the same way as ground sites, which could have added additional homogeneity to the study.

Recommendations for Water Resource Managers

Using the results of this study, the following recommendations are suggested for future stormwater management practices to effectively and efficiently reduce TSS, TP, and Cl inputs:

- Targeted spring season stormwater management practices
- Targeted streets pollutant removal
- Utilize stormwater management practices that capture the first flush of storms
- Reduce the amount of salt applied as much as possible and remove excess after application and before forecasted rain or melt events

These recommendations are supported by other research, including a study in California that investigated seasonal buildup of pollutants (Lee et al, 2004). Their results suggest utilizing best management practices (BMPs) early in the season to remove several times more pollutant mass than randomly used BMPs.

Conclusions

Key findings:

- First flush effect evident in all sampling events
- Highest TSS, TP, and Cl EMCs found in spring
- TSS and Cl EMCs are significantly different by surface type and season
- TP EMCs are significantly different by season but cannot conclude that they differ by surface type
- Elevated Cl concentrations found on roofs in the winter
- Loading calculations modeling found that using individual surface type EMC values resulted in loads that were significantly different from loading calculations that used the average EMC of all surface types.

From this study and review of similar studies, it is clear that the first flush effect and spring season are key to optimize pollutant removal from stormwater runoff. In addition, data from this study show that streets contribute the most to pollutant inputs in stormwater runoff and that there are significant differences between pollutant contributions of different types of impervious surfaces. Finally, there are differences between stormwater runoff characteristics of different types of impervious surfaces, further implicating the variability of pollutant wash-off characteristics that could affect watershed modeling efforts.

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