THESIS

HYDROLOGIC RESPONSES TO URBANIZATION IN DENVER WATERSHEDS AND INVESTIGATION OF PRECIPITATION THRESHOLDS FOR STREAMFLOW GENERATION IN PRE-DEVELOPMENT SEMI-ARID RANGELAND

Submitted by

Stacy Wilson

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Aditi Bhaskar

Stephanie Kampf
Tim Green

ABSTRACT

HYDROLOGIC RESPONSES TO URBANIZATION IN DENVER WATERSHEDS AND INVESTIGATION OF PRECIPITATION THRESHOLDS FOR STREAMFLOW GENERATION IN PRE-DEVELOPMENT SEMI-ARID RANGELAND

Urbanization alters stream hydrographs and has been shown to have detrimental effects on water quality, stream morphology, and riparian ecosystem function. A thorough understanding of this alteration is crucial for effective and sustainable water management as communities in semi-arid areas continue to grow at an accelerated pace. However, the hydrologic response to urbanization in semi-arid rangeland environments has not been well documented. Using eight years of instantaneous flow data for twenty-one watersheds ranging in size from 1 to 90 km^2 with impervious areas ranging from 1 to 47%, this study provides a comprehensive analysis of hydrologic alteration occurring with urbanization in the semi-arid area of Denver, Colorado, USA. Using a semi-automated method to identify 2,877 streamflow events, we analyzed event-based metrics of peak flow, runoff depth, runoff ratio, time to peak, and duration, in addition to precipitation threshold and number of streamflow events occurring in response to precipitation events and zero flow. We found that number of events and peak flow increased significantly with the fraction of impervious area (imperviousness), while duration, precipitation threshold, and zero flow decreased significantly with imperviousness. Runoff depth, runoff ratio, and time to peak either gave mixed results or did not vary significantly with imperviousness. Our results suggest that urban watersheds in semi-arid environments are more hydraulically efficient than their undeveloped counterparts, resulting in an increased number of streamflow events generated by smaller precipitation events, with a quicker delivery of runoff to receiving streams. This research also

characterized the flow in West Stroh Gulch rangeland in Parker, Colorado through time-lapse photography in conjunction with climatological data. Our monitoring period was limited to one year in duration, while no streamflow events were observed throughout our study, suggesting the precipitation threshold to generate runoff in this undeveloped rangeland exceeds the largest rainfall events observed (30 mm depth and a 60-minute maximum intensity of 5 mm/hour). Our data provides important baseline information for future comparison as development in semi-arid areas rapidly progresses, contributing physical data useful for model calibration. Overall, this research makes an important contribution to understanding the streamflow response of grasslands and urban watersheds to precipitation in semi-arid environments.

ACKNOWLEDGEMENTS

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And finally, a very special thank you to my dad. In the year of COVID-19 restrictions, he stepped in as my partner in the field and was invaluable in constructing the monitoring setup in West Stroh Gulch (multiple times!). He made numerous trips with me to Parker, and I am thankful for his company and his hard work. This project was truly a team effort, and I am grateful to all who helped along the way.

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CHAPTER 1—INTRODUCTION

The "urban stream syndrome" is broadly understood to result in significant changes to the natural stream hydrology, often resulting in higher peak flows and flashier systems and causing instability in receiving water bodies (Meyer et al., 2005; Walsh et al., 2005). Channel erosion, ecosystem degradation, and water quality issues may develop, and remediation efforts are costly and challenging to complete.

However, recent studies suggest the streamflow response to urbanization is not as consistent as once thought (Booth et al., 2015), because climate and geologic setting are important factors in pre- and post-development hydrologic regimes. These few studies show that changes to the storm hydrograph with urbanization are not the same in semi-arid and arid settings as compared to the more commonly studied humid settings. A recent study in central Arizona (McPhillips et al., 2019) found that streamflow metrics in this environment do not demonstrate the typical response recorded in more mesic environments. Streams in arid areas tend to be naturally flashier, and McPhillips et al. (2019) hypothesized that increased opportunities for water storage in urban systems may decrease variability in streamflow response. Another study in Arizona found that while streamflow duration and frequency of runoff generation increased with urbanization, the time to peak, runoff depth, and water yield did not (Gallo et al., 2013). The authors concluded that the stormwater control system design may influence the hydrologic response more than land cover. The former study was completed in an arid environment, while the latter, while completed in a semi-arid area, included only a limited study group (5 watersheds) and time period (2 years), and did not incorporate a spectrum of urbanization that included undeveloped watersheds, except by reference to a previous study. Our goal is to complete a robust analysis of streamflow responses in a semi-arid environment in watersheds occupying a range of imperviousness. In addition, event-based metrics applied to streamflow responses in semi-arid areas will reveal trends in hydrologic response with increasing urbanization.

Rangelands make up 31% of the U.S. (Carey et al., 2019), yet the hydrologic response in undeveloped grasslands in semi-arid climates is poorly understood and characterization of the streamflow response from rangelands to urbanization not well-documented. Studies looking specifically at rangeland sites found a general lack of identifiable trends in the hydrologic response (Weltz et al., 2000; Carey et al., 2019; Pierson et al., 2002). Annual water budgets were evaluated at Long-Term Agroecosystem Research (LTAR) sites across the United States, and runoff was treated as "negligible" in the semi-arid region of the Central Plains Experimental Range (CPER) in northeastern Colorado (Bauffaut et al., 2020). A flume installed at the CPER site in 2017 saw no runoff from the time of installation until the completion of the study (Baffaut et al., 2020). In pre-development grassland settings in the Denver region, what precipitation thresholds produce a runoff response is unknown.

Significant population growth is occurring in many semi-arid areas, and understanding the undisturbed streamflow response in these environments is crucial for effective stormwater management decisions and optimum urban water system design and implementation. The previous research referenced above highlights the lack of knowledge regarding the pre-development hydrology in semi-arid areas and the need for a more comprehensive understanding of the stream response to urbanization to inform water management.

Our study aims to address this gap in two ways. Monitoring of an undeveloped watershed in the semi-arid region of Denver, CO, allows us to characterize the natural flow response to rainfall events using time-lapse photography paired with rainfall data for direct observation of flow/no flow. Secondly, an analysis of streamflow metrics through urbanization gradients in the Denver area will provide valuable insight into how watersheds in this environment respond to increasing imperviousness in terms of number of events, peak discharge, streamflow duration, total runoff, runoff ratio (defined in this study as total runoff depth divided by precipitation depth), time to peak discharge, precipitation threshold, and proportion of zero flow measurements.

