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Influence of Sewershed Characteristics on Rainfall-Derived Inflow and Infiltration

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Research Impact Statement: Fast direct inflows and slow infiltration in sanitary sewer systems are correlated with the pipe density and land use characteristics of a sewershed.

ABSTRACT: Basement backups and sewer overflows from rainfall-derived inflow and infiltration (RDII) are a significant threat to human and environmental health; however, reducing inflow and infiltration is a challenge for municipalities due to the difficulty and resources required to accurately identify source areas. This case study seeks to address this challenge by evaluating the influence that sewershed characteristics have on inflow and infiltration into sanitary sewer systems. To do so, we used 4.5 years of monitoring data from 19 sanitary sewer locations in Milwaukee, Wisconsin to explore the relationships between RDII defined using the RTK unit hydrograph method and sewershed physical, land cover, and pipe characteristics. Results demonstrate that inflow, or fast direct flows into the system, is positively correlated to pipe length per acre, number of parcels, and medium intensity land use. Infiltration, or slow inputs from groundwater sources, is negatively correlated with imperviousness, pipe length per acre, low intensity, and medium intensity land use. Multivariable linear regression using these parameters explained between 55% and 72% of the variance in normalized inflow and infiltration. These findings demonstrate a way in which collection system managers may be able to narrow the search areas for RDII sources within their sanitary sewer systems by evaluating sewershed characteristics.

(KEYWORDS: rainfall-derived inflow and infiltration; sewersheds; hydrology; collection systems.)

INTRODUCTION

Aging sanitary sewer systems pose a significant challenge to collection system operations due to cracks and deteriorating pipes that result in unwanted increases in flows during storm events from rainfall-derived inflow and infiltration (RDII) (Zhang et al. 2018). Pipes in collection systems can have cracks from settling, tree roots, or inadequate joint connections that result in the introduction of stormwater, groundwater, or snowmelt. In addition, they may have connections of source water from roof drains, foundation drains, or sump pumps on residential properties. In fact, it has been shown that up to 68% of residential properties in a sewershed can contribute to inflow and infiltration (Pawlowski et al. 2014). The result is an increase in the volume of water that must be treated at the water treatment plant during rainfall events. This is a significant problem for water reclamation plants as treating unnecessary stormwater can drive up the cost of water treatment and in the worst situations cause overflows or basement backups. To this end, sanitary sewer systems are estimated to overflow 23,000–75,000 times per year in the United States, resulting in the discharge of 3–10 billion gallons of untreated wastewater (USEPA 2004). In addition to overflows, these systems can experience basement backups of untreated water into citizens homes, which results in property damage and risk of serious illnesses (USEPA 2006).

As such, municipalities invest significant resources into improving the function of their sewer systems to

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prevent overflows and basement backups. For example, Kansas City has committed to invest $2.5 billion dollars to eliminate overflows of untreated wastewater (Whitley 2010). In most cases, it is much costlier to upsize existing treatment systems than to try to reduce inflow and infiltration at the source (Sola et al. 2020). Efforts to reduce inflow and infiltration include direct actions on the system such as lining of lateral pipes, repairing disjointed or cracked manholes, and upgrading capacity of the sewer system, as well as prevention actions such as the implementation of green infrastructure or low impact development (Nasrin et al. 2017).

In many cases, municipalities are thrust into addressing their inflow and infiltration issues due to a consent decree from a state or regulator agency. The first step in these cases is to determine where in a sewer system the inflow and infiltration is occurring. This can be a significant challenge as cities can cover areas that are hundreds of square kilometers and that have thousands of kilometers of pipes. Therefore, municipalities rely on costly monitoring programs to identify areas within their system that are contributing the most inflow and infiltration into their systems for targeted remediation. These monitoring studies can take a significant amount of time (4–6 months) and resources, including sensor, maintenance, operations, and engineering costs. As such, entities with limited capital may not have the resources for carrying out such tasks necessary for identifying inflow and infiltration.

Furthermore, once monitoring data are collected, many municipalities use hydraulic models to help provide them with a picture of what is happening within their sewers and understand where inflow and infiltration may be occurring. These models of inflow and infiltration can help to understand where sources are located within these systems; however, they too require significant resources to build, calibrate, and validate, which may not be available to municipalities with resources and personnel constraints. Therefore, there is a need for additional screening-level tools that can help to augment existing monitoring and modeling tools to identify likely locations of inflow and infiltration into a sanitary sewer system. While several approaches for screening-level analysis exist (Thapa et al. 2019; Herckis 2020), none of these are based upon empirical data that can identify the characteristics of sewersheds and their potential for RDII.

This paper presents a case study to explore the relationship between RDII and sewershed characteristics for sewersheds in the Milwaukee region. To do so, we evaluated the inflow and infiltration of 19 sewersheds over 4.5 years using an RTK unit hydrograph approach and explored its relationship to physical and hydrologic characteristics of the sewershed. Given the challenge of inflow and infiltration in older more dense developments, we hypothesized that inflow and infiltration would be correlated to the land use classification, pipe density, and pipe materials. The outcome is an improved understanding of the impact that physical and hydrologic characteristics at a sewershed scale have on different components of inflow and infiltration. Ultimately, this understanding can equip water reclamation managers with a high-level planning tool that can help them make informed decisions based upon the spatial characteristics of their sewersheds. This would allow water reclamation managers to prioritize remediation efforts on areas most likely to have high RDII based on spatial characteristics.

METHODOLOGY

Site Description

The sewersheds selected in this study were located throughout the Milwaukee Metropolitan Sewerage District (MMSD) service area (Figure 1). MMSD has both combined and sanitary sewer systems within their jurisdiction with the combined system located in the historic area of the city closest to downtown and separated systems outside of the city center. The focus of this study is on inflow and infiltration into separate sanitary systems; therefore sewersheds selected in this study were constrained to the separated area. Sewersheds are monitored for flow rate by MMSD at various locations throughout their network using ISCO 2150 acoustic doppler velocimeters that collect water level and velocity data in 15-min intervals. Using this database, we selected monitoring locations in sewersheds that had continuous data over a 4.5-year period from January 2015 to June 2019. We also searched for sewersheds that had a range of physical and hydrologic characteristics to capture the diversity of sewershed types in the area. In total, 19 sewersheds were selected based upon their location in separate systems, the availability of up to 4.5 years of data 2015–2019, and their spatial distribution across the Milwaukee metro area. In addition, rain gage data were obtained from MMSD gages throughout the Milwaukee Metro area (Figure 1).

