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Urbanization of grasslands in the Denver area affects streamflow responses to rainfall events

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Abstract

A thorough understanding of how urbanization affects stream hydrology is crucial for effective and sustainable water management, particularly in rapidly urbanizing regions. This study presents a comprehensive analysis of changes in streamflow response to rainfall events across a rural to urban gradient in the semi-arid area of Denver, Colorado. We used 8 years of April to October instantaneous streamflow data in 21 watersheds ranging in size from 0.8 to 90 km² and with impervious areas ranging from 1% to 47%. With these data, we applied a semi-automated method to identify a total of 2877 streamflow responses, which were analysed for event-based metrics of peak flow, runoff depth, runoff to rainfall ratio, time to peak, duration and number of streamflow responses to rainfall events. We also determined whether streamflow responses could be predicted by a precipitation threshold. Watersheds with >10% impervious cover had a precipitation threshold of 1–2 mm/hr needed to produce a streamflow response, compared to thresholds of 4–36 mm/hr for watersheds with less than 10% impervious surface cover. This lower precipitation threshold in more impervious watersheds led to more frequent streamflow responses. On average, streamflow responses had shorter duration and higher peak flows in watersheds with more impervious surface cover. In contrast to other regions, runoff depth, runoff to rainfall ratio and time to peak either gave mixed results or did not vary significantly with imperviousness. These alterations in streamflow response to rainfall events indicate the specific ways that urban development changes how streams respond to rain events in a semi-arid setting. This work points to the need for local adaptation of stormwater management to mitigate the effects of streamflow changes with urbanization.

KEYWORDS

grasslands, hydrograph, semi-arid hydrology, stormwater, threshold response, urbanization

1 | INTRODUCTION

Urbanization alters stream hydrographs, and these changes in flow can cause channels to incise and degrade channel habitat conditions

for the aquatic ecosystem (Meyer et al., 2005; Shuster et al., 2005; Walsh et al., 2005). The most common hydrograph alterations with urbanization observed in humid climates are more frequent high flow events, higher peak flows, shorter time to peak flow, higher runoff to

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rainfall ratios and greater variability in streamflow (O'Driscoll et al., 2010; Walsh et al., 2005). However, drier climates may not always have this type of response, as the effects of urbanization on streamflow in part depend on climate (Booth et al., 2016; Hale et al., 2016; Hopkins et al., 2015). For example, flashiness (as quantified by the daily Richards-Baker flashiness index) can decrease with urbanization in areas where streams are naturally flashy because urban stormwater control reduces flashiness, as was documented in arid Phoenix, Arizona (McPhillips et al., 2019). Another example is that the time to peak flow and event runoff ratio remained similar to undeveloped conditions, and baseflow recession took longer in more urbanized areas in semi-arid Tucson, Arizona (Gallo et al., 2013).

One of the challenges with understanding how streams respond to urbanization is that the initial or pre-development streamflow characteristics are typically unknown. This may be particularly true in dry climates where streams may have little to no flow prior to urbanization. Although semi-arid and arid rangelands make up 31% of the United States (Carey et al., 2019) the runoff response from rangelands is challenging to characterize (Carey et al., 2019; Pierson et al., 2002; Weltz et al., 2000), partly because runoff may be infrequent enough that even a multi-year study does not capture any runoff (Baffaut et al., 2020). Many semi-arid cities in the United States and globally are growing rapidly (CWCB, 2015; Luthy et al., 2020; MacDonald, 2010; Nouri et al., 2019; Sabo et al., 2010) with potentially detrimental effects on streams in and around those cities. Therefore, understanding how streams respond to storm events in these environments is crucial for effective stormwater management decisions and optimum design and implementation of urban water systems.

In this study, our goal was to analyse streamflow responses across a gradient of rural-to-urban watersheds in the semi-arid area metropolitan area of Denver, Colorado. In particular, this study explored how the following metrics of streamflow response to rainfall events change with urban development: (1) number of streamflow responses, (2) peak streamflow rate, (3) total runoff, (4) runoff ratio (defined as stormflow depth divided by precipitation depth), (5) time to peak streamflow, (6) duration of streamflow response to storms and (7) threshold response to precipitation.

2 | METHODS

2.1 | Study area

The Denver, Colorado metropolitan area is well suited for this analysis because it has both a stream gauge network that monitors watersheds spanning a range of development and an extensive rain gauge network maintained by Mile High Flood District (Figure 1). The City of Denver is located 19 km east of the foothills of the Rocky Mountains, and the metropolitan area is home to approximately 3 million people; population grew by 17% from 2010 to 2020 (US Census Bureau, n.d.). The semi-arid climate exhibits seasonal variability, with an average

annual precipitation on the plains of 391 mm, highest precipitation during April – September, average annual temperature of 10.1°C, and monthly average minimum temperature of −1.3°C and maximum of 23.1°C (NOAA, 2020). Denver is situated within the South Platte River Basin, which has its headwaters in the Rocky Mountains. The eastern portion of the South Platte watershed is composed of primarily grasslands and cultivated agricultural land (South Platte Basin Implementation Plan, 2015). The geology underlying our study watersheds primarily consists of clastic sedimentary and unconsolidated, undifferentiated deposits (Horton, 2017) reworked by alluvial and aeolian processes (e.g., [Sherrod et al., 2015]).

2.2 | Study watersheds

To select watersheds for analysis, all of the stream gauges managed by the Colorado Department of Water Resources, United States Geological Survey (USGS) and Department of Energy (DOE) in the Denver area were screened to determine whether they would be used for this study. Gauges along the mainstem of the South Platte River were excluded due to their large drainage area, which includes the higher elevation mountains west of Denver. We set an upper limit of 150 km² for drainage area to avoid a large variation in size between our watersheds as a complicating factor. We excluded watersheds with mean annual precipitation >550 mm or minimum watershed elevation >2286 m (7500 ft), as these watersheds were more influenced by mountain topography to the west. Gauges that were located at the inlet or outlet of a reservoir, pond, canal diversion, or wastewater treatment plant with effluent discharge (from EPA NPDES) >50% of mean annual streamflow were also excluded to remove sites impacted by human-controlled water releases. We selected watersheds that had recorded streamflow between 7 June 2013 and 30 September 2020.

We used watersheds in the Rocky Flats site as the least disturbed monitored reference grassland watersheds (O-U in Figure 1). Manufacturing of nuclear weapon components occurred on the site in the second half of the twentieth century, with site decommissioning spanning the years 1995 through 2005 (Rocky Flats Fact Sheet, 2020; <https://www.energy.gov/sites/default/files/2020/06/f75/RockyFlatsFactSheet.pdf>). Instantaneous streamflow (ranging from 5 to 15-min resolution) is monitored by the DOE Office of Legacy Management (DOE LM). In Rocky Flats, our analysis focused on Walnut Creek, which is fed by three main tributaries: No Name Gulch, North Walnut Creek and South Walnut Creek. Watershed U records discharge from No Name Gulch and is the least impacted by prior use of the site, although there are remnants of stock ponds. Watersheds R, P and O are located along North Walnut Creek, while S and Q are located along South Walnut Creek (Figure 1). The South Interceptor Ditch discharge is measured at watershed T (DOE, 2020). Although legacy effects of the former Rocky Flats plant include canals, ponds and some roads that may alter streamflow, these watersheds are still less affected by land use changes than other watersheds within the Denver metro area. We did not find any other grassland