CHAPTER 2—METHODS

Setting

Denver

The Denver area is uniquely suited for this analysis as the stream gauge network is dense, and monitoring of drainages with a range of development is ongoing (Figure 1). The city of Denver is located roughly 19 km east of the foothills of the Rocky Mountains, and the metropolitan area is home to approximately 3 million people (www.denver.org). The continental climate here exhibits seasonal variability, with an average annual precipitation on the plains of 300 – 400 mm, most of which falls April – September (Dennehy et al., 1993). Denver is situated within the South Platte River Basin, which has its

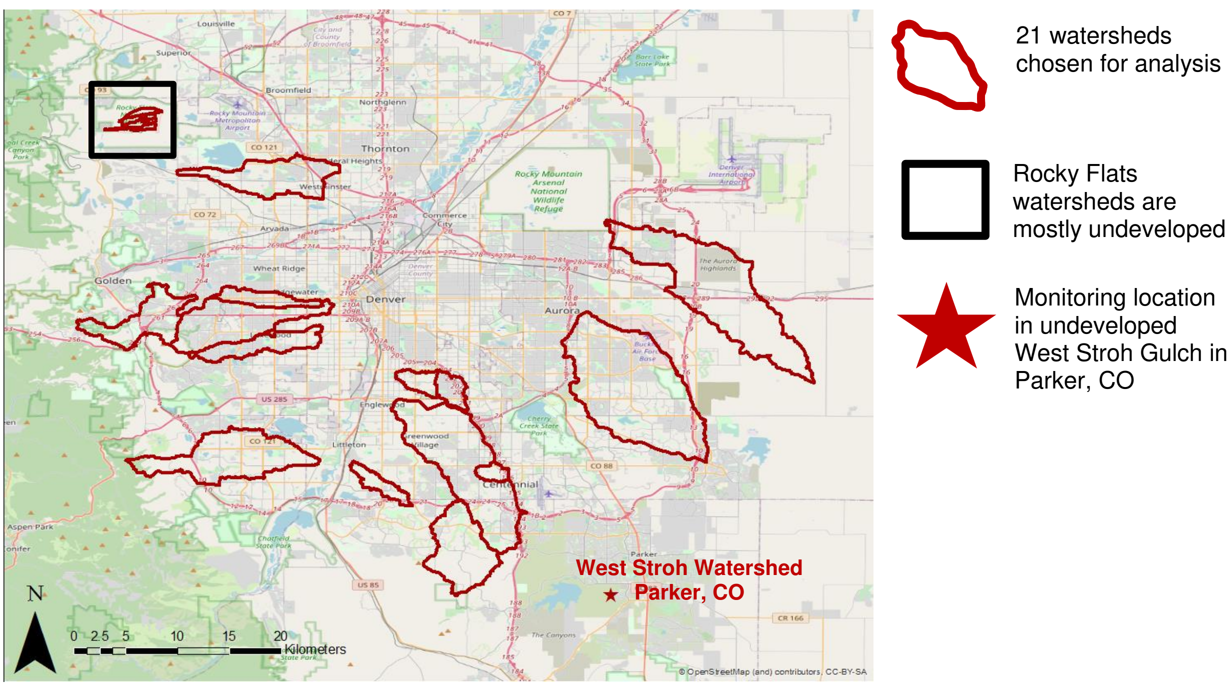

Figure 1. Locations shown of an undeveloped watershed in Parker, CO and 21 watersheds of varying degrees of imperviousness located in the Denver, CO area.

headwaters in the Rocky Mountains. The elevation of the foothills is approximately 1,675 m (5,500 ft), sloping eastward to 1,600 m (5,280 ft) at Denver, and descending to 850 m (2,788 ft) at the confluence with the North Platte River in Nebraska. The far western portion of the South Platte watershed is composed of a vegetation community that is primarily forested montane and subalpine, with the eastern portion of the watershed consisting primarily of grasslands and cultivated agricultural land (HDR Engineering & West Sage Water Consultants, 2015). The geology underlying our study watersheds primarily consists of clastic sedimentary and unconsolidated, undifferentiated deposits (Horton, 2017) (Figure 2).