Geographic information system Data Development

Once sewersheds were selected, ESRI's ArcMap was used to obtain spatial parameters for each

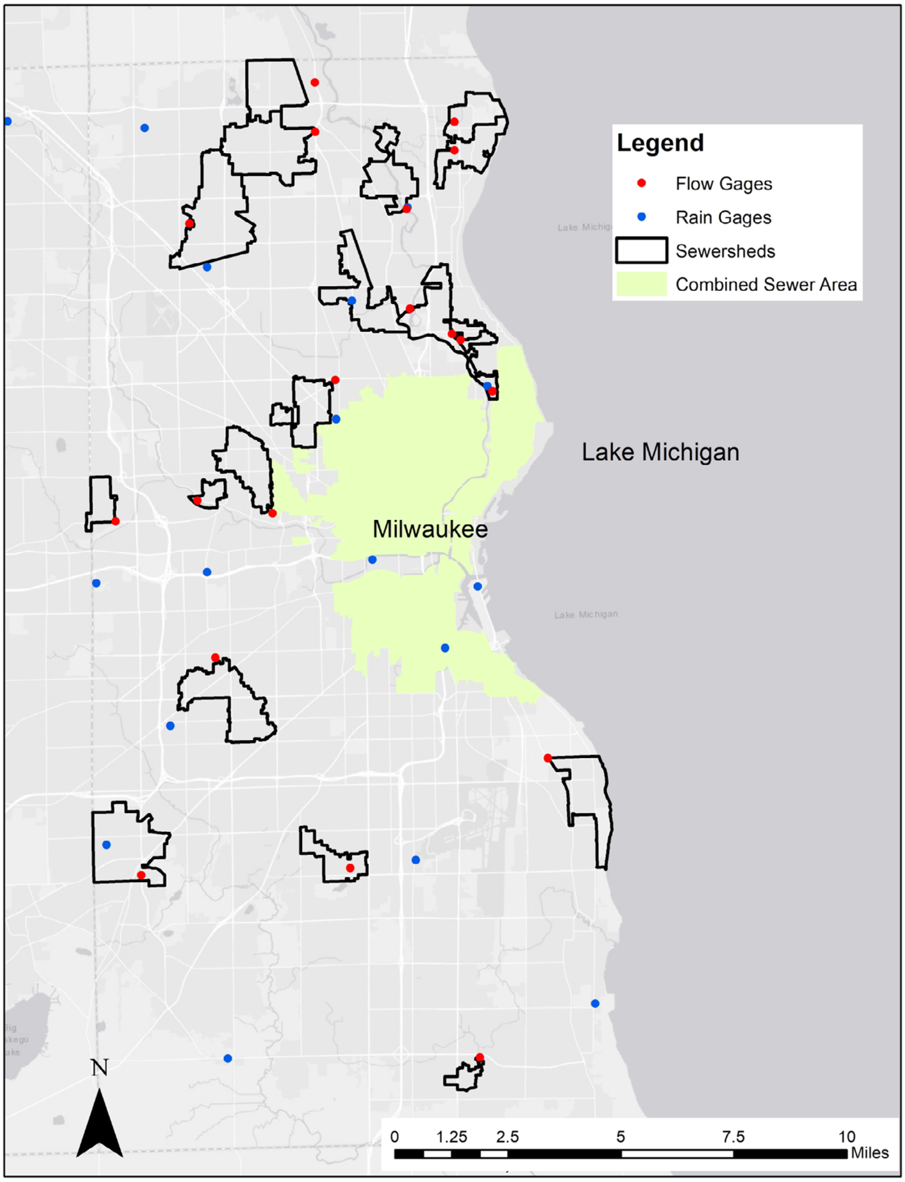

FIGURE 1. Map of the selected sewershed locations within the separated sewer system in the Milwaukee metropolitan area, as well as the location of the rain and flow gages used in the study.

sewershed (ESRI, Redlands, CA, USA). This includes sewershed area, land cover type, imperviousness, parcels, road length, and pipe characteristics. Land cover and impervious data were obtained from the 2016 National Land Cover Dataset (Homer et al. 2012), which provides a raster of 30 m resolution and is divided up into 16 classes of land cover and falls within the study period of the gage data used (2015–2019). Parcel, road, and assessment data were obtained from Milwaukee County. From this data, parcel counts, road lengths, and average assessed home values were obtained. Summary statistics of the watershed attributes were computed in ESRI's ArcMap using zonal statistics (ESRI). Large interceptor pipe data were obtained from MMSD and municipal-owned pipes and lateral data were obtained from 14 municipalities within the study area: Bayside, Brown Deer, Cudahy, Glendale, Greendale, Greenfield, Heles Corners, Milwaukee Oak Creek, River Hills, Shorewood, Fox Point, Wauwatosa, and West Allis. While this represents a significant portion of the pipes in the system, it does not include privately owned laterals for which there is no available system-wide spatial data and from which infiltration may be occurring. Once obtained, all pipe data were integrated into a single geodatabase with a consistent format for all pipe attributes including length, type, material, and slopes. ArcGIS was then used to develop attributes for each sewershed including pipe length and length of specific pipe materials.

Inflow and Infiltration Modeling

The USEPA SSOAP model was used to quantify the inflow and infiltration into the sanitary sewer system for every storm over 4.5 years at each sewershed (USEPA 2012). The USEPA SSOAP model analyses rainfall and sewer flow data to determine the volume of water that enters the system as inflow and infiltration. It does this through an RTK synthetic unit hydrograph approach (Figure 2), which divides the unit hydrograph into three separate synthetic unit hydrographs representing fast (1), medium (2), and slow (3) flows. These components of flow can then be used to determine the probable sources of flow in the pipe. Fast flows represent inflow, such as direct connections to the system from roof or foundation drains, that enter the system quickly; slow flows represent infiltration from groundwater sources that enter the system through cracks or gaps within the pipes; and medium flows are a combination of both inflow and infiltration. Using the USEPA SSOAP model, we minimized the error between the observed and simulated hydrographs by adjusting values of R (a unitless variable that represents the fraction of rainfall entering the sanitary sewer), T (time to peak), and K (ratio of time to recession). In total, across all 19 gages, 1,632 total storm events were identified using USEPA SSOAP functionality and defined as rainfall over 0.5 inches and a corresponding rise in flow. Using these RTK parameters for all storms across the project period, we explored the relationships between inflow and infiltration and the time of year, size of storm, and other event-based characteristics (i.e., rainfall volume, rainfall intensity, antecedent conditions, etc.). In addition, we developed summary statistics (mean, median, and standard deviation) of the RTK values at each site for use as dependent variables in the regression analysis described in the next section.

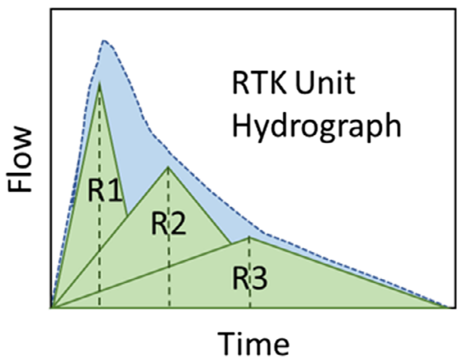

FIGURE 2. Example of an RTK unit hydrograph. The dashed blue line represents the total flow from the rainfall-derived inflow and infiltration (RDII), $R1$ represents the component of RDII that is attributed to quick inflows, $R3$ is the portion of flow that is attributed to slower infiltration, and $R2$ is a combination of the two.

Regression Analysis

Once hydrologic characteristics and RTK summaries were defined for each gage, simple linear regression was performed using JMP software (SAS Institute Inc., Cary, NC, USA). For the regression, summary statistics of the RTK parameters were used as dependent variables including the median R (total), $R1$ (fast), $R2$ (medium), and $R3$ (slow), as well as components of inflow and infiltration normalized to the total volume (i.e., $R1/R$). Independent variables included hydrologic characteristics from geographic information system (GIS) analysis (e.g. land over type, pipe characteristics). Goodness of fit was evaluated using R^2. To evaluate whether the regression has statistical significance, we performed the hypothesis test for whether the linear correlation coefficient (i.e., slope) differs from zero based upon the t-ratio (Helsel et al. 2020). The multicollinearity of the independent variables was also evaluated using Pearson product–moment correlation and other assumptions of linear regression were checked including normal distribution, and heterogeneity of residuals.