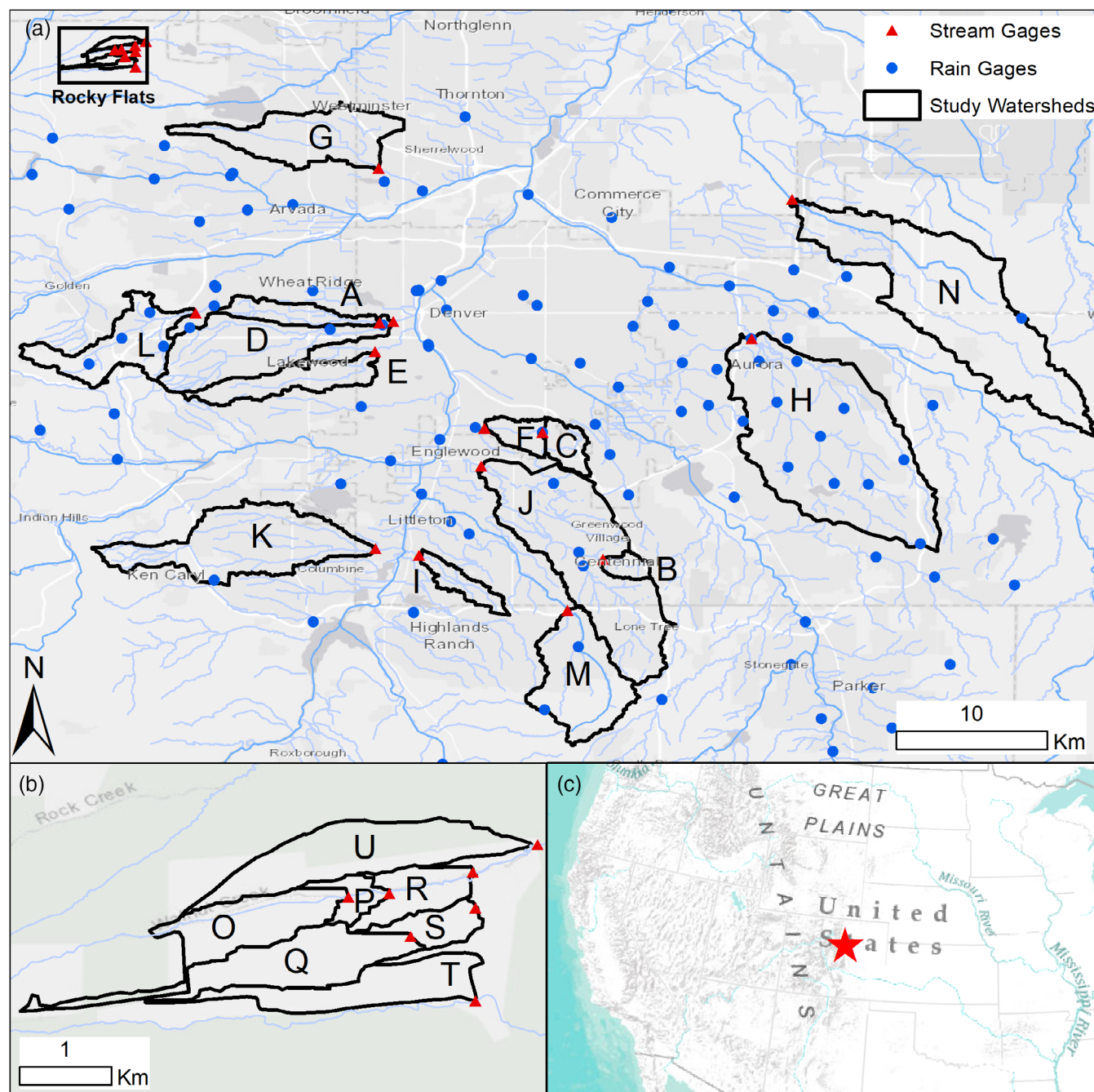


FIGURE 1 (a) Twenty-one study watersheds located in the Denver, Colorado area and network of rain gauges monitored by Mile High Flood District. (b) Inset showing watersheds O–U in Rocky Flats, indicated by black box in (a). (c) Location of Denver, Colorado indicated by a star

streams that have long-term streamflow monitoring in the Denver area.

For the selected stream gauges, watersheds were delineated using a $\frac{1}{3}$ arc second (~ 10 m) DEM (Bell et al., 2016; Lee & Heaney, 2003; O'Driscoll et al., 2010; Shuster et al., 2005). This was done to use the finest resolution DEM available for watershed delineation for both USGS and DOE gauges. We then compared our delineated watershed areas to the watershed areas on USGS NWIS (United States Geological Survey, 2022) for USGS gauges only, and those watersheds with more than 10% disagreement in total area were manually edited to align with

the USGS boundaries. USGS StreamStats was used to delineate the Toll Gate Creek Above 6th Ave at Aurora, CO watershed because the delineation in ArcMap produced a vastly different area for this watershed than the USGS one (<https://streamstats.usgs.gov/ss/>). We edited the watershed boundaries for DOE-gauged watersheds (O–U) to match those shown as maps in reports (DOE, 2020), as these delineations by DOE already reflected modifications to these small watersheds by canals. The mean annual precipitation for each watershed was calculated using 1981–2010 normals from PRISM (PRISM Climate Group, Oregon State U, n.d.). The eRams Watershed Rapid Assessment Tool

was used to quantify publicly-available data on wastewater treatment plant effluent (EPA NPDES) and transbasin diversions (in Colorado) (<http://www.coloradowaterdata.org/eramswrapcdsn.html>). The NHD (United States Geological Survey, 2019) flowlines indicated that there were 5.6 km of connectors, 261 km of canals or ditches and 86 km of pipelines in our study watersheds (Table S1).

To understand how hydrologic metrics change with urbanization, we used impervious surface cover as a representation of urbanization. Imperviousness is commonly used, easily available, and elsewhere is predictive of event-scale hydrologic response (Bell et al., 2016; Lee & Heaney, 2003; O'Driscoll et al., 2010; Shuster et al., 2005). The 2016 National Land Cover Database (NLCD) was used to determine the percent of watershed area with impervious surfaces (Wickham et al., 2021). The 2016 NLCD has not been updated to reflect the decommissioning of the Rocky Flats plant. Therefore, we used a land cover classification tool developed in Google Earth Engine based on National Agriculture Imagery Program (NAIP) imagery to determine percent imperviousness in the Rocky Flats area (Fillo, 2020). The final selection resulted in 21 watersheds used in our analysis ranging in size from 1 to 90 km² with impervious areas ranging from 1% to 47% (Table 1).

2.3 | Streamflow and precipitation analysis

The 21 study gauges (Table 1) had streamflow records at a 5-to-15-min frequency over our period of analysis from 7 June 2013 to 30 September 2020. Many of these gauges are operated seasonally, so our analysis was limited to the months of April – September. Manual identification of the start and end times defining streamflow responses to rain events (called streamflow responses here) by visual inspection over this many storms and watersheds would be time-consuming and not reproducible. Researchers have developed semi-automated methods to identify event responses in a streamflow time series (Hopkins et al., 2020; Nimmo & Perkins, 2018; Tang & Carey, 2017), who used the BaseflowSeparation tool in the EcoHydRology package in R (Hopkins et al., 2020), which is a digital filter for separating quickflow (stormflow) and baseflow. We used a 0.99 digital filter parameter with 3 passes (Nathan & McMahon, 1990), as this has been found to work best with sub-hourly data (Hopkins et al., 2020). For each stream gauge, threshold values were determined for the four streamflow metrics below, such that any instantaneous streamflow measurement found to exceed one or more of the threshold values for these streamflow metrics was assigned a value of 1 and considered to be part of a streamflow response, while a measurement that did not exceed any of the thresholds was assigned a value of 0 and was considered to be baseflow, or not part of a streamflow response.

1. Streamflow rate (e.g., cubic feet per second [cfs])
2. Quickflow (as defined by the baseflow separation)
3. Instantaneous quickflow minus minimum quickflow of previous 6 h
4. Instantaneous quickflow minus minimum quickflow of proceeding 12 h

We identified the four threshold values by starting from the thresholds used in Hopkins et al. (2020), then modifying values for each gauge (Table S1). We inspected hydrographs visually for appropriate response capture, looking for threshold values that captured as much of the storm responses in streamflow as possible, while limiting false identification of responses due to diurnal variations. A series of instantaneous streamflow measurements given a value of 1 (part of a streamflow response) along with an inter-event period of 6 h was used to identify discrete streamflow responses. Any response shorter than 15 min was eliminated because characteristics of interest could not be quantified for such short responses. We quantified the number of streamflow responses that contained missing streamflow data and were included in our analysis. We found a maximum of 8% of responses had missing streamflow data in Dry Gulch and Toll Gate Creek, and less than 3% of responses contained missing streamflow data in 90% of our watersheds; 67% of watersheds had less than 1% of streamflow responses containing missing streamflow, and 38% had no missing streamflow.