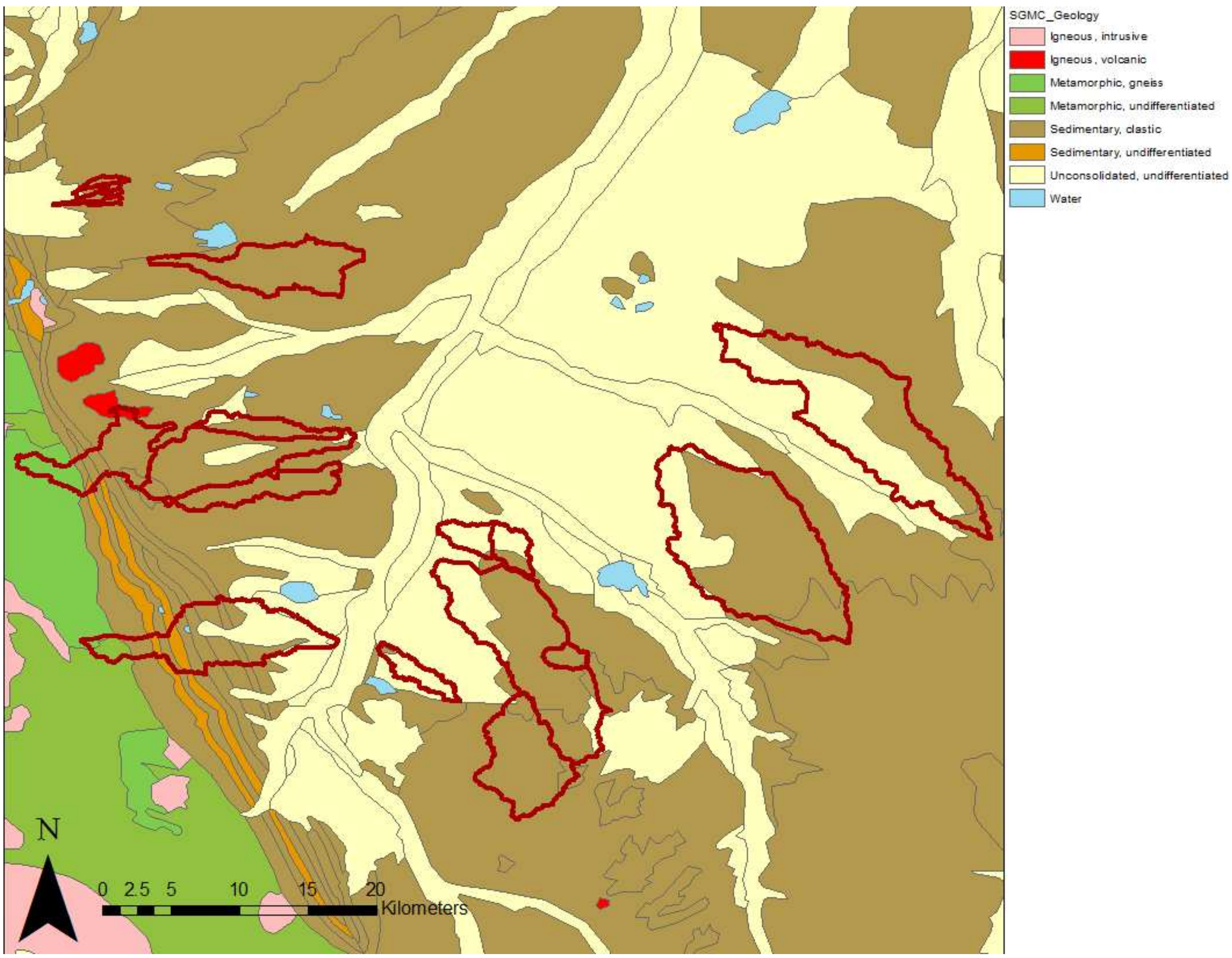

Figure 2. Geology of the study area indicates primarily clastic sedimentary and unconsolidated, undifferentiated deposits. Black polygons outline our study watersheds. Source: The State Geologic Map Compilation (SGMC) Geodatabase of the Conterminous United States, USGS, 2017.

Rocky Flats

The watersheds of Rocky Flats are uniquely suited for use as reference watersheds. The manufacturing of nuclear weapons components occurred on the site throughout the second half of the previous century. The site was shut down and decommissioning commenced in 1995 and was completed in 2005 (Rocky Flats Fact Sheet, 2020). As a CERCLA/RCRA site (Comprehensive Environmental Response, Compensation, and Liability Act/Resource Conservation and Recovery Act), groundwater and surface water are closely monitored by the Department of Energy Office of Legacy Management (DOE LM). Although legacy effects of the former operations are undoubtedly a factor, no other opportunities exist in the Denver area that compete with Rocky Flats for quantity and quality of water monitoring data available for streamflow analysis.

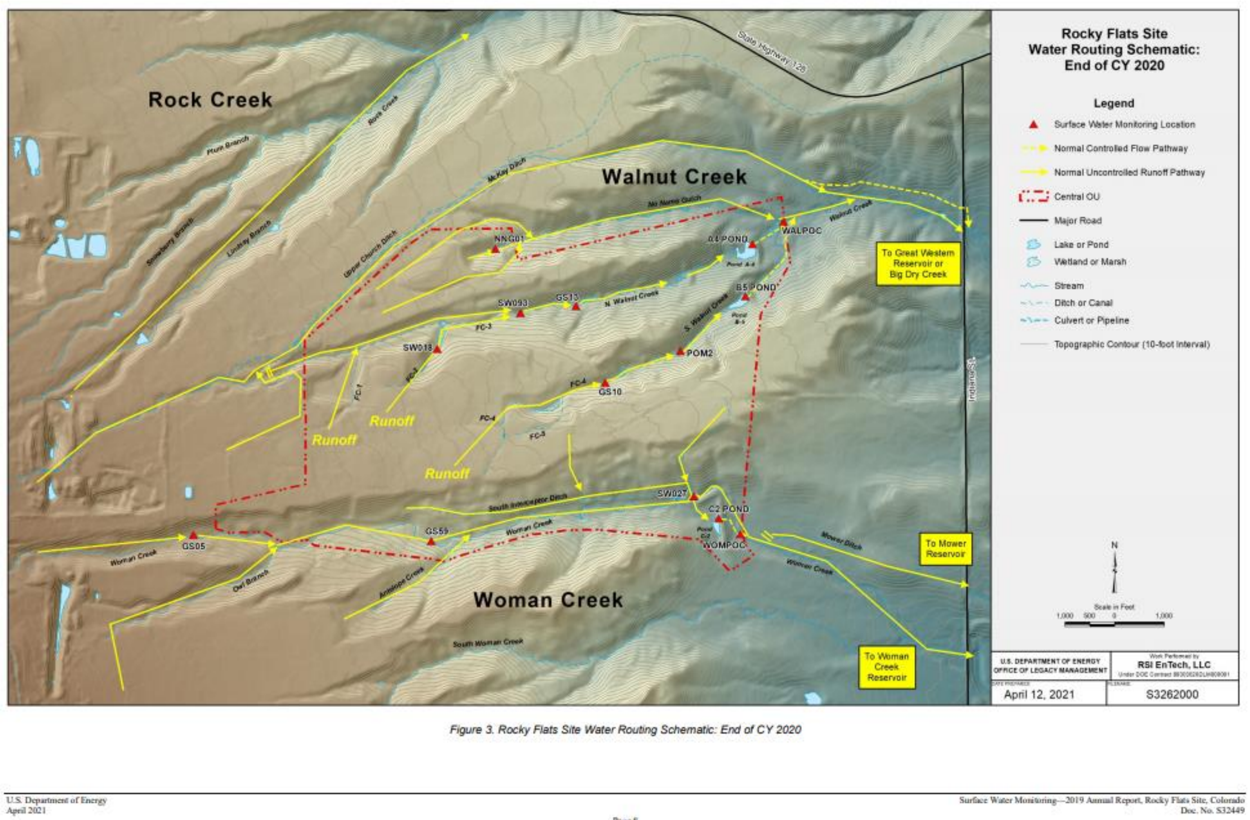

Figure 3. Map of three major drainages in Rocky Flats with flow direction indicated (*Annual Report of Site Surveillance and Maintenance Activities at the Rocky Flats Site, Colorado. Calendar Year 2019. Surface Water Monitoring*, 2020).