In addition, stepwise multivariable linear regression was performed to develop equations that could predict the inflow and infiltration based upon multiple sewershed characteristics:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \quad (1)$$

where y is the independent variable (i.e., inflow and infiltration), β represents the regression coefficients, and x represents the dependent variables (i.e., sewershed characteristics). These models were evaluated using goodness of fit metrics include R^2, adjusted R^2, and root mean square error.

RESULTS AND DISCUSSION

GIS Analysis

The sewersheds in this study had a wide range of hydrologic characteristics as shown in Table 1. For example, the total number of parcels ranged between 53 and 4,133, medium intensity land uses (i.e., mostly single-family housing units with 50%–79%

TABLE 1. Sewershed characteristics.

	Average	Standard deviation	Maximum	Minimum
Area (acres)	761	465.9	1,756.5	106.4
Mean elevation (ft)	702.61	48.59	801.07	635.82
Mean slope (%)	4.5	1.7	8.03	1.08
Imperviousness (%)	36.18	10.77	51.44	15.54
Parcels per acre	2.49	1.37	5.45	0.50
Pipe length (ft)	129,453	87,258	291,734	23,665
Pipe length per acre (ft)	177.0	68.4	390.6	96.7
Number of parcels	1,795	1,232	4,133	53
Open space (%)	17.06	12.05	51.92	0.06
Low intensity (%)	47.40	12.56	68.79	26.57
Medium intensity (%)	20.48	12.28	42.19	2.96
High intensity (%)	5.21	4.90	16.11	0.20

impervious cover) ranged between 3% and 42%, and the average imperviousness of each sewershed ranged between 16% and 51%. The spatial distribution of imperviousness is shown in Figure 3. As illustrated, while more imperviousness is located closer to the city center, there are still areas of significant imperviousness in the outer northwest and southeast suburbs.

Some municipalities had pipe material data that were used to further evaluate pipe characteristics in each sewershed. In Figure 4, the pipe materials are shown as a percent of the system and as total linear feet for 19 sewersheds. As illustrated, many of the pipe systems are a composite of PVC, concrete, clay, and other materials. In addition, for several of the sewersheds, there is a significant portion of the pipes — sometimes well over 50% — that is unknown. While these data do not capture all of the pipes, it does provide us with a large sample of the pipes within each network.

Inflow and Infiltration Analysis

Analyzing the rainfall and sewer flow data with USEPA SSOAP resulted in the identification of 1,632 total storm events across the 19 sewersheds. These storms were modeled with the RTK synthetic unit hydrograph method with an average area normalized difference in the volume between the observed and simulated hydrographs of 0.09 mm. Using this method, RTK parameters were developed for each storm and there were several general trends that

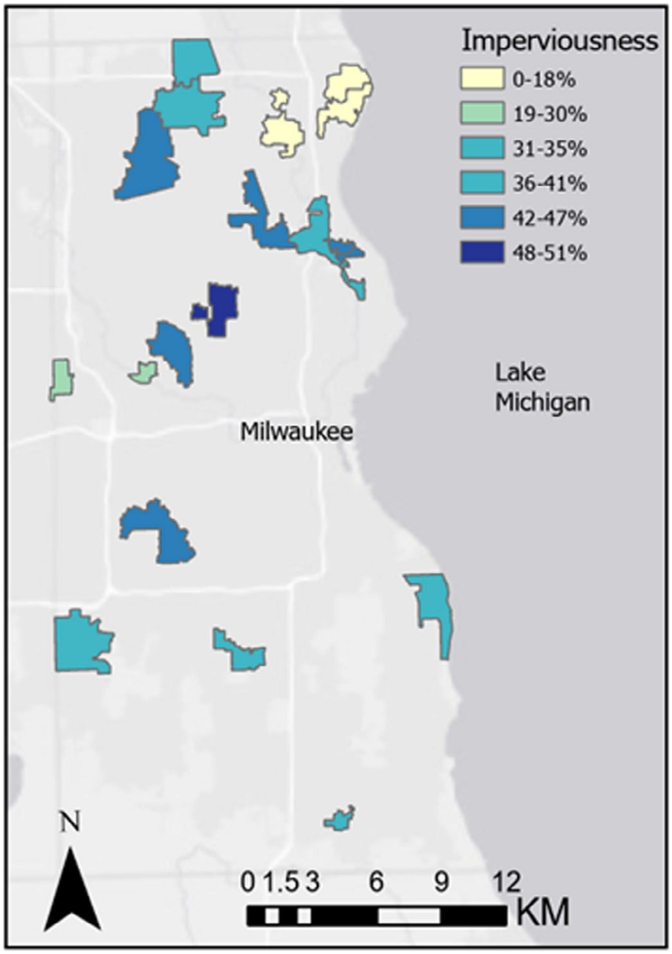

FIGURE 3. Distribution of imperviousness in sewershed.

were found. The median fraction of rainfall that is inflow and infiltration (R) across the sewersheds was 0.14, which indicates that on average 14% of rainfall is being infiltrated into the sanitary sewer system. Across all sewersheds, this median R value ranges between 0.034 and 0.312 (Figure 5b). This is similar in magnitude to other studies that have found the fraction of rainfall that is inflow and infiltration to range between 4% and 27% (Gheith 2010; Zhang et al. 2011; Nasrin et al. 2017).

We also explored whether there were any relationships between the fraction of inflow and infiltration (R) and other variables such as rainfall volume, rainfall intensity, antecedent conditions (i.e., prior 24, 48, and 72 h rainfall), length of storm, and seasons. Throughout all gages, there were only six statistically significant linear relationships ($p < 0.05$) between the fraction of inflow and infiltration (R) and rainfall volume, and none for rainfall intensity, antecedent conditions, or length of storm. However, there were statistically significant linear trends between the total volume of inflow and infiltration and rainfall volume at all sites (R^2 0.11–0.78).