Mile High Flood District (MHFD) operates a network of 61 rain gauges that was used to relate to streamflow responses (Figure 1). Most gauges are 1 mm tipping bucket gauges and are calibrated 3–5 times per year. Each time a bucket tips, an electronic transmission of that tip is logged. The bucket may tip faster than the tips can be logged, so multiple transmissions may be received and logged at once. Given the limited rate at which the transmissions may occur, any incremental accumulation in rainfall depth greater than 5 mm is considered invalid by the maintenance contractors (i.e., OneRain) for MHFD. All rain gauges record a value of 0 at least every 12 h when no rain occurs, and we used this signal to determine when rain gauges were out of operation.

The USGS Rainmaker R package (<https://rdr.io/github/USGS-R/Rainmaker/>) was used to identify rain events and determine rainfall intensities. We used an inter-event duration of 6 h to define rain events. For each rainfall event, total depth, duration, mean storm intensity, and 5, 10, 15, 30 and 60-min maximum intensities were calculated.

2.3.1 | Pairing of streamflow responses with rain events

Due to the density of rain gauges in the Denver area, Thiessen polygons were calculated in ArcMap for these rain gauges to determine which gauges best represented the rainfall in each study watershed. We defined “rain gauges of influence” for each watershed to include any rain gauge that had a Thiessen polygon intersecting the watershed of interest. Streamflow responses were then paired with rainfall events where all the rain gauges of influence were considered for each stream gauge. Because their areas were small relative to rain gauge spacing, we aggregated the Rocky Flats watersheds (O-U) and treated them as one polygon for purposes of determining the Thiessen polygon area from each rain gauge that resided within the Rocky Flats watersheds boundaries.

TABLE 1 Characteristics of study watersheds

	Station name	Data provider/ USGS ID	Drainage area (km ²)	Min/max elevation (m)	Mean precip (mm)	% impervious cover
A	Dry Gulch at Denver, CO	USGS 06711770	8.63	1606 1739	426	47.3
B	Little Dry Creek NR Arapahoe Rd at Centennial, CO	USGS 06711515	3.30	1710 1785	477	40.5
C	Harvard Gulch at Colorado Blvd. at Denver, CO	USGS 06711570	5.84	1644 1716	448	40.1
D	Lakewood Gulch at Denver, CO	USGS 06711780	40.18	1594 2063	440	38.4
E	Weir Gulch Upstream from 1st Ave. at Denver, CO	USGS 06711618	14.35	1615 1970	433	37.6
F	Harvard Gulch at Harvard Park at Denver, CO	USGS 06711575	11.18	1620 1716	450	37.4
G	Little Dry Creek at Westminster, CO	USGS 06719840	26.86	1608 1749	410	35.3
H	Toll Gate Creek above 6th Ave. at Aurora, CO	USGS 394329104490101	89.61	1640 1865	462	34.9
I	Lee Gulch at Littleton, CO	USGS 06709740	6.03	1638 1751	452	30.1
J	Little Dry Creek above Englewood, CO	USGS 06711555	62.40	1626 1921	469	29.7
K	Dutch Cr at Platte Canyon Drive Near Littleton, CO	USGS 06709910	39.55	1635 2422	459	25.7
L	Lena Gulch at Lakewood, CO	USGS 06719560	21.17	1710 2312	505	22.3
M	Big Dry Creek below C-470 at Highlands Ranch, CO	USGS 06710150	28.84	1737 2006	517	22.3
N	First Cr Bel Buckley Rd, at Rocky Mtn Arsenal, CO	USGS 06720460	76.06	1614 1793	441	8.9
O	North Walnut Creek	DOE SW093	0.83	1789 1875	444	7.3
P	North Walnut Creek	DOE GS13	1.00	1777 1875	430	6.1
Q	South Walnut Creek	DOE GS10	0.87	1793 1853	436	5.3
R	North Walnut Creek	DOE GS12	1.41	1758 1875	431	4.8
S	South Walnut Creek	DOE B5Inflow	1.13	1771 1853	436	4.5
T	South Interceptor Ditch	DOE SW02	0.73	1759 1853	433	2.4
U	No Name Gulch	DOE GS33	1.16	1740 1843	435	0.8

To pair rain events and streamflow responses, we identified time windows for storm events. Any streamflow response overlapping with this event window at one of its rain gauges of influence was

considered a response to that rain event. An event window was started at the beginning time of a rain event and stopped 2 h after the end of the rain event (Hopkins et al., 2020) (Figure 2). A total of 2 h

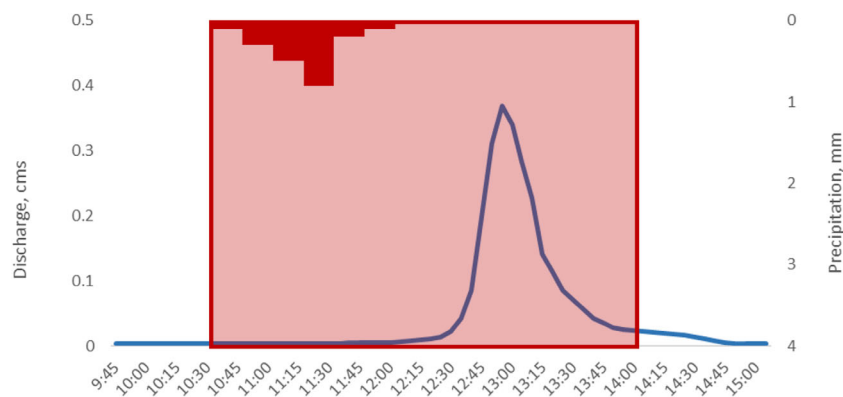


FIGURE 2 Example demonstrating the pairing of a streamflow response (blue) with a rainfall event (red). The shaded pink box represents the event window which lasts from the start of the rain event to 2 h after the rain event ends. Any rainfall and streamflow responses occurring within the same event window were paired.

was selected because this was long enough for streams to respond to rainfall in these watersheds; longer time windows created more errors in associating rain and streamflow. Because the purpose of our study was specifically to evaluate streamflow responses to rain events, any identified streamflow responses not overlapping with this event window were eliminated from further analysis of streamflow metrics.

Eliminating streamflow responses not paired with a rainfall event helped to remove any diurnal variations erroneously identified as a streamflow response. Rain events associated with more than one streamflow response were also eliminated from further analysis because of ambiguity of which rain metrics to assign to the separate streamflow responses. These events were less than 2% of the total number of responses analysed. On the other hand, a single streamflow response may have been paired with multiple rain events (e.g., long streamflow responses that do not fully return to baseflow before another rain event occurred). Rain events are included in the analysis even if they were not paired with any streamflow response; these no-response events are used to compute the percentage of rain events that produced streamflow responses in each watershed.

2.3.2 | Defining rain depth for events

Once a streamflow response was paired with one or more rain events, the paired rain data from all the rain gauges of influence were used to compute an area-weighted rainfall depth using Thiessen polygons. Not all rain gauges were functioning during the entire study period. We identified dates without a rain record (missing dates within period of record) for each rain gauge and excluded that gauge from the area-weighted average calculation for each individual rain event.

To focus on event-based streamflow responses to rain, we accounted for the possible influence of snowmelt on streamflow responses using normalized difference snow index (NDSI) from MODIS Terra Daily (Hall et al., 2015) where NDSI of 0.5–1.0 is considered to indicate snow cover (www.app.climateengine.org/climateEngine). We determined the dates within our study period with snow cover and disregarded any streamflow responses on these dates or the day after snow cover was detected.

Many studies have found that the effect of urban land cover on streamflow response depends strongly on the magnitude of rainfall

(Gallo et al., 2013; Hopkins et al., 2020), so rain events were partitioned into bins based on area-weighted average rainfall depth in order to detect patterns in different sized storm events. Four bin sizes were chosen to provide enough discretization to reveal patterns in metrics relative to storm size, while partitioning streamflow responses into bins with sufficient sample size to result in meaningful statistics. The rainfall depth bins used were $1 \leq p \leq 3$, $3 < p \leq 10$, $10 < p \leq 25$ and $p > 25$ mm, where p is the rainfall depth. These rainfall depth bins are referred to below as Bin 1: 1–3 mm, Bin 2: 3–10 mm, Bin 3: 10–25 mm, Bin 4: > 25 mm. The rain gauges report a resolution of 1 mm, so we omitted rain events with an area-weighted average rainfall depth of less than this value. The bin cutoff for the Denver area was 3 mm because stormwater management guidance assumed that the first 0.1 inch (2.54 mm) of rainfall is captured as depression storage (Mile High Flood District, 2018). The bin cutoff was 25 mm as this approximates the 60-min, 5-year rainfall event (Mile High Flood District ALERT Tables, n.d.).