Rocky Flats sits on a huge alluvial fan (George Squibb, verbal communication, 2020), and three major drainages run through the area: Rock Creek, Walnut Creek, and Woman Creek. Rock Creek falls to the north and outside of the Central Operable Unit (COU) and is not included in the LM's monitoring program (Figure 3). Walnut Creek is fed by three main tributaries: No Name Gulch, North Walnut Creek, and South Walnut Creek. GS33 records discharge from No Name Gulch, which runs along the northern boundary of the COU. No Name is a well-defined drainage and least impacted by prior development of the site, although there are remnants of stock ponds. GS12, GS13, and SW093 are located along North Walnut Creek, while B5INFLOW and GS10 are located along South Walnut Creek (Figure 4). The South Interceptor Ditch (SID) drains an area just north of Woman Creek and discharge is measured at SW027 (*Annual Report of Site Surveillance and Maintenance Activities at the Rocky Flats Site, Colorado. Calendar Year 2019. Surface Water Monitoring*, 2020). Monitoring locations along Woman Creek were determined unacceptable due to complicating effects from canals and ditches further up the watershed.

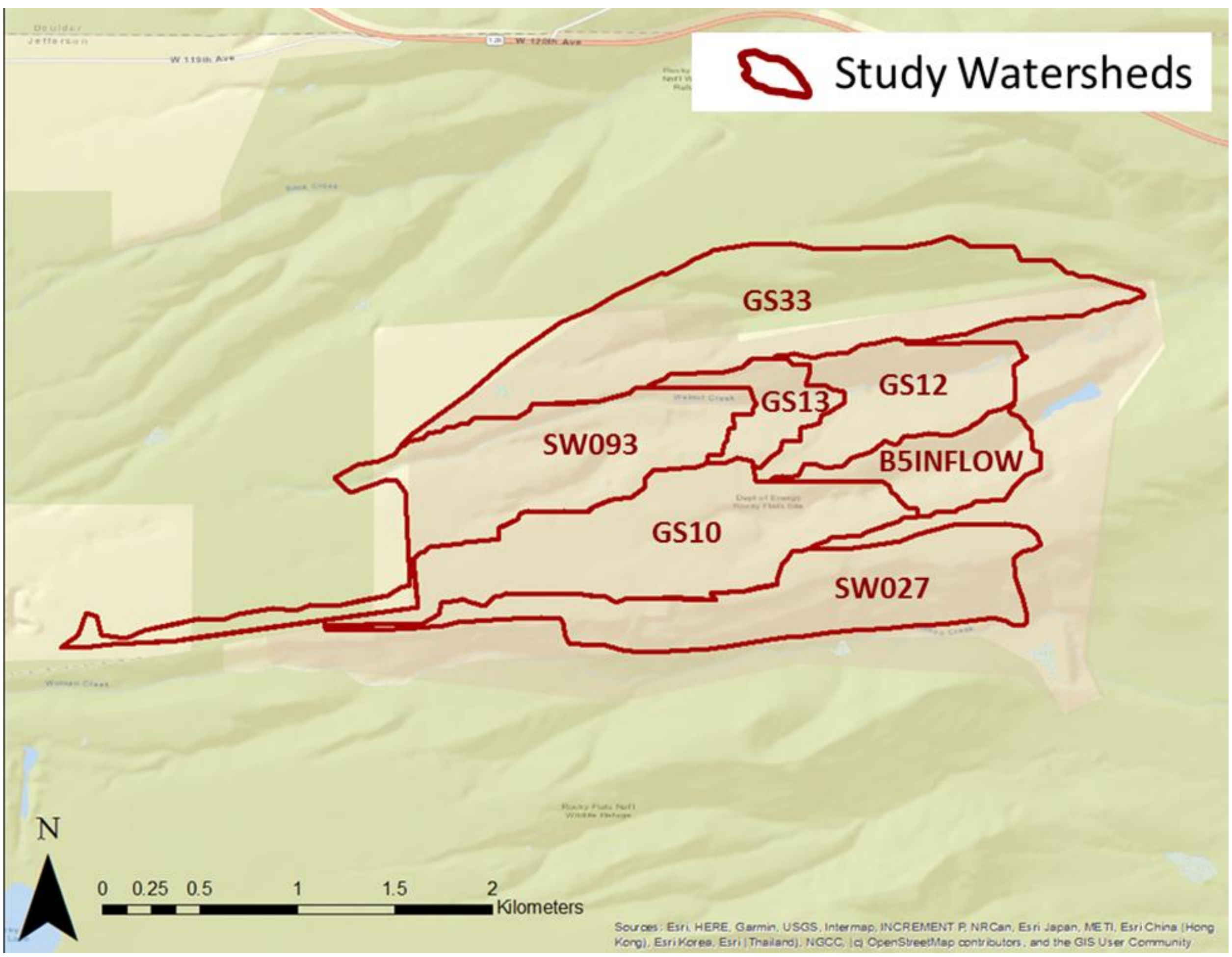

Figure 4. Rocky Flats watersheds used as reference for less developed watersheds.

Rainfall rarely generates a streamflow response in these channels, and runoff is highly dependent on antecedent conditions (George Squibb, verbal communication, 2020).

West Stroh Gulch

West Stroh watershed in Parker, CO, is a 1.5 km^2 ephemeral wash that is mostly undeveloped rangeland and is scheduled for residential development within the next two years (Figure 5). The projected development plan is to incorporate green infrastructure (GI) and low impact development (LID) strategies, including maintaining or mimicking the natural channel network in order to preserve as much of the area's undisturbed hydrology as possible. West Stroh Gulch is one part of the larger study area of Oak Gulch, which is currently serving as a test case for the effectiveness of the implementation of these innovative strategies from pre-development through completion (Earles et al., 2018). Our work characterizing the hydrology in this watershed will inform water managers of the effectiveness of strategies implemented and provide physical data for modeling. The site has a history of agricultural use and is currently being used for cattle grazing. Factors complicating the hydrology include the presence of stock ponds, remnants of a historical ditch, and stormwater outfalls from neighboring residential areas.