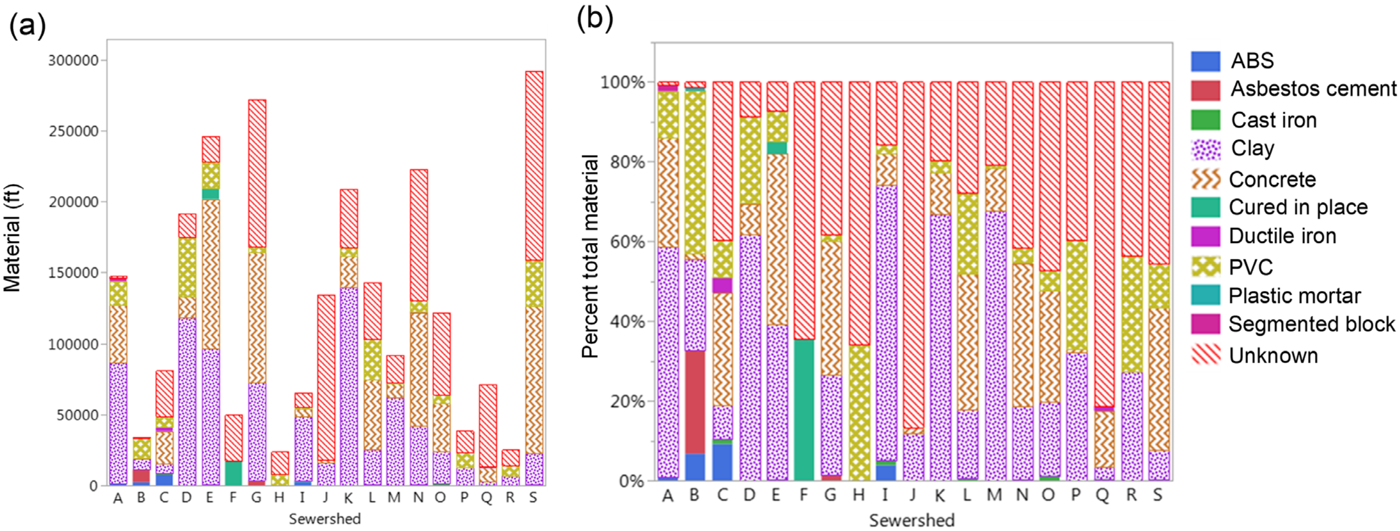

FIGURE 4. Pipe materials in each sewershed as a total length (a); and as a percentage of the overall sewershed pipe length (b).

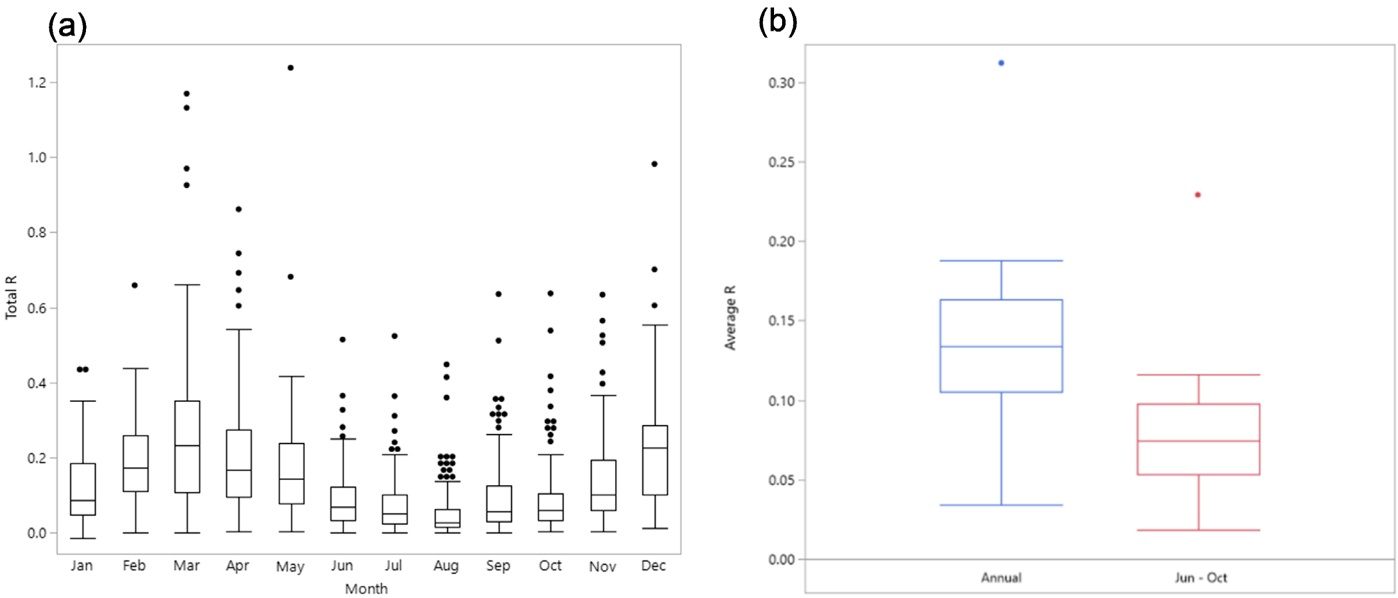

FIGURE 5. Monthly distribution of the total R for every storm and across all sites (a); and the distribution of the median total R at each sewershed for the entire year (blue) and the months June–October (red) (b).

We also noticed seasonal trends in the inflow and infiltration data, with more inflow and infiltration occurring during the winter months. Figure 5a illustrates the distribution of total R across all sites for each month of the year. As illustrated, the inflow and infiltration is generally highest in early winter and mid-spring. This could be due to the seasonality of groundwater levels that are lower in summer when evapotranspiration rates are high, or due to rain on snow events in which the snow on the ground is not represented within the precipitation data, yet contributes significant volume to inflow and infiltration. Because the rainfall data cannot capture the unknown groundwater-level fluctuations or snowmelt volume, we decided to restrict our regression analysis to storms that occurred in June–October. Doing so maintains the integrity of the water balance by ensuring that our rain gages properly capture inputs into the system. This also removes the artificial increase in the fraction of rainfall that contributes to inflow and infiltration during rain on snow events, and in doing so reduces the median total inflow and infiltration as represented in the right image Figure 5b. This approach is consistent with most

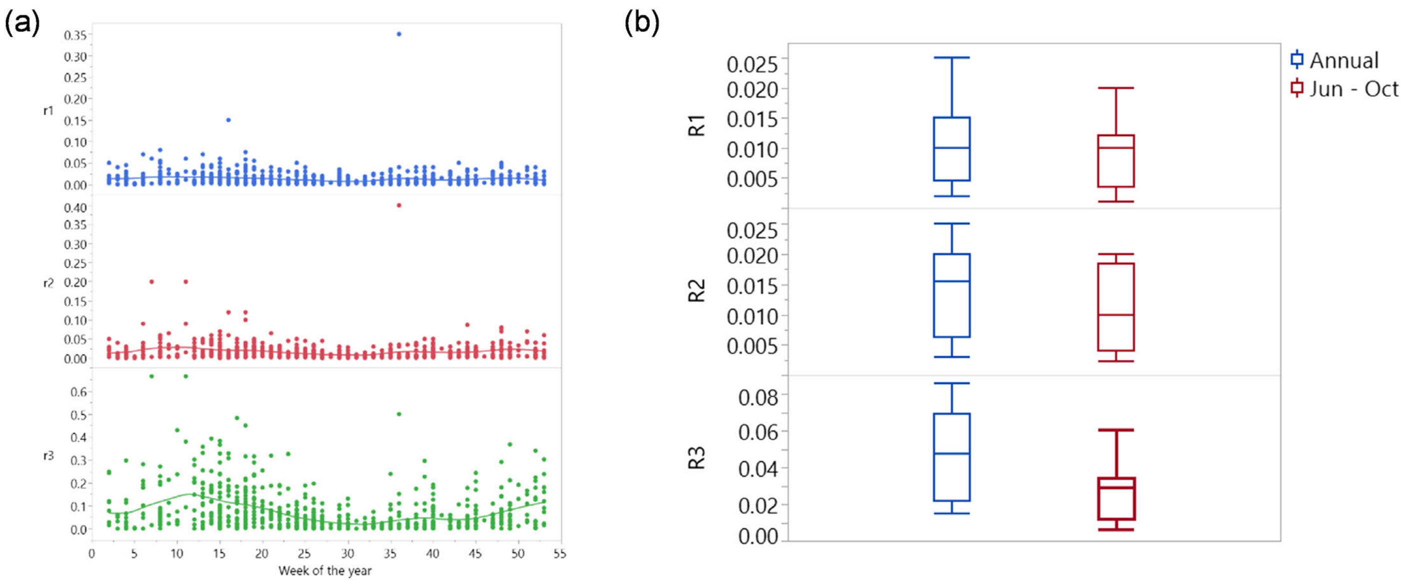

FIGURE 6. Values of $R1$, $R2$, and $R3$ over the course of a calendar year (a) and a comparison of median annual and June–October $R1$, $R2$, and $R3$ values across all sewersheds (b).

sanitary sewer monitoring studies for inflow and infiltration that recognize the difference between summer and winter flows (O'Dowd 2019).