Spearman's ρ rank correlations were calculated between percent impervious area and mean event metrics: percent of rain events that produced a streamflow response, number of streamflow responses in each watershed and bin, mean area-normalized peak flow, mean area-normalized runoff (quickflow), mean area-normalized runoff ratio (defined as mean-area normalized runoff [i.e., quickflow] depth divided by rainfall depth), mean time to peak (calculated as the time of peak streamflow response minus the time the streamflow response started), and mean duration. We used Spearman's ρ rank correlations because of potential non-linearity in the relations of interest and the method's robustness to outliers. We used the mean of event metrics for each watershed to avoid having more samples in the correlation for watersheds with more events. Six of our study watersheds are nested within larger watersheds and were treated as separate streams in our correlation analysis. All event metrics were also evaluated for correlation with watershed area and rainfall depth. To address any error in the process of event identification and rain event – streamflow response pairing, we eliminated any streamflow response with runoff ratios greater than five from further analysis. Runoff ratios above the theoretical limit of 1 have been shown to occur in urban watersheds as a result of non-precipitation inputs (for example from irrigation) or inputs from outside the topographically delineated boundaries (Bell et al., 2016; Chang, 2007; Manago & Hogue, 2017).

2.3.3 | Defining rainfall intensity for rain events

Streamflow responses were also partitioned into bins based on rainfall intensity to investigate effects of intensity on streamflow. Because multiple rain gauges were associated with each stream gauge, we chose to use only the rain gauge with the largest Thiessen polygon covering a watershed for analysis by rainfall intensity. We did not average multiple rain gauges of influence (as was done for rainfall depth) to avoid reducing the maximum intensity. In most cases, the single rain gauge used was missing only a few days throughout the study period (76% of watersheds were missing fewer than 10 days of precipitation record), with the largest lengths of missing data in the rain gauges associated with Toll Gate Creek and Big Dry Creek C-470 (125 and 112 days, respectively). If multiple rainfall events occurred at that rain gauge and were associated with a single streamflow response, we chose to use the rain event with the highest maximum 60-min rainfall intensity for this analysis. A similar approach was used in a previous study by Wilson et al. (2018), where the rain event with the highest erosivity was associated with the streamflow response. We used bins of 60-min maximum intensity discretized as ≤ 2 , $>2 \leq 5$, $>5 \leq 9$ and >9 mm/hr.

We applied methods presented in previous studies (Kampf et al., 2018; Wilson et al., 2018) to determine the 60-min rainfall intensity threshold likely to produce a streamflow response in each of our watersheds. Using the rain gauge with the Thiessen polygon with greatest area within each watershed, we first calculated the precipitation intensity that maximized the number of streamflow responses and non-responses correctly predicted using Equation 1 based on Wilson et al. (2018):

$$F = \frac{TP + TN}{P} \quad (1)$$

Where TP is total number of rain events with intensity above the tested threshold that produced a streamflow response (true positives), TN is total number of rain events with intensity below the tested threshold that produced no streamflow response (true negatives), and P is the total number of rain events that occurred during the period of study (rain events). The intensity that produced the highest fraction (F) of correctly predicted responses was accepted as the precipitation intensity threshold for that watershed.

Then we evaluated the strength of agreement between our observed responses and predicted responses based on the precipitation threshold using the kappa statistic, K (Gallo et al., 2013; McPhillips et al., 2019; Viera & Garrett, 2005):

$$K = \frac{(p_o - p_e)}{(1 - p_e)} \quad (2)$$

Where p_o is the maximized fraction of true positives and negatives, F, calculated in Equation 1, and the expected chance agreement, p_e , is calculated as:

$$p_e = R_o * R_e + NR_o * NR_e \quad (3)$$

Where R_o is the fraction of rain events producing an observed streamflow response, R_e is the fraction of events producing a response as expected based on the threshold 60-min intensity, NR_o is the fraction of rain events resulting in no streamflow response, and NR_e is the fraction of events with no response expected based on the threshold. The kappa statistic is considered to demonstrate fair agreement at 0.21–0.40, moderate agreement at 0.41–0.60, and substantial agreement at 0.61–0.80 (Viera & Garrett, 2005).

3 | RESULTS

3.1 | Analysis by rainfall depth

There were 2877 total streamflow responses to rain events identified, with 14–224 in each watershed (Table S1). Watersheds with greater imperviousness produced more streamflow responses to rain events, regardless of rain event size (Figure 3). The percentage of rain events that led to streamflow responses ranged from 8–34% (mean of 20%) for watersheds with less than 10% impervious surface cover, and from 33–75% (mean 53%) for watersheds with more than 10% impervious surface cover. Watersheds with >10% impervious surface cover had significantly more streamflow responses to rain events (Wilcoxon rank sum exact test p -value $<1e-4$). Based on the nonlinear relations shown in Figure 3, the correlation between the number of streamflow responses and imperviousness is strongest for imperviousness $<10\%$. The percent of rain events that produced streamflow responses was also positively correlated with drainage area for smaller rain events (Table 2).

3.1.1 | Area normalized peak flow

Mean area-normalized peak flow increased significantly with imperviousness, except in the largest event bin (Figure 4; Table 2). For Bin 2, the significance of the increase in area-normalized peak flow with imperviousness was driven by high impervious watersheds (above 40% impervious surface cover). No significant relation between area-normalized peak flow and area was noted (Table 2). Area-normalized peak flow significantly increased with precipitation depth in all the bins except Bin 3 (Table 2). Variability in area-normalized peak flow within one watershed and bin increased with impervious cover, indicating a wider range in peak flows for a given precipitation amount as impervious cover increased. For some watersheds, the variability in area-normalized peak flow was skewed such that the mean value was greater than the third quartile value, particularly for the smallest storms and the least impervious watersheds.

3.1.2 | Runoff depth and runoff ratio

Depth of runoff (mean, area-normalized) exhibited a significant positive correlation with imperviousness in Bins 1 and 3, but not 2 and 4 (Figure 5). Area-normalized runoff increased with precipitation depth across rainfall Bins (Table 2). Only the Bin 4 (>25 mm) events