A stockpond located a short distance up the watershed captures all the runoff from above, while stormwater outfalls contribute the majority of runoff at the culvert outlet. While there are a few gullies present, much of the ephemeral channel network in this watershed is not well-defined. We selected a monitoring location upstream of the stockpond along what appeared to be a flow path for runoff. Approximately 1.0 km^2 (67%) of the West Stroh watershed drains to this monitoring location. Previous research found time-lapse photography to be an effective tool in capturing flow events in ephemeral channels using 5-minute time intervals to ensure small events were not missed (Schoener, 2018). A game camera with time-lapse photography capability was installed next to the channel on June 7, 2020, with monitoring continuing beyond the completion of this study. We chose the SpyPoint Solar-Dark solar trail camera for its solar-charged internal battery, time-lapse mode, and night photography capability. The camera was mounted on a post, aimed at the channel, and programmed to take one photograph every five minutes, 24 hours per day (Figure 6). Discharge measurements were beyond the scope of our study, but we were able to include a staff gauge positioned in the middle of the channel to provide an approximation of flow depth.

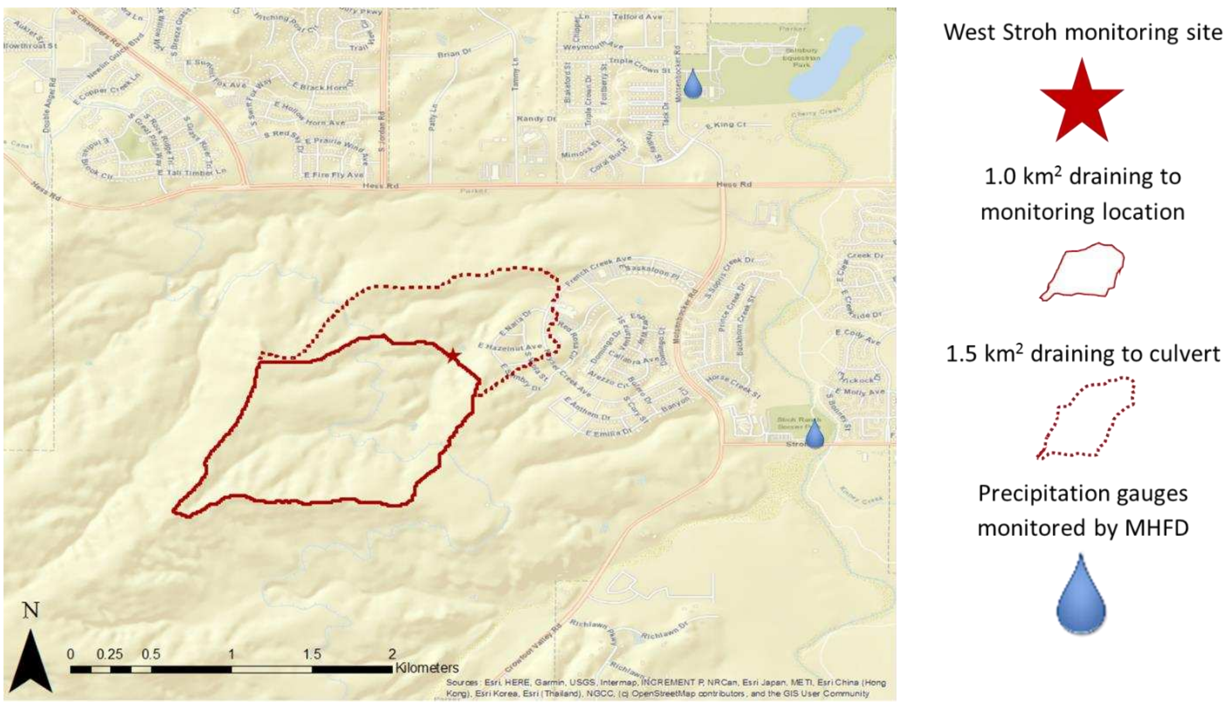

Figure 5. The portion of West Stroh watershed draining to our monitoring site (approximately 1.0 km^2). Precipitation gauges monitored by MHFD are shown. A third rain gauge in the area is located off the map, approximately 3.75 km east of the monitoring site.

Three rain gauges are located close to West Stroh and are operated by Mile High Flood District. Rainfall data were collected from each of these gauges. These rain gauges were not designed to measure snow depth and we were not attempting to capture runoff responses to snowmelt. The closest gauge (1.8 km away) was used as the primary, while the other two served as backups in case of missing data. The Rainmaker package from USGS was used with R Software to process precipitation data from each of these gauges (https://rdrr.io/github/USGS-R/Rainmaker/). Rain events were identified, and metrics of depth and intensity were calculated. All photos were reviewed beginning 30 minutes prior to a rainfall event, soil conditions described, and presence/absence of channelized flow noted. On dates with no recorded rainfall, one photo per 24-hr time period was reviewed and any noteworthy conditions recorded.

Figure 6. SpyPoint solar game camera installed next the channel and pointed at the staff gauge positioned in the center of the channel. The location of this monitoring site is indicated by a star in Figure 5.

Denver Watershed Comparison

To select which study watersheds to use for our second research question, we started with all the stream gauges managed by the Colorado Department of Water Resources, USGS, and DOE in the Denver area. Gauges along the mainstem of the South Platte River were not considered due to their large drainage area. To best isolate the effect of urban development on streamflow response to storms, gauges that had the following criteria were eliminated: located at the inlet or outlet of a reservoir, pond, canal diversion, or wastewater effluent discharge point; drainage area >150 km^2, as we wanted to avoid too great of variation in size between our watersheds as a complicating factor; period of record that did not include 2013 – 2020; mean annual precipitation >550 mm or minimum watershed elevation >2286 m (7500 ft.), as these watersheds may be more influenced by the mountain topography to the west; and wastewater treatment plant (WWTP) effluent discharge >50% mean annual streamflow. The sources for this information are described below.