Different components of inflow and infiltration — $R1$, $R2$, and $R3$ — were computed for each storm event and a summary of those components across all watersheds is illustrated in Figure 6. As illustrated, the most significant portion of inflow and infiltration comes from $R3$ (median of 0.03 in June–October data) followed by $R2$ and $R1$ (medians of 0.01 in June–October data). The components of the fraction inflow and infiltration — $R1$, $R2$, and $R3$ — also had no statistical relationship with rainfall volume, rainfall intensity, length of storm, or antecedent conditions; however, they had seasonal trends that mirrored R, with greater amounts of inflow and infiltration during the winter months (Figure 6a). The winter storms with high inflow and infiltration values were often rain on snow events, which skewed high the ratio of inflow and infiltration to rainfall volume due to the snowmelt that is unaccounted for by the rain gages. Therefore, only the months of June–October when snowpack is not present were considered during the subsequent regression analysis. Similar to the total R, this noticeably affects the distribution of median $R1$, $R2$, and $R3$ values as shown in Figure 6b.

Simple Linear Regression

Total Inflow and Infiltration. Linear regression was performed to predict the average inflow and infiltration fraction of rainfall (R) between June and October for each sewershed based upon the sewershed characteristics. Table 2 presents the results from the linear regression with the R^2 value, the standardized slope, and the statistical significance of the slope ($p > |t|$). Results found that mean elevation ($R^2 = 0.149$) and low intensity development ($R^2 = 0.175$) had the strongest negative correlation, and both had marginal statistical significance near $p < 0.1$. Based upon these results, there could be several reasons why a decrease in elevation or low intensity development would impact inflow and infiltration. It could be that the depth to the water table is closely related to the elevation of the land surface (Snyder 2008), and therefore as the elevation goes down the depth to the water table goes down,

TABLE 2. Linear regression results predicting total R based upon sewershed characteristics.

	Total R		
	R^2	Slope	$p > \|t\|$
Mean elevation	0.149	−0.386	0.103
Mean slope	0.036	0.190	0.435
Imperviousness	0.026	−0.160	0.512
Parcels per acre	0.025	−0.172	0.482
Pipe length	0.003	0.056	0.819
Pipe length per acre	0.026	−0.160	0.512
Number of parcels	0.009	0.010	0.686
Open space	0.001	0.028	0.910
Low intensity	0.175	−0.419	0.075
Medium intensity	0.011	−0.104	0.673
High intensity	0.064	0.253	0.295

providing a greater chance for infiltration of groundwater into sanitary sewer systems. In addition, low intensity development may not have as many households contributing flows and therefore less chances for inflow into these systems. However, each relationship had relatively low predictability and none had a statistically significant slope at $p < 0.05$. Linear regression was also performed to predict total R based upon the pipe materials in the sanitary sewer system, and linear feet of ductile iron was found to have a statistically significant slope ($p < 0.05$) and an R^2 of 0.79; however, due to the low number of data points (5), the regression had a single point with both high influence and leverage that impacted the results (Table 3). In addition, the percentage of clay pipes was negatively correlated with total R ($p < 0.01$ and R^2 of 0.61).

Components of Inflow and Infiltration. Linear regression was performed to predict the median inflow and infiltration in June–October ($R1$, $R2$, and $R3$) based upon sewershed characteristics (Table 4). For $R1$ — representing quick inflows into the system — variables with statistically significant slopes at $p < 0.05$ included positive correlations with pipe length per acre ($R^2 = 0.245$) and number of parcels ($R^2 = 0.209$). There could be several reasons for these findings. The number of parcels is directly related to the number of homes that have a sanitary connection to the sanitary sewer system. It may be that in these areas, there are also direct connections from foundation drains or downspout that are contributing to inflow. The pipe length per acre represents the density of pipes within the network, which could also be related to the number of homes with connections.

The regression also found that $R2$ had a negative relationship with low intensity residential land use ($R^2 = 0.149$), although no regression equations for $R2$ had a slope that was significant at $p < 0.05$. Finally, $R3$ was negatively correlated with imperviousness ($R^2 = 0.305$), pipe length per acre ($R^2 = 0.308$), and medium intensity residential land use ($R^2 = 0.267$). This reflects sewershed areas in which residential homes are densely built, pipe density is high, and there is high imperviousness. In these areas, high home density and imperviousness would increase runoff and decrease the amount of water that is infiltrated into the ground, therefore limiting the amount of water available for infiltration into the sanitary sewer system.

We also explored the relationship between $R1$, $R2$, and $R3$ and pipe materials in linear feet and as a percentage of the total pipe length in the sewershed (Table 5). It was found that linear feet of concrete pipe and concrete pipe as a percentage of the total pipe length was positively correlated to $R1$. In addition to concrete pipe, there were several other materials that had a relatively high R^2 with $R1$, $R2$, and $R3$, such as ductile iron; however, these had small

TABLE 3. Linear regression results predicting total R based upon pipe materials.

		Total R		
	n	R^2	Std slope	$p > \|t\|$
Cast iron (ft)	8	0.305	0.552	0.156
Cast iron (%)	7	0.128	0.358	0.431
Clay (ft)	6	0.333	−0.577	0.230
Clay (%)	6	0.606	−0.779	0.068
Concrete (ft)	15	0.001	−0.031	0.917
Concrete (%)	15	0.028	0.167	0.569
Ductile iron (ft)	5	0.788	−0.887	0.045
Ductile iron (%)	5	0.760	−0.872	0.054
PVC (ft)	17	0.007	−0.084	0.748
PVC (%)	17	0.157	−0.396	0.116
ABS (ft)	4	0.008	−0.087	0.913
ABS (%)	4	0.165	−0.406	0.594

Notes: ABS, acrylonitrile butadiene styrene; PVC, polyvinyl chloride.

TABLE 4. Linear regression results predicting $R1$, $R2$, and $R3$ based upon sewershed characteristics.