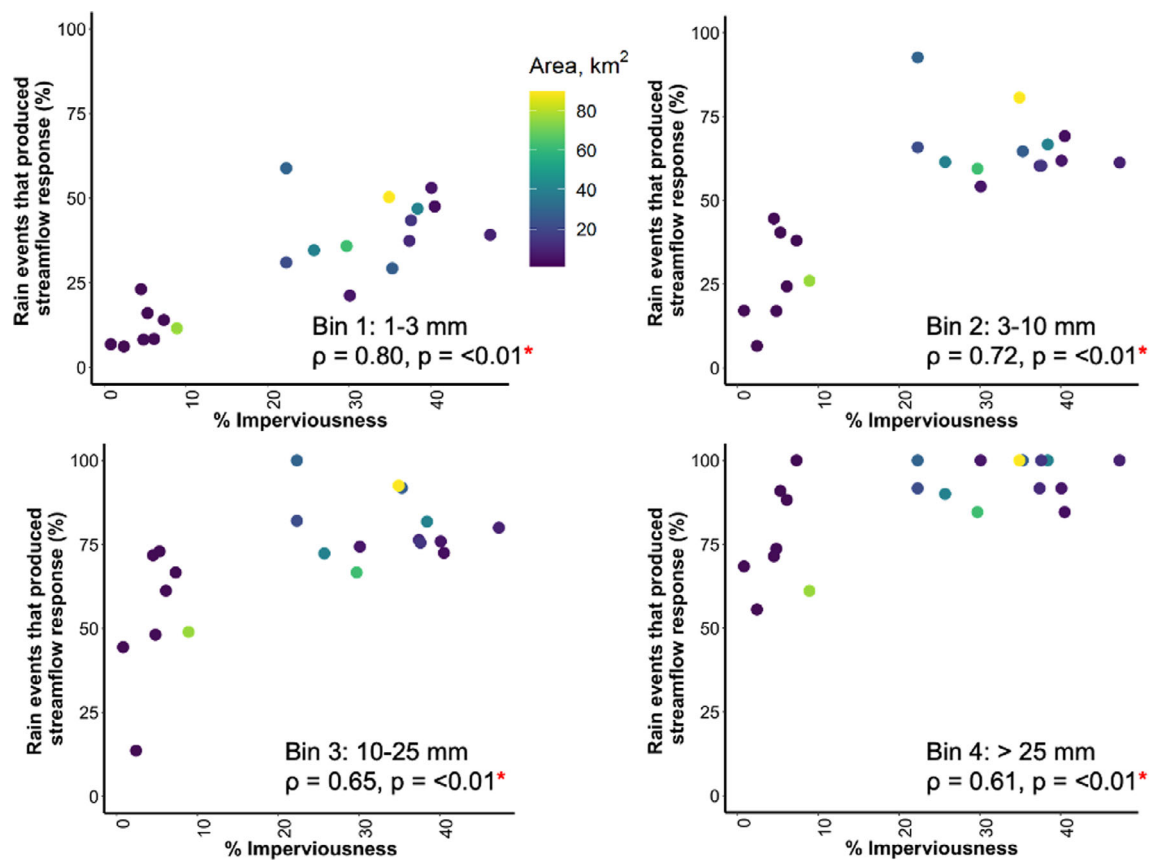


FIGURE 3 Percentage of rain events that produced streamflow responses plotted against imperviousness and binned by rainfall event depth. Points are colour-coded by watershed area (km²). Spearman's ρ correlation and p -values are also shown.

TABLE 2 Spearman's ρ correlation results for each metric and binned by rainfall event depth

Rainfall bins	1–3 mm	3–10 mm	10–25 mm	>25 mm
Percent of rain events that produce streamflow responses versus Imperviousness	0.80*	0.72*	0.65*	0.61*
Percent of rain events that produce streamflow responses versus Area	0.56*	0.62*	0.53*	0.32
Number responses versus Imperviousness	0.85*	0.86*	0.80*	0.63*
Number responses versus Area	0.45*	0.42 ⁺	0.61*	0.61*
Mean area-normalized peak flow versus Imperviousness	0.68*	0.65*	0.80*	0.35
Mean area-normalized peak flow versus Area	−0.15	−0.13	0.11	−0.40 ⁺
Area-normalized peak flow versus Precipitation depth	0.09*	0.18*	0.02	0.28*
Mean area-normalized runoff versus Imperviousness	0.45*	0.27	0.51*	−0.20
Mean area-normalized runoff versus Area	−0.20	−0.25	−0.09	−0.56*
Area-normalized runoff versus Precipitation depth	0.23*	0.34*	0.26*	0.51*
Mean runoff ratio versus Imperviousness	0.49*	0.27	0.62*	0.20
Mean runoff ratio versus Area	−0.11	−0.13	0.00	−0.36
Runoff ratio versus Precipitation depth	−0.04	0.02	0.01	0.08
Mean time to peak versus Imperviousness	−0.33	−0.10	−0.10	−0.04
Mean time to peak versus Area	0.13	0.40 ⁺	0.34	0.45*
Time to peak versus Precipitation depth	0.18*	0.08*	0.13*	0.20*
Mean duration versus Imperviousness	−0.62*	−0.60*	−0.63*	−0.63*
Mean duration versus Area	0.12	0.09	0.08	0.07
Duration versus Precipitation depth	0.21*	0.27*	0.31*	0.39*

Note: Correlations with $p \leq 0.05$ are indicated with *, and $p \leq 0.10$ are indicated with ⁺.

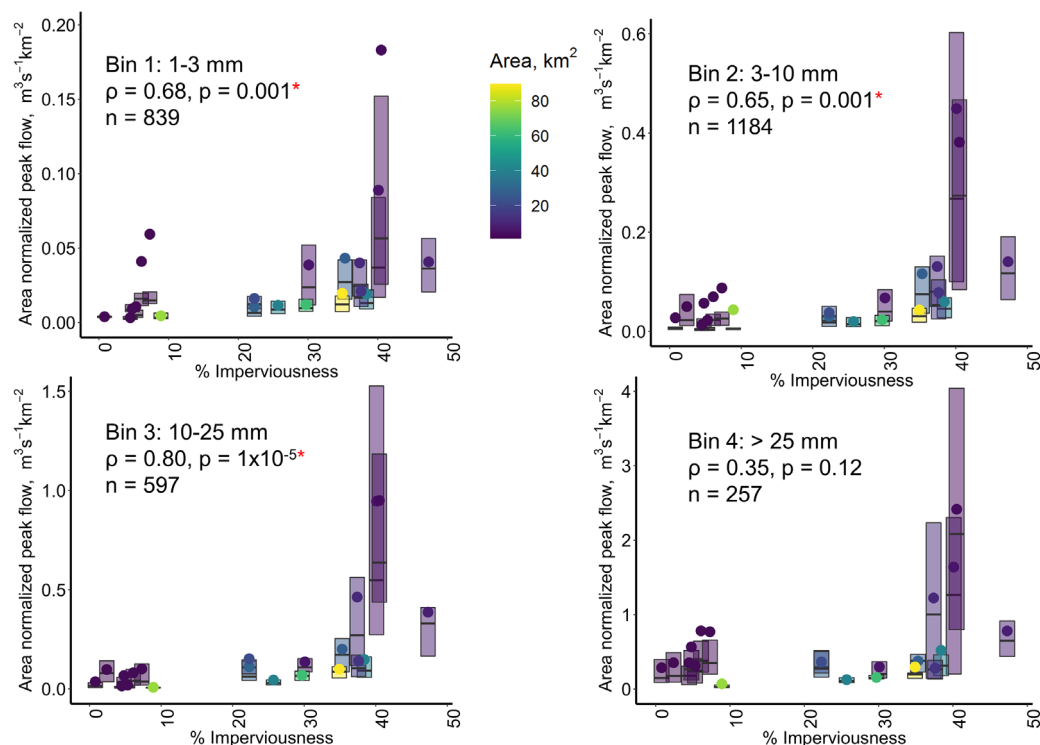


FIGURE 4 Area-normalized peak flow versus percent imperviousness binned by rainfall event depth, where the spread in each watershed is shown by a boxplot (first quartile, median and third quartile; whiskers and outliers have been removed for simplicity) and the mean (point). Note that the peak flow y-scale increases with rainfall bin. The Spearman's ρ correlation coefficient and p -value were calculated for the mean values. Boxes and points are coloured by watershed area. The number of rainfall events in each bin (n) decreases as bin depth increases, because larger storms occur less frequently.

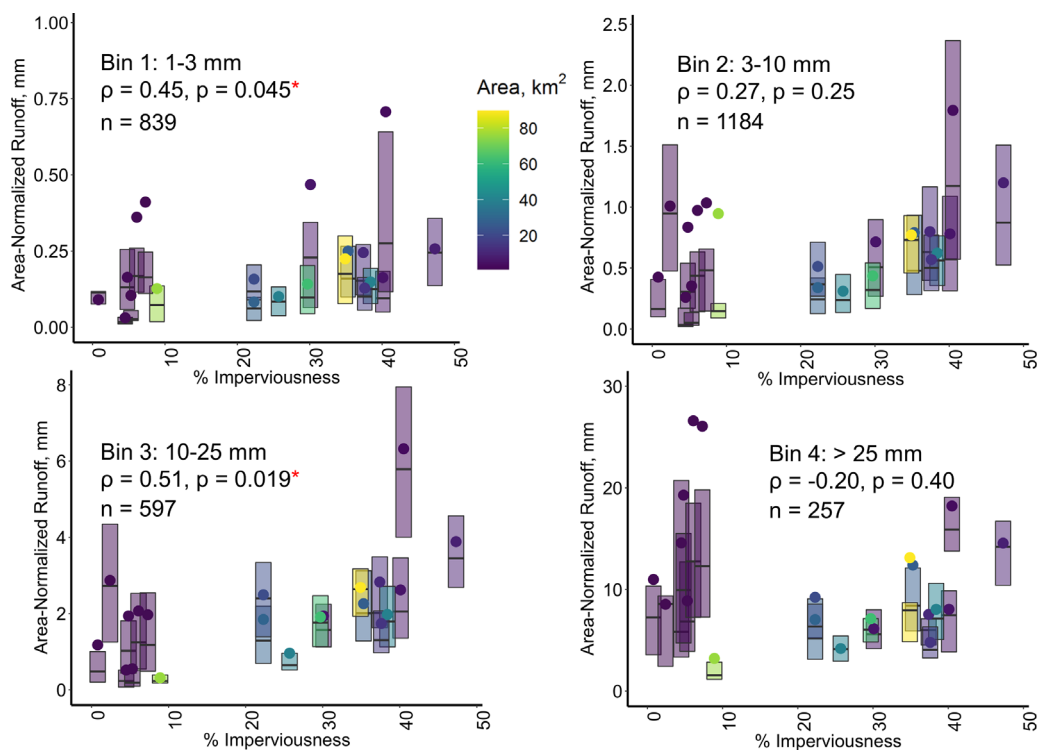


FIGURE 5 Boxplots showing area-normalized runoff versus percent imperviousness and colour-coded by drainage area. See Figure 4 caption for additional details