Relevant watershed characteristics were calculated for the area draining to each stream gauge. The ⅓ arcsecond DEM dataset from The National Map was used in ESRI's watershed delineation procedure to establish watershed boundaries (https://viewer.nationalmap.gov/basic/). Watershed areas were compared with those stated by USGS for their gauges and checked for agreement (https://waterdata.usgs.gov/nwis/rt). Those watersheds with significant disagreement were manually edited to align more closely with the boundaries used by USGS. StreamStats was used to delineate the Toll Gate Creek Above 6th Ave at Aurora, CO watershed as the delineation in ArcMap produced a vastly different area for this watershed (https://streamstats.usgs.gov/ss/). The Rocky Flats region is heavily influenced by the presence of canals and ponds. DOE provides watershed boundary information for all stream gauges used in this analysis (*Annual Report of Site Surveillance and Maintenance Activities at the Rocky Flats Site, Colorado. Calendar Year 2019. Surface Water Monitoring*, 2020), and our watershed polygons were manually edited to align with the documented DOE boundaries. The minimum and maximum elevation of each watershed was determined from the DEM. The 30-year annual normal precipitation (mm) using 800 m spatial resolution was downloaded from the PRISM Climate Group at Oregon State University and used to calculate the mean precipitation for each watershed using the Zonal Statistics Table tool in ArcMap (https://prism.oregonstate.edu/normals/). The One Water Solutions Institute and the Colorado Department of Public Health and Environment developed the eRams Watershed Rapid Assessment Tool (WRAP), which provides data regarding WWTP effluent and transbasin diversions (http://www.coloradowaterdata.org/eramswrapcdsn.html). This tool was used to evaluate each watershed for possible contributions from either of these sources. The 2016 National

Land Cover Database (NLCD) was used with the Zonal Statistics tool to determine percent imperviousness of each watershed (https://www.mrlc.gov/data). The 2016 NLCD has not been updated

Table 1. Twenty-one watersheds chosen for further analysis and their characteristics.

	Station Name	Data Provider/USGS ID	Drainage Area (km^2)	Min/Max Elevation (m)	Mean Precip (mm)	% Imp
A	DRY GULCH AT DENVER, CO	USGS 6711770	8.63	1606 1739	426	47.3
B	LITTLE DRY CREEK NR ARAPAHOE RD AT CENTENNIAL, CO	USGS 6711515	3.30	1710 1785	477	40.5
C	HARVARD GULCH AT COLORADO BLVD. AT DENVER, CO	USGS 6711570	5.84	1644 1716	448	40.1
D	LAKEWOOD GULCH AT DENVER, CO	USGS 6711780	40.18	1594 2063	440	38.4
E	WEIR GULCH UPSTREAM FROM 1ST AVE. AT DENVER, CO	USGS 6711618	14.35	1615 1970	433	37.6
F	HARVARD GULCH AT HARVARD PARK AT DENVER, CO	USGS 6711575	11.18	1620 1716	450	37.4
G	LITTLE DRY CREEK AT WESTMINSTER, CO	USGS 6719840	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 6709740	6.03	1638 1751	452	30.1
J	LITTLE DRY CREEK ABOVE ENGLEWOOD, CO	USGS 6711555	62.40	1626 1921	469	29.7
K	DUTCH CR AT PLATTE CANYON DRIVE NEAR LITTLETON, CO	USGS 6709910	39.55	1635 2422	459	25.7
L	LENA GULCH AT LAKEWOOD, CO	USGS 6719560	21.17	1710 2312	505	22.3
M	BIG DRY CREEK BELOW C-470 AT HIGHLANDS RANCH, CO	USGS 6710150	28.84	1737 2006	517	22.3
N	FIRST CR BEL BUCKLEY RD, AT ROCKY MTN ARSENAL, CO	USGS 6720460	76.06	1614 1793	441	8.9
O	SW093	DOE	0.83	1789 1875	444	7.3
P	GS13	DOE	1.00	1777 1875	430	6.1
Q	GS10	DOE	0.87	1793 1853	436	5.3
R	GS12	DOE	1.41	1758 1875	431	4.8
S	B5Inflow	DOE	1.13	1771 1853	436	4.5
T	SW027	DOE	0.73	1759 1853	433	2.4
U	GS33	DOE	1.16	1740 1843	435	0.8

to reflect the decommissioning of the Rocky Flats plant. Instead, we used a land cover classification previously developed in Google Earth Engine to determine percent imperviousness in the Rocky Flats area (Fillo, 2020). The final selection of watersheds used in our analysis and the characteristics of each are indicated in Table 1.

The 21 study gauges (Table 1) had streamflow records at a 5 to 15 minute frequency over our period of analysis from 06/07/2013 to 09/30/2020 (two of our gauges became operational on 06/07/2013). Many of these gauges are only operated seasonally, so our analysis is limited to the months of April – September. Manual identification by visual inspection of the start and end time defining streamflow responses to storm events (called streamflow events here) over this many storms and watersheds would be time-consuming and not reproducible. Other studies have used automated methods to separate components of the hydrograph. Baseflow separation through the use of a master recession curve followed by a smoothing curve was developed by Duncan (Duncan, 2019). Another study used the semi-log recessional method to separate baseflow and produced dimensionless unit hydrographs for analysis (Hung et al., 2018). Tang and Carey (2017) described a process using MATLAB for baseflow separation and streamflow event identification, followed by pairing with precipitation events. Nimmo and Perkins (2018) explored the use of Master Recession Curve and Episodic Master Recession methods. Semi-automated event identification has been used successfully in previous studies (Hopkins et al., 2020). The Hopkins et al. (2020) study was performed in the Clarksburg, MD area and the authors developed R code to identify streamflow events using instantaneous (5 or 15 minute) streamflow data. The R code developed by Hopkins et al. (2020) was adapted for use with our selected Denver area gauges. The BaseflowSeparation tool in the EcoHydRology package in R applies the digital filter method of baseflow separation and was used to determine the quickflow of streamflow. We used a 0.99 filter parameter with 3 passes as this has been found to work best with sub-hourly data (Hopkins et al., 2020). As established by Hopkins and adapted to our semi-arid basins, threshold values were determined for the following four parameters, such that any instantaneous streamflow measurement found to exceed one or more of the threshold values for these four parameters was assigned a value of 1 (part of a streamflow event), while a measurement that did not exceed a threshold was assigned a value of 0 (not part of a streamflow event, or baseflow).