	$R1$			$R2$			$R3$		
	R^2	Slope	$p > \|t\|$	R^2	Slope	$p > \|t\|$	R^2	Slope	$p > \|t\|$
Mean elevation	0.063	−0.252	0.300	0.076	−0.276	0.253	0.033	−0.180	0.459
Mean slope	0.000	−0.010	0.970	0.093	0.305	0.204	0.191	0.437	0.062
Imperviousness	0.101	0.317	0.186	0.079	−0.282	0.242	0.305	−0.553	0.014*
Parcels per acre	0.093	0.305	0.205	0.014	−0.116	0.635	0.113	−0.336	0.160
Pipe length	0.137	0.370	0.118	0.002	0.048	0.845	0.009	−0.094	0.700
Pipe length per acre	0.245	0.500	0.031*	0.049	−0.220	0.363	0.308	−0.555	0.014*
Number of parcels	0.209	0.457	0.049*	0.012	0.111	0.651	0.006	−0.077	0.754
Open space	0.135	−0.367	0.121	0.029	0.171	0.484	0.138	0.372	0.117
Low intensity	0.017	−0.130	0.595	0.149	−0.385	0.103	0.264	−0.513	0.025*
Medium intensity	0.200	0.447	0.055	0.056	−0.236	0.331	0.267	−0.517	0.023*
High intensity	0.037	0.192	0.430	0.021	0.143	0.558	0.009	0.095	0.700

*Statistical significance of the slope at $p < 0.05$.

TABLE 5. Linear regression results predicting $R1$, $R2$, and $R3$ based upon pipe materials.

		R1			**R2**			**R3**		
	n	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$
Cast iron (ft)	8	0.054	0.232	0.581	0.313	0.560	0.150	0.387	0.622	0.100
Cast iron (%)	7	0.041	0.203	0.662	0.099	0.317	0.490	0.188	0.435	0.330
Clay (ft)	6	0.001	−0.750	0.090	0.002	−0.400	0.435	0.014	−0.194	0.712
Clay (%)	6	0.013	−0.875	0.022*	0.004	−0.553	0.255	0.057	−0.393	0.441
Concrete (ft)	15	0.202	0.539	0.047*	0.003	−0.036	0.903	0.025	−0.377	0.184
Concrete (%)	15	0.190	0.602	0.023*	0.023	0.132	0.653	0.002	−0.207	0.479
Ductile iron	5	0.177	−0.421	0.481	0.883	−0.939	0.018*	0.118	−0.343	0.572
Ductile iron (%)	5	0.246	−0.497	0.394	0.765	−0.875	0.052	0.048	−0.219	0.724
PVC (ft)	17	0.005	0.071	0.787	0.006	−0.076	0.771	0.002	−0.044	0.867
PVC (%)	17	0.124	−0.352	0.167	0.131	−0.362	0.153	0.107	−0.327	0.200
ABS (ft)	4	0.001	−0.026	0.974	0.025	0.157	0.843	0.004	−0.063	0.937
ABS (%)	4	0.305	−0.553	0.448	0.034	−0.185	0.815	0.099	−0.315	0.685

*Statistical significance of the slope at $p < 0.05$.

sample sizes and therefore it is tough to draw conclusions as it is unclear whether it is the representative of the sample as a whole.

Normalized Components of Inflow and Infiltration. In addition to absolute values, regression was also performed on normalized inflow and infiltration values by dividing $R1$, $R2$, and $R3$ by the total R (Table 6). This fraction allows us to compare inflow and infiltration characteristics across watersheds of various scales more directly by normalizing the components of inflow and infiltration values to the total R. In essence, while the absolute values of $R1$, $R2$, and $R3$ tell us what fraction of rainfall will become either inflow or infiltration, the normalized values tell us what fraction of total RDII is attributed to either inflow or infiltration. As a whole, these ratios have a higher strength of prediction than the absolute values.

For normalized $R1$, variables with statistically significant slopes at $p < 0.05$ included positive correlations with pipe length per acre (R^2 0.48), medium intensity residential land use (R^2 0.371), imperviousness (R^2 0.249), and number of parcels (R^2 0.218); and a negative correlation with open space land use (R^2 0.237). While the absolute values of $R1$ also had statistically significant correlations with pipe length per acre and the number of parcels, the ratio provides new variables correlated with normalized $R1$: imperviousness, medium intensity residential, and open space land uses. There could be several reasons for these new relationships. Medium intensity residential land use is representative of relatively dense single-family homes, and in these locations, there may therefore be more opportunities for direct connections of foundation or roof drains that contribute to inflow. Meanwhile, in areas of open space land use, there are no structures connected to the sanitary sewer system and therefore less opportunities for inflow. While imperviousness is correlated, it is less clear why this would be directly connected to inflow other than the fact that impervious areas

TABLE 6. Linear regression results predicting $R1$/total R, $R2$/total R, and $R3$/total R based upon sewershed characteristics.

	R1/total R			**R2/total R**			**R3/total R**		
	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$
Mean elevation	0.001	0.036	0.884	0.024	0.155	0.526	0.057	0.239	0.324
Mean slope	0.015	−0.121	0.620	0.108	0.329	0.169	0.329	0.573	0.010*
Imperviousness	0.249	0.500	0.030*	0.109	−0.330	0.167	0.568	−0.754	0.000*
Parcels per acre	0.322	0.567	0.011*	0.013	0.113	0.646	0.135	−0.367	0.122
Pipe length	0.158	0.397	0.092	0.010	−0.100	0.684	0.047	−0.218	0.371
Pipe length per acre	0.476	0.690	0.001*	0.041	−0.202	0.410	0.608	−0.780	<0.001*
Number of parcels	0.218	0.467	0.044*	0.001	−0.032	0.900	0.058	−0.241	0.320
Open space	0.237	−0.487	0.035*	0.066	0.257	0.288	0.394	0.628	0.004*
Low intensity	0.026	0.162	0.507	0.007	0.085	0.731	0.089	−0.298	0.216
Medium intensity	0.371	0.609	0.006*	0.134	−0.366	0.124	0.614	−0.784	<0.001*
High intensity	0.003	0.056	0.819	0.069	−0.262	0.279	0.031	−0.176	0.470

*Statistical significance of the slope at $p < 0.05$.

could be correlated with medium intensity land uses that have more homes and therefore more opportunities for direct connections of foundation or roof drains. There were no statistically significant parameters correlated with normalized $R2$; however, for normalized $R3$, variables with statistically significant slopes at $p < 0.05$ included negative correlations with medium intensity residential land use (R^2 0.614), pipe length per acre (R^2 0.608), and imperviousness (R^2 0.568); and positive correlations with open space (R^2 0.394) and mean slope (R^2 0.329). In this case, a decrease in medium intensity land use and imperviousness could mean that there are less connections to the system, less opportunities for inflow, and more pervious space for infiltration; therefore, the amount of infiltration relative to the whole will be higher. While more pipes in the ground should provide more opportunities for infiltration, the negative relationship between normalized $R3$ and pipe density could be because areas with more dense pipes have more opportunities for direct connections, and therefore a higher fraction of RDII as inflow. Finally, the increase in infiltration with increases in slope runs contrary to other studies that have found that as the slope of the land surface increases, the runoff volume increases and infiltration decreases (Huang et al. 2013). However, these results may indicate that in areas of higher slope — which typically consist of more hills and valleys — rainfall may be pooled into valleys and depressions where it has more time to infiltrate and raise the groundwater table.