had a significant correlation (negative) between mean area-normalized runoff and watershed area (Table 2). No other watershed characteristics were highly correlated to mean area-normalized runoff (Figure S1).

A similar pattern was seen in correlations between mean runoff ratio versus imperviousness, with Bins 1 and 3 showing a positive correlation with imperviousness, but not Bins 2 and 4 (Table 2). No relationship between mean runoff ratio and area or runoff ratio and precipitation depth was seen in any bins (Table 2).

3.1.3 | Time to peak and streamflow duration

There were no significant correlations observed between mean time to peak and imperviousness (Table 2). Time to peak increased with drainage area in Bin 4, but not the other bins. Mean time to peak increased with precipitation depth across all Bins (Table 2). This indicates that smaller rainfall events produce streamflow responses that occur closer to the time of rainfall, whereas larger rainfall events produced longer runoff responses, including a longer time to peak streamflow.

Mean streamflow response duration decreased with imperviousness (Figure 6). No significant relation between mean duration and

area was seen. Mean streamflow response duration increased with precipitation depth in all Bins (Table 2).

3.2 | Analysis by rainfall intensity

Binning by rainfall intensity in general did not yield stronger correlations between streamflow response and imperviousness than rain depth. Rain events were analysed by binning 60-min maximum precipitation intensity (Table S1). Comparing the relations seen for bins by rain intensity (Table 3) and those with rain depth (Table 2), many relations are similar. Correlations with area were stronger when binned by intensity for peak flow, runoff and time to peak than they were when binned by precipitation depth, while correlations with number of streamflow responses, runoff ratio and duration were mostly consistent. Correlations between peak flow and intensity were significant in all bins, but Bin 3 of peak flow versus depth was not. Runoff and precipitation depth were positively correlated in all bins, and runoff and intensity were only positively correlated in Bins 1, 2 and 4. Duration and rainfall depth were positively correlated in all bins, and duration and intensity were positively correlated in Bins 1, 2 and 4. Time to peak was positively correlated with precipitation depth in all bins, but only showed a significant positive correlation

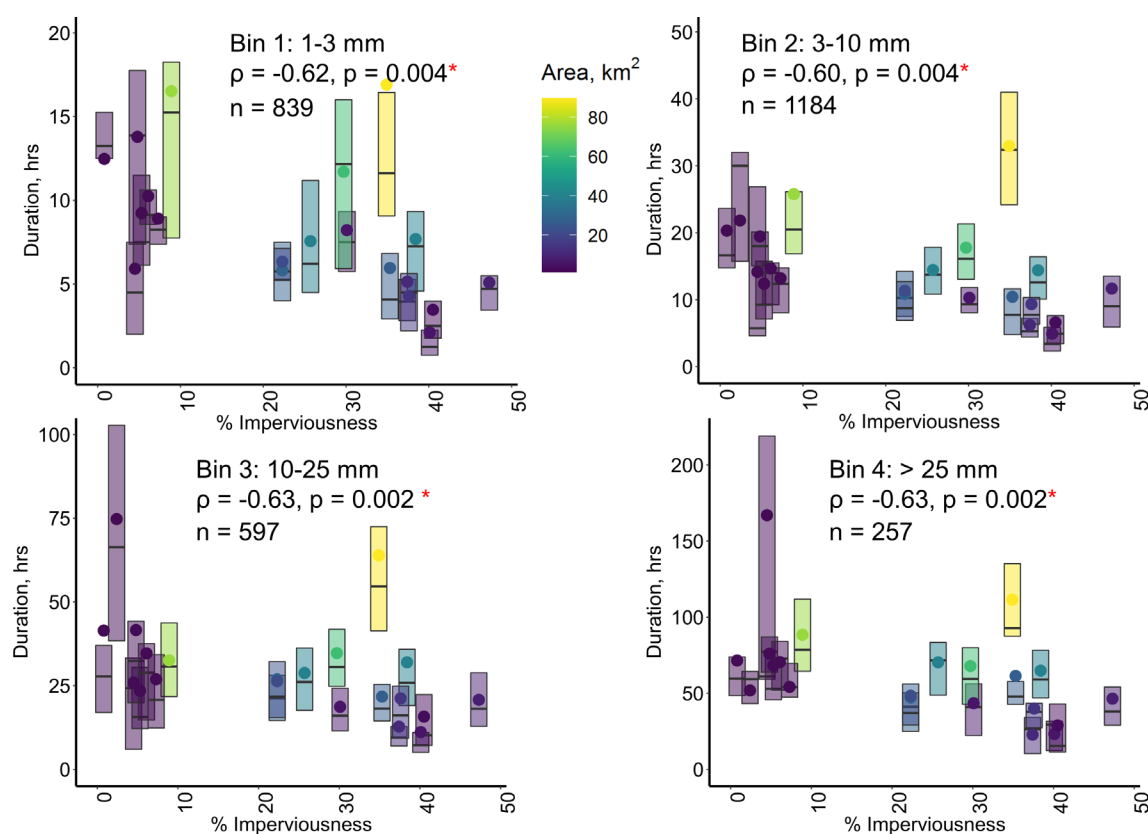


FIGURE 6 Duration of streamflow response to rain versus percent imperviousness colour-coded for watershed area. See Figure 4 caption for additional details

TABLE 3 Spearman's ρ correlation results for each metric and binned by rainfall event maximum 60-min intensity

Rainfall intensity bins	≤ 2 mm/hr	$>2 \leq 5$ mm/hr	$>5 \leq 9$ mm/hr	>9 mm/hr
Number responses versus Imperviousness	0.81*	0.83*	0.87*	0.79*
Number responses versus Area	0.47*	0.40 ⁺	0.51*	0.63*
Mean area-normalized peak flow versus Imperviousness	0.35	0.39 ⁺	0.67*	0.39 ⁺
Mean area-normalized peak flow versus Area	-0.40 ⁺	-0.51*	-0.14	-0.38 ⁺
Area-normalized peak flow versus Precipitation intensity	0.12*	0.23*	0.10*	0.35*
Mean area-normalized runoff versus Imperviousness	0.00	-0.35	0.30	-0.23
Mean area-normalized runoff versus Area	-0.35	-0.75*	-0.19	-0.60*
Area-normalized runoff versus Precipitation intensity	0.23*	0.30*	0.07	0.37*
Mean runoff ratio versus Imperviousness	0.18	0.31	0.53*	0.55*
Mean runoff ratio versus Area	-0.30	-0.25	-0.15	< 0.01
Runoff ratio versus Precipitation intensity	-0.01	0.13*	-0.01	0.22*
Mean time to peak versus Imperviousness	0.01	-0.12	0.04	0.04
Mean time to peak versus Area	0.51*	0.35	0.47*	0.56*
Time to peak versus Precipitation intensity	0.11*	0.03	-0.04	-0.05
Mean duration versus Imperviousness	-0.70*	-0.81*	-0.59*	-0.65*
Mean duration versus Area	-0.10	-0.24	0.02	0.10
Duration versus Precipitation intensity	0.17*	0.20*	0.02	0.14*

Note: Correlations with $p \leq 0.05$ are indicated with *, and $p \leq 0.10$ are indicated with ⁺.

with intensity in Bin 1. In general, binning data by rain intensity did not yield stronger correlations with imperviousness than binning by rain depth.