1. Streamflow (e.g., cfs)
2. Quickflow (as defined by the baseflow separation)
3. Instantaneous quickflow minus minimum quickflow of previous 6 hours
4. Instantaneous quickflow minus minimum quickflow of proceeding 12 hours

A series of instantaneous streamflow measurements given a value of 1 (part of a streamflow event) were identified as a discrete streamflow event. Event characteristics such as time of peak discharge, peak flow, event duration, and total quickflow were calculated for each event. Given the broad range of imperviousness in our study watersheds, we found identification parameters functioned best when tailored for each gauge individually. Identification values were adjusted for each gauge and visually inspected for appropriate event capture. One challenge associated with this method is the capture of as much of the streamflow curve on the hydrograph as possible, while avoiding the capture of diurnal variation, as seen at some of our gauges (hydrographs illustrating this challenge may be seen in Figure A1 in the appendix). An inter-event period of 6 hours was used to identify discrete events, and any event shorter than 15 minutes in duration was eliminated. We quantified the number of events containing missed discharge measurements and found a maximum of 8.3% of events in Dry Gulch and 8% of events in Toll Gate Creek contained missed measurements, while less than 3% of events contained missing discharge measurements in 90% of our watersheds. Sixty-seven percent of watersheds had less than 1% of events containing missed discharge measurements, while 38% had no missed discharge measurements.

Mile High Flood District in Denver operates a network of precipitation gauges, providing rainfall data useful for pairing with streamflow events (Figure 7). The network of gauges is maintained by OneRain in Longmont, CO. 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 sent. Given the limited rate at which the transmissions may occur, any incremental accumulation in rainfall depth greater than 5 mm is considered invalid by OneRain, maintenance contractors for MHFD (Scott Bores, 3/17/2021, personal communication). All gauges record a value of zero at least every 12 hours when no precipitation occurs.

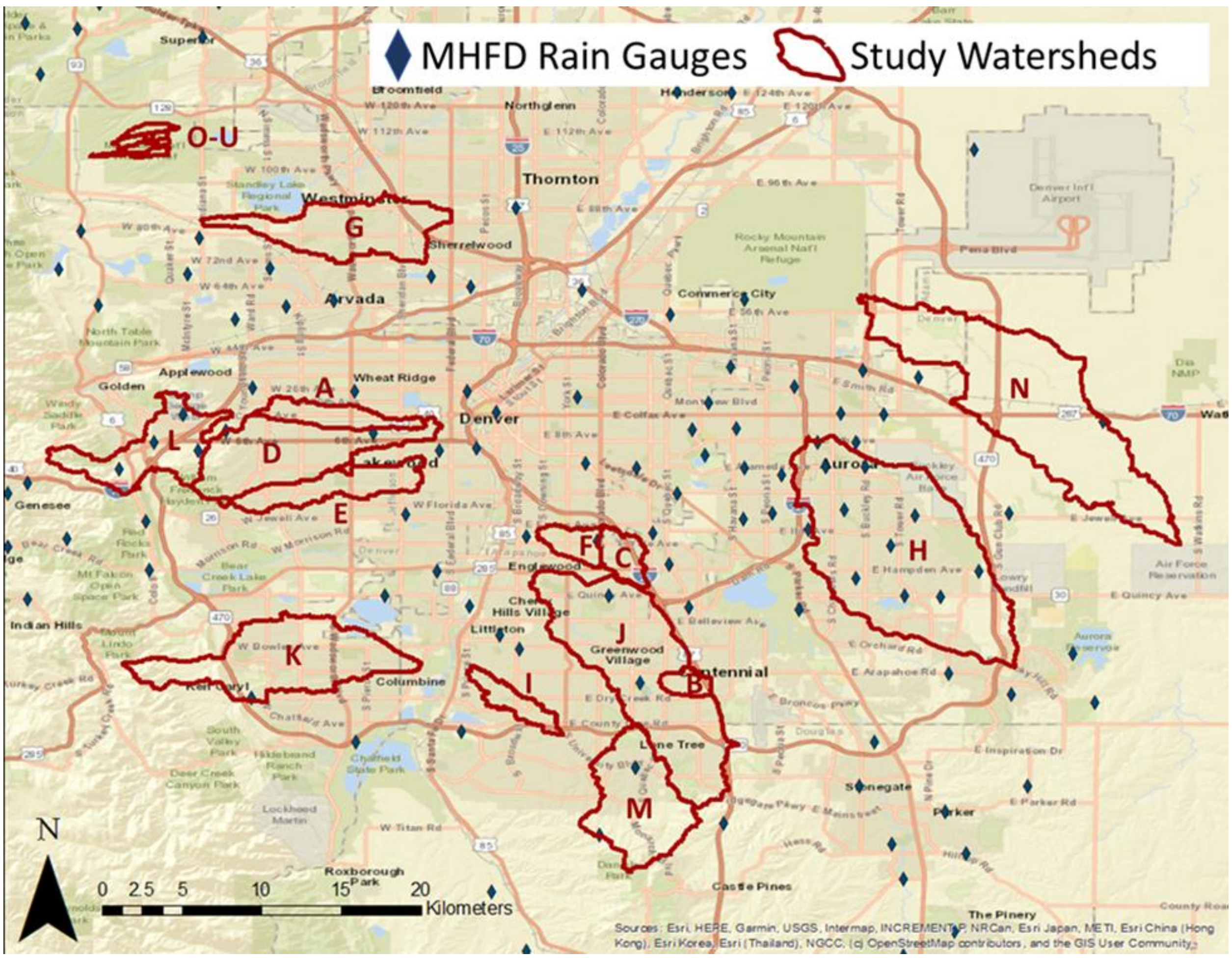

Figure 7. Twenty-one watersheds chosen for analysis and network of rain gauges monitored by Mile High Flood District.

USGS-R/Rainmaker code (https://rdrr.io/github/USGS-R/Rainmaker/) was used to identify rain events and determine rainfall intensities. For each rainfall event, total depth, duration, overall intensity, and 5-, 10-, 15-, 30-, and 60-minute intensities were calculated. Due to the density of rain gauges in the Denver area, Thiessen polygons were calculated in ArcMap to determine which rain gauges to associate with each watershed (rain gauge of influence).