The opposite relationships between $R1$ and $R3$ when it comes to several predictors may suggest that these predictors can explain where the fraction of inflow and infiltration will come from. For pipe length per area, medium intensity land use, and imperviousness, there is a positive relationship with $R1$ (i.e., inflow) and a negative relationship with $R3$ (i.e., infiltration) for both the absolute and normalized values (Tables 4 and 6). This is illustrated graphically in Figure 7. All three of these parameters are representative of the density of development. As the density increases, there are more buildings and therefore more chances for direct connections to the sanitary sewer system through foundation or roof drains. Conversely, as density increases, there is less permeable ground for rainfall to infiltrate and therefore in these areas there may be a lower relative volume of water in the ground for infiltration.

We also explored the relationship between normalized R values and pipe characteristics, and it was found that concrete had a statistically significant positive relationship to $R1$ and a negative relationship to $R3$ (Table 7). This would suggest that for sewershed with concrete pipes, there is an increasing amount of quick inflow into the system and a decreasing amount of slower infiltration. However, it could be that concrete pipes are correlated with other explanatory variables. Therefore, we evaluated the predictor variables for multicollinearity using Pearson product–moment correlation. It was found that concrete pipes were correlated with medium intensity land use ($p = 0.004$) and imperviousness ($p = 0.029$). The correlation with concrete pipes and inflow and infiltration may therefore be a function of its relationship to land use characteristics, rather than a function of the concrete pipes themselves.

Multivariable Linear Regression

Forward and backwards stepwise regression was performed to develop multivariable linear regression models to predict inflow and infiltration based upon sewershed characteristics. Candidate variables were selected as those that were statistically significant in the linear regression model discussed previously. Final selected variables required significance of each variable at the $p < 0.15$ level and to be free of multicollinearity. Table 8 illustrates the final equations that were developed. As illustrated, for both $R1$ and $R1$/total R, the pipe length per acre and number of parcels are significant predictors, with each improving the predictive power of the equation. For $R3$, low intensity and medium intensity development explain 49% of the variance, while for $R3$/total R the medium intensity and pipe length per acre explain 72% of the variance.

Application of Results

This study explored the relationship between sewershed characteristics and RDII and found several statistically significant correlations. The results showed that the amount of inflow into sanitary sewers increases with high imperviousness, medium intensity residential land use, and dense pipe networks. On the other hand, the amount of infiltration into sanitary sewers increases with more open space, more pipe density, less dense development, and less imperviousness. This information in turn has several practical implications for informing inflow and infiltration remediation efforts.

For municipalities that are under a new consent decree to reduce inflow and infiltration, the findings from this study can help to target areas in an initial monitoring phase. From this case study, it is clear that if the goal is to reduce inflow, it would be prudent to target monitoring efforts in sewersheds that have medium density residential land use, higher imperviousness, and less open space. This follows

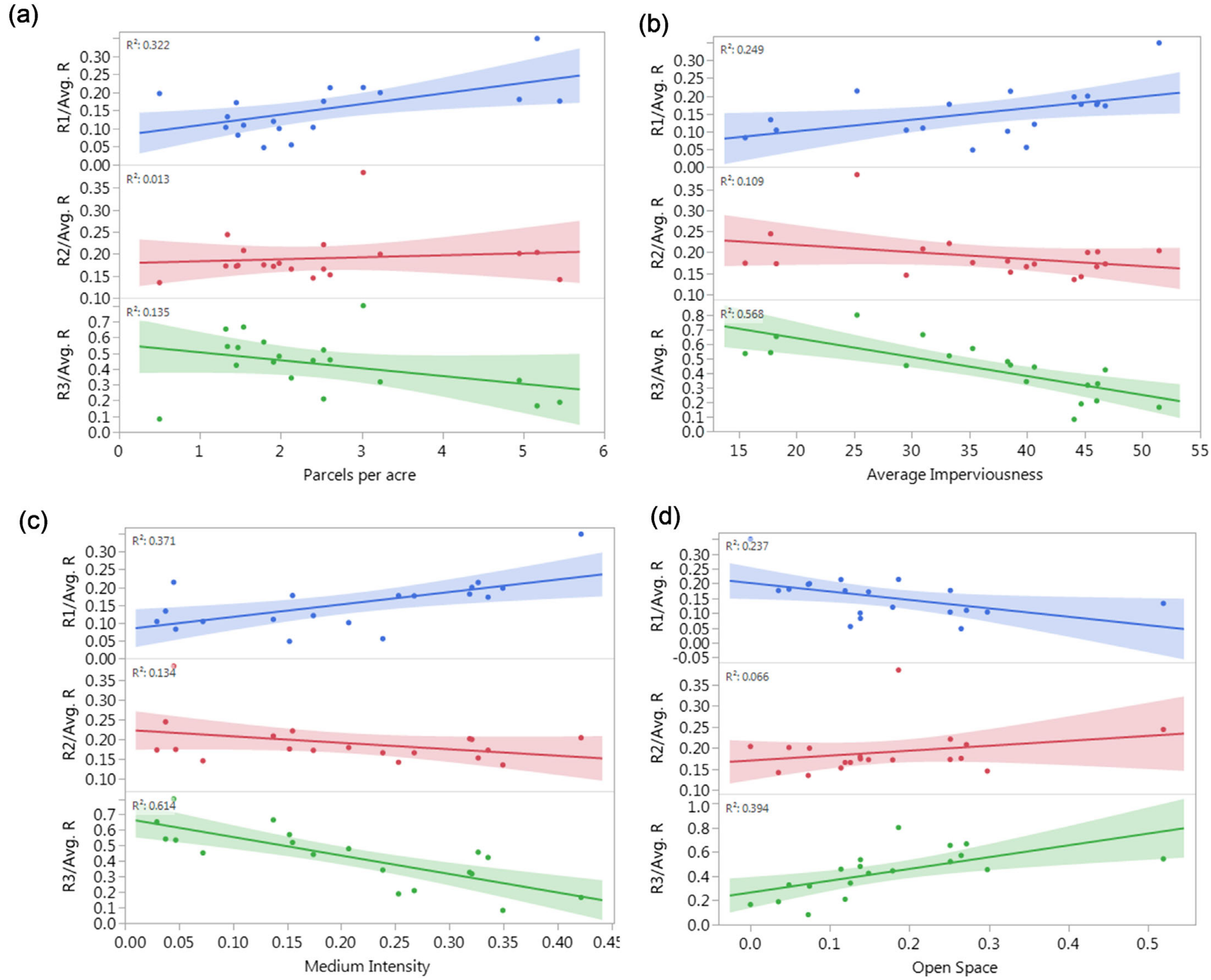

FIGURE 7. Plot of the normalized R values and their linear relationship and confidence intervals (95%) as a function of parcels per acre (a), the average imperviousness (b), medium intensity land use (c), and open space land use (d).

with other studies that have found that in general, urbanization correlates with inflow into sanitary sewer systems (Levin et al. 2020). Where inflow is suspected in a sewershed, municipalities could target micro-metering efforts in areas with higher imperviousness and more dense residential land uses (Barton et al. 2013). Further actions to reduce inflow could include disconnections of foundation drains, roof drains, or illicit connections (Staufer et al. 2012), which can reduce inflow volumes by up to 85% (Jiang et al. 2019). However, if slower infiltration is a concern, efforts could focus on areas that are less dense, less impervious, and have more open space. Actions could include replacing or relining cracked pipes and fixing improper joints and connections in the sanitary sewer system (Staufer et al. 2012). Relining has been found to decrease sanitary sewer system exfiltration by up to 99% (Jacobsen 2012).