3.3 | Precipitation threshold analysis

The watersheds with greater than 10% impervious surface cover had response thresholds of 1–2 mm/hr maximum 60-min intensity (Table 4). The largest 60-min precipitation intensity thresholds of over 20 mm/hr were seen in the least impervious watershed (0.8% impervious surface cover) and in the largest watershed, which had less than 10% imperviousness. The precipitation intensity threshold was significantly higher in watersheds with less than 10% imperviousness (Wilcoxon test with $W = 104$ and p -value $< 10^{-4}$). However, streamflow responses in these watersheds were also least well predicted by a precipitation threshold based on kappa (Table 4).

Precipitation intensity thresholds decreased significantly both with greater watershed imperviousness and greater watershed area (Figure 7a; Table 5). However, the kappa statistic that evaluates performance of the precipitation threshold was below a reasonable confidence interval (0.41) for roughly half of the calculated thresholds (Table 4). The kappa statistic itself was larger in watersheds with greater imperviousness, meaning that precipitation intensity is more predictive of whether there will be a streamflow response for more urban watersheds compared to grassland watersheds (Figure 7b; Table 5). This may also be because the kappa statistic also tends to be less reliable with fewer

number of observations (Viera & Garrett, 2005) and kappa increased with the number of streamflow responses (Table 5). The fraction of rain events producing a streamflow response (not separated by rainfall bin; Figure 7c) increased significantly with imperviousness (Table 5).

4 | DISCUSSION

4.1 | Key findings

Our study included many watersheds in the Denver area covering a wide range of imperviousness (0.8%–47%) with 8 years of instantaneous streamflow data. Similar to other studies conducted in arid and semi-arid environments (Gallo et al., 2013; McPhillips et al., 2019), we found that some streamflow metrics conformed to the typically reported urban response of increased peak flow, increased runoff, decreased time to peak and decreased duration, whereas other streamflow metrics (runoff depth, runoff ratios and time to peak) did not follow these responses (Leopold, 1968; Shuster et al., 2005; Walsh et al., 2005). Urbanized watersheds in the Denver region had more streamflow responses, a smaller precipitation intensity needed to produce a streamflow response, greater peak flow and shorter duration streamflow responses, but they did not exhibit clear changes in runoff (i.e., quickflow) depth, runoff ratio and time to peak compared to their grassland counterparts (Figure 8). Overall, this supports the concept of regional or climate-specific patterns in changes to storm hydrographs with urban development.

TABLE 4 Precipitation threshold analysis using the maximum 60-min intensity (mm/hr) and R_0 (fraction of rain events that produced an observed streamflow response from Equation 3)

Station label	% Imperviousness	Drainage area (km ²)	Maximum 60-min intensity (mm/hr)	Maximized fraction, F	Kappa, K	R_0
A	47.3	8.63	1	0.82	0.57	0.69
B	40.5	3.3	1	0.71	0.34	0.75
C	40.1	5.84	1	0.69	0.30	0.75
D	38.4	40.18	1	0.83	0.56	0.77
E	37.6	14.35	1	0.77	0.49	0.68
F	37.4	11.18	1	0.77	0.51	0.64
G	35.3	26.86	1	0.78	0.57	0.49
H	34.9	89.61	1	0.75	0.40	0.74
I	30.1	6.03	2	0.79	0.54	0.41
J	29.7	62.4	1	0.68	0.35	0.57
K	25.7	39.55	1	0.71	0.39	0.59
L	22.3	28.84	1	0.78	0.47	0.77
M	22.3	21.17	1	0.73	0.44	0.58
N	8.9	76.06	36	0.82	0.02	0.19
O	7.3	0.83	4	0.82	0.50	0.24
P	6.1	1	6	0.83	0.45	0.23
Q	5.3	0.87	6	0.78	0.31	0.27
R	4.8	1.41	7	0.82	0.33	0.18
S	4.5	1.13	4	0.74	0.33	0.30
T	2.4	0.73	16	0.94	0.20	0.06
U	0.8	1.16	23	0.85	0.06	0.16

Note: Rows are bolded where the kappa value is moderate or better (>0.41). Watersheds are ordered by descending percent imperviousness.

4.1.1 | Frequency of streamflow responses increase with urbanization

The number of streamflow responses increased significantly with greater watershed imperviousness regardless of rain depth and rain intensity (Figure 3; Tables 2 and 3). As more impervious surfaces replace permeable surfaces, opportunities for depression storage and infiltration decrease, and those impervious surfaces are often directly connected to streams, leading to increases in streamflow even for small rain events. This may also indicate runoff generation in more urbanized watersheds (i.e., greater impervious area) is less sensitive to antecedent moisture conditions whereas less urbanized watersheds are more sensitive.

This finding is consistent with more stormflow responses in other arid and semi-arid study regions (Gallo et al., 2013; McPhillips et al., 2019). We found that as imperviousness increased, the intensity of rainfall needed to produce a streamflow response decreased (Figure 7). In prior studies, the rainfall causing runoff generation has been reported in depth rather than intensity, as depth has the same units as depression storage (Shuster et al., 2005). The rainfall depth that produces runoff on directly connected impervious surfaces has been reported to range from 0.8 to 2.3 mm (Albrecht, 1974; Wibben, 1976). We found urban watersheds had a streamflow response to rain events at or close to the lowest measurable 60-min intensities (1–2 mm/hr).

4.1.2 | Area-normalized peak flow increases with urbanization

Our results showed that peak flow (measured as mean area-normalized peak flow) increased with imperviousness in Bin 1 (1–3 mm), Bin 2 (3–10 mm) and Bin 3 (10–25 mm) when binned by precipitation depth (Figure 4). This aligns with results from a study in southern California that found urbanization to be the third strongest predictor of peak flow (behind watershed area and precipitation), with urbanization effects more pronounced in moderate flows than high flows (Hawley & Bledsoe, 2011). There was significant positive correlation between peak flow and precipitation intensity in all intensity bins and precipitation depth in Bins 1, 2 and 4 (>25 mm). Watershed area was not consistently related to area-normalized peak flow (Tables 2 and 3), meaning that normalizing by area removed the area effect. Our results indicated that regardless of area, area-normalized peak flows generally increased with imperviousness and with precipitation amount and intensity.

4.1.3 | Runoff and runoff ratio patterns were mixed with urbanization

Runoff (i.e., mean area-normalized quickflow) and runoff ratio did not show a clear pattern with imperviousness. Based on events

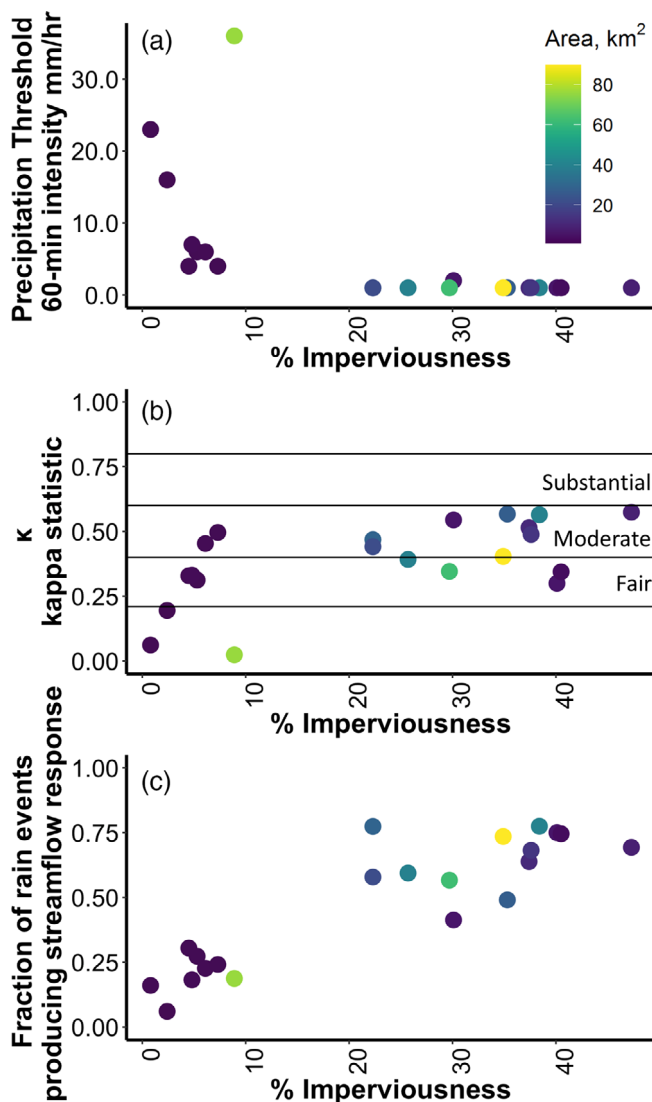


FIGURE 7 (a) Precipitation threshold versus percent imperviousness, colour-coded by watershed area. (b) Kappa statistic versus percent imperviousness, colour-coded by watershed area, with agreement classes indicated (Viera & Garrett, 2005). (c) Fraction of rain events producing an observed streamflow response (R_o in Equation 3) versus percent imperviousness.

TABLE 5 Correlation results of precipitation threshold analysis

	Spearman's ρ
Precipitation threshold versus Imperviousness	−0.81
Precipitation threshold versus Area	−0.55
Kappa versus imperviousness	0.57
Kappa versus number of responses	0.59
R_o (fraction of rain events producing streamflow response) versus imperviousness	0.83

Note: All p -values were <0.01 .

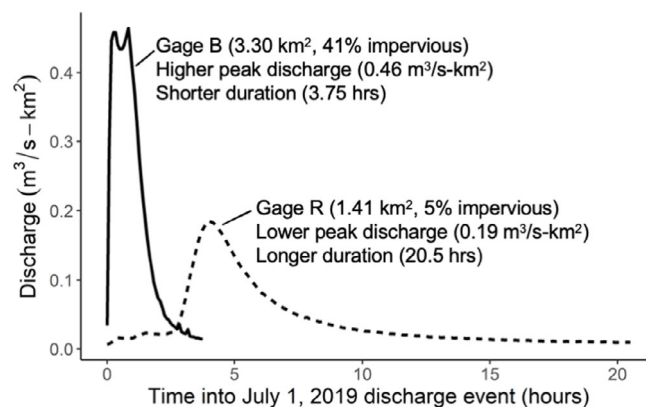


FIGURE 8 Hydrographs from the 1 July 2019 rain event at an urban stream gauge (B; solid line) and a rural stream gauge (R; dashed line). Gauge B received 7.8 mm of rainfall after 20 h of dry time and gauge R received 9.1 mm of rainfall after 21 h of dry time.

binning by precipitation depth, both runoff and runoff ratio increased with imperviousness in Bins 1 and 3, but not 2 and 4 (Figure 5; Table 2). In Bin 2, and particularly Bin 4, the runoff in the small, grassland watersheds in Rocky Flats was relatively high compared to the more impervious watersheds (Figure 5). This may be because the grassland watersheds are at the higher end of the elevation range in the study area or because they are small; streams in this region tend to lose water to the subsurface for larger drainage areas (Martin et al., 2021). In the urbanized areas, the implementation of storm-water control strategies targeted at reducing runoff may also have a greater effect on total stormflow than on peak discharge and response duration (Hopkins et al., 2020). Rainfall in the more urban watersheds produced higher peak flows but shorter duration streamflow events, and these combined can lead to little or no change in overall storm runoff. In another semiarid region study from Arizona, Gallo et al. (2013) did not find a relation between storm runoff and urbanization. The lack of a clear pattern in the runoff results suggests that complex processes are involved that further analysis may help to discern.

4.1.4 | Duration decreased with urbanization

Time to peak was not influenced by imperviousness in our study watersheds, but streamflow responses reduced in duration as imperviousness increased (Figure 6). Interestingly, a study of five watersheds ranging from 22%–90% imperviousness in Tucson, Arizona also found time to peak was unrelated to imperviousness, but, in contrast to our work, that study found streamflow duration increased with urbanization (Gallo et al., 2013). Although we did not find a correlation between imperviousness and time to peak, in arid Phoenix, Arizona, McPhillips et al. (McPhillips et al., 2019) found hydrograph rise and fall rates (mm/hr d^{-1} , related to time to peak) decreased with

imperviousness. The decreasing duration with greater imperviousness is the only major difference between our work and findings from these previous studies (Gallo et al., 2013; McPhillips et al., 2019) on the changes to hydrographs with urbanization. Exploration of the potential impact of stormwater control measure and conveyance networks on urban hydrologic response was outside the scope of this study but could be a highly influential factor.

4.2 | Limitations and future work

The watersheds with less than 10% impervious cover in our study were seven streams in Rocky Flats (0.8%–7.3% impervious surface cover; <1.5 km²) and First Creek Bel Buckley (8.9% impervious surface cover; 76 km²). The watersheds in Rocky Flats currently have low impervious surface cover, but the soils are expected to still be recovering from the decommissioning of the Rocky Flats Plant from 1995–2005 (<https://www.energy.gov/sites/default/files/2020/06/f75/RockyFlatsFactSheet.pdf>). We selected the watersheds in Rocky Flats that were least impacted by the canal and pond system, but these may still influence the hydrology of the area. The Rocky Flats watersheds are also the smallest watersheds, which makes separating the effects of impervious surface cover and watershed area challenging. Using monitored grassland watersheds across a range of drainage areas and locations in the Denver metropolitan area would be useful. However, there are no other previously monitored grassland watersheds in the Denver area with similar drainage area to the urbanized watersheds.

Interactions between impervious areas and run-on to pervious areas within the study watersheds were not analysed but would be expected to affect watershed responses. The arrangement of impervious surfaces has been found elsewhere to affect stream response, modulating the effect of total impervious surface cover (Beighley & Moglen, 2002; Debbage & Shepherd, 2018; Mejía & Moglen, 2009). Other areas for future study are a longer study period for capturing a broader range of events (many of the study stream gauges were installed in 2013); analysis of other factors affecting streamflow including stormwater control measures in the urbanized watersheds, flow modifications, rainfall spatial and temporal variability and other landscape characteristics such as soil properties and slopes; and further evaluation of the parameters and application of the semi-automated method for event identification (Hopkins et al., 2020).

5 | CONCLUSIONS

Urban development is rapidly modifying land cover in formerly grassland watersheds, and planners need to know how much runoff to expect from these urbanizing areas. We analysed streamflow response hydrograph metrics paired with rain events over an 8-year study period in 21 watersheds ranging from 1% to 47% impervious surface cover in the semi-arid Denver area of Colorado.

We found:

- Semi-arid urbanization increased magnitudes of area-normalized peak flow (Figure 4; Table 2) and decreased duration of storm responses in streamflow (Figure 6; Table 2; Figure 8).
- Semi-arid urbanization increased the responsiveness of watersheds to even small rain events, leading to lower 60-min precipitation intensities required to produce a streamflow response with increasing urbanization (Figure 7; Table 5), and resulting in more than twice as many streamflow responses occurring in watersheds >10% impervious area compared to less (Figure 3; Table 2).
- Neither storm runoff (quickflow) nor time to peak discharge (i.e., time from streamflow response start to streamflow peak) changed consistently and significantly with imperviousness (Table 2).

Despite the widespread use of stormwater control measures, urbanized watersheds in the semi-arid Denver area have higher peak flow and shorter duration of storm responses than their less developed counterparts. Our work suggests the design of new stormwater systems in these urbanized watersheds could be optimized by focusing on reducing the magnitude of peak flow, increasing the duration of stream response, and improving capture of small to moderate sized events. When considered with previous studies, this work adds to the evidence that the effects of urbanization do not lead to the same hydrograph changes across all urban areas.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study were derived from the following resources available in the public domain: USGS NWIS (United States Geological Survey, 2022); Rocky Flats instantaneous streamflow data is available from DOE and the reader should contact DOE for data access. The supplementary material of this article includes parameters used to process streamflow data. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The R codes used in this study are available on CUAHSI HydroShare at <http://www.hydroshare.org/resource/6653ee4d09cf47488b29c800ccbe0bbd>.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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