While results of this study have several implications for collection systems operators that need to reduce inflow and infiltration in their systems, there are several factors to consider in generalizing the data. Milwaukee is a post-industrial Midwest city in which much of the development occurred in the early to mid-20th Century. Therefore, much of the infrastructure in place is older and subject to deterioration due to aging and many of the homes built may have foundation or roof connections built prior to codes that discouraged them. Given the age of the infrastructure, they may have more cracks or failures that allow for more slow groundwater infiltration into the system. In municipalities that serve areas that have developed more recently, the

TABLE 7. Linear regression results predicting $R1$/total R, $R2$/total R, and $R3$/total R based upon pipe materials.

		R1/total R			**R2/total R**			**R3/total R**		
	n	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$	R^2	**Slope**	$p > \|t\|$
Cast iron (ft)	8	0.046	−0.215	0.609	0.002	0.044	0.919	0.075	0.274	0.511
Cast iron (%)	7	0.000	−0.003	0.995	0.021	−0.145	0.756	0.028	0.165	0.724
Clay (ft)	6	0.000	0.067	0.900	0.007	0.426	0.400	0.200	0.517	0.293
Clay (%)	6	0.028	0.174	0.741	0.006	0.516	0.295	0.164	0.417	0.411
Concrete (ft)	15	0.223	0.714	0.004*	0.007	−0.026	0.930	0.099	−0.727	0.003*
Concrete (%)	15	0.160	0.623	0.017*	0.005	−0.119	0.684	0.033	−0.690	0.006*
Ductile iron	5	0.036	0.189	0.760	0.175	0.418	0.483	0.020	0.140	0.822
Ductile iron (%)	5	0.011	0.103	0.870	0.231	0.481	0.412	0.065	0.256	0.677
PVC (ft)	17	0.010	0.098	0.710	0.001	−0.034	0.900	0.002	0.044	0.870
PVC (%)	17	0.013	−0.114	0.664	0.024	0.156	0.551	0.000	−0.015	0.960
ABS (ft)	4	0.031	0.176	0.824	0.993	0.997	0.003*	0.039	0.197	0.803
ABS (%)	4	0.113	−0.337	0.664	0.697	0.834	0.166	0.017	−0.132	0.869

*Statistical significance of the slope at $p < 0.05$.

TABLE 8. Multivariable linear regression models.

Parameter	**Equation**	R^2	**Adj** R^2	**RMSE**
Total R	$=0.342 + 2.9\text{e-}4 \times \text{ME} - 0.126 \times \text{LI}$	0.269	0.178	0.041
$R1$	$=1.75\text{e-}3 + 3.84\text{e-}5 \times \text{PLA} + 1.83\text{e-}6 \times \text{NP}$	0.348	0.266	0.006
$R3$	$=0.103–0.1 \times \text{LI} - 0.103 \times \text{MI}$	0.491	0.427	0.02
$R1$/total R	$=0.014 + 6.2\text{e-}4 \times \text{PLA} + 1.6\text{e-}5 \times \text{NP}$	0.547	0.491	0.05
$R3$/total R	$=0.794–0.001 \times \text{PLA} - 0.709 \times \text{MI}$	0.719	0.684	0.1

Notes: LI, low intensity development; ME, mean elevation; MI, medium intensity development; NP, number of parcels; PLA, pipe length (ft) per acre; RMSE, root mean square error.

function of the sanitary sewer system and design of built environment may be different. In addition, in regions with different precipitation patterns, groundwater levels, and tidal influences, among other variables, the dynamics between precipitation and groundwater infiltration may behave differently. Therefore, application of these findings outside of the Milwaukee region should consider these factors.

CONCLUSION

This paper presents a study that explored the relationship between sewershed characteristics and inflow and infiltration in sewersheds in Milwaukee, Wisconsin. Spatial analysis of sewershed characteristics was performed in GIS and we found that there is significant variability in the surface and pipe characteristics of sewersheds throughout the case study area. In addition, 4.5 years of sewer flow data at each gage were analyzed in USEPA SSOAP and on average the median inflow and infiltration was found to be 14% of the rainfall volume. Finally, simple and multiple linear regression identified the relationships between sewershed characteristics and inflow and infiltration. Specific findings from this study are as follows:

1. There is significant variability in sewershed characteristics throughout the Milwaukee area, both in surface characteristics (e.g., medium intensity land use 3%–42%) and the collection systems infrastructure (e.g., concrete pipe 1%–39% of total pipe length).
2. Inflow (i.e., $R1$) is positively related to pipe length per acre, number of parcels, and medium intensity land use. All three variables are related to the density of development where more housing and sewer connections increases the potential for direct connections of roof drains, foundation drains, and sump pumps.
3. Infiltration (i.e., $R3$) is negatively correlated with imperviousness, pipe length per acre, and medium intensity land use. This suggests that as medium intensity land use and imperviousness increase, rainfall has less available surface area to infiltrate into the sanitary sewer network.
4. Infiltration (i.e., $R3$) is positively correlated with open space land use and mean slope. Areas of higher mean slope typically consist of more hills and valleys, where rainfall may be pooled and

have time to infiltrate and raise the groundwater table. Similarly, open space provides area for rainfall to infiltrate into the ground and make its way into the sanitary sewer network.
5. Sewershed characteristics that are reflective of development density, such as imperviousness and medium intensity residential land us, have opposite effects on inflow and infiltration with positive correlations to inflow and negative correlations to infiltration.
6. No sewershed or pipe characteristics were statistically significant predictors of $R2$. This may be because $R2$ is a middle ground between inflow and infiltration and is made up of both late inflow and early infiltration, thus making it difficult to attribute to a single source type.
7. Sewershed characteristics were able to predict the normalized $R1$, $R2$, and $R3$ better than the absolute values. This may be because the normalized values allow for more direct comparison of sewersheds with differing levels of total inflow and infiltration by defining the proportion of RDII attributed to each source.
8. Multivariable linear regression found that pipe length per acre and number of parcels explained 55% of the variability in $R1$/total R. Since inflow is cause by direct connections to the sanitary sewer from downspouts and foundations, more pipe length and parcels would drive an increase in $R1$.
9. Multivariable linear regression found that pipe length per acre and medium intensity residential land use explained 72% of the variability in $R3$/total R. This reinforces the relationships seen with $R3$ and indicates that inflow is increased, and infiltration is decreased, in areas of higher density.

This case study demonstrates how the hydrologic and pipe characteristics of a sewershed can influence inflow and infiltration within a sanitary sewer collection system. As infrastructure continues to age across the world, it is important to have as many tools as possible to diagnose where failures are occurring and to prioritize limited resources for remediation actions. Studies such as this can help to elucidate the factors that influence inflow and infiltration and improve our understanding of hydrologic processes in the urban environment.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. This includes sewer flow time series, model files, and GIS data.

AUTHOR CONTRIBUTIONS

Spencer Sebo: Formal analysis; investigation; methodology; software; writing – original draft; writing – review and editing. Walter McDonald: Conceptualization; funding acquisition; investigation; project administration; supervision; validation; writing – original draft; writing – review and editing.

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