Streamflow events were then paired with rainfall events. An event window was started at the beginning time of the rain event and stopped two hours after the end of the rain event (Hopkins et al., 2020) (Figure 8). Any streamflow event overlapping with this event window at one of its rain gauges of influence was considered a response to that rain event. As the purpose of our study was to specifically evaluate streamflow responses to rain events, any identified streamflow events not overlapping with this event window were eliminated from further analysis of streamflow metrics. The elimination of

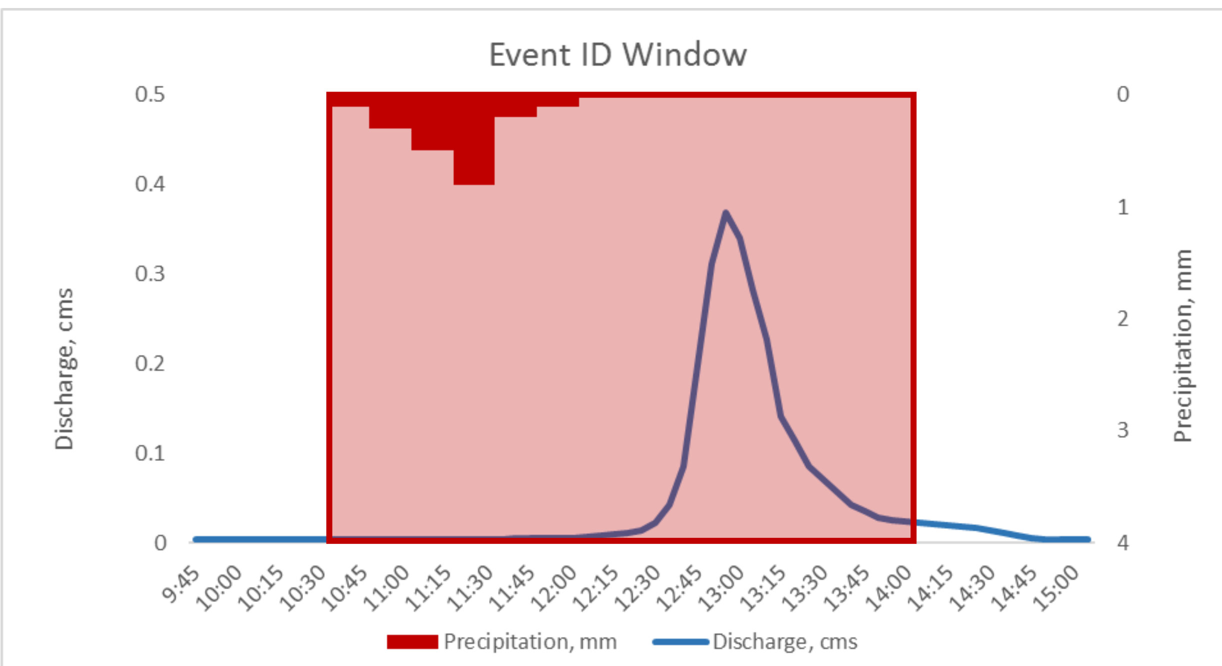

Figure 8. Example demonstrating the pairing of a streamflow event with a rainfall event. The shaded box represents the event window. Any rainfall and streamflow events occurring within the same event window were paired.

streamflow events not paired with a rainfall event also helped to disqualify diurnal variation erroneously identified as a streamflow event, as discussed above. Any rain events identified as having more than one associated streamflow event resulted in the elimination of those streamflow events from further analysis as they were deemed too complex.

Once a streamflow event was identified as a response to a rain event or multiple rain events, all rainfall events paired with that streamflow response were included in determining an area-weighted rainfall depth. Given the density of rain gauges in the Denver area (a total of 61 gauges were used), area-weighted averages were used to calculate rainfall depth across each watershed. Thiessen polygons were created in ArcMap from rain gauge point data and area-weights applied. Not all rain gauges were functioning during the entire study period. We identified dates without a precipitation 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.

In order to account for the possible influence of snowmelt on our streamflow responses, we used climateengine.org to calculate the Normalized Difference Snow Index (NDSI) for our area of study. NDSI of 0.5 – 1.0 is considered to indicate snow cover (www.app.climateengine.org/climateEngine). We used the tool to determine what dates within our study period demonstrated snow cover and eliminated any events on these dates or the day after snow cover was detected.

As rainfall depth was found to be important to storm response in other urban watersheds (e.g., Hopkins et al. 2020; Gallo et al., 2013), 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. In the Denver area, it is assumed that the first 2.54 mm of rainfall is captured as depression storage (USDCM, Vol. 3). The 5-year rainfall event may be approximated by 25 mm (MHFD Alert). We chose bins that would provide enough discretization to reveal patterns in metrics relative to storm size, while partitioning streamflow events into bins with sufficient sample size to result in meaningful statistics. The precipitation gauges have a resolution of 1 mm, so we omitted events with an area-weighted average rainfall depth of less than this value. Final rainfall depth bins used were ≥ 1 ≤ 3 mm, > 3 ≤ 10 mm, > 10 ≤ 25 mm, and > 25 mm. Spearman's ρ correlations were calculated between imperviousness and mean area-weighted peak flow, mean area-weighted runoff, mean area-weighted runoff ratio (defined as runoff depth divided by rainfall depth), mean time to peak (calculated as $\text{Time}_{\text{peak of streamflow event}} - \text{Time}_{\text{start of streamflow event}}$), and mean duration. We used Spearman's ρ correlations because of potential non-linearity in the relationships of interest and its resistance to outliers. All metrics were also correlated with watershed area and rainfall depth. To address any error in the process of event identification and pairing, we chose to eliminate any events with runoff ratios greater than five from further analysis. It is important to acknowledge that six of our study watersheds are nested within larger watersheds, an effect that has not been factored into our analysis here.

Streamflow events were also partitioned into bins based on rainfall intensity to explore possible trends or relationships in the data when partitioned this way. Because multiple rain gauges were associated with each stream gauge, we chose to use the rain gauge with the largest Thiessen polygon covering a watershed for analysis by rainfall intensity. In most cases, the single rain gauge used was missing only a small number of 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 event, we chose to use the rain event with the highest maximum 60-minute 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 chose to use bins of 60-minute maximum intensity ≤ 2 mm/hr, > 2 ≤ 5 mm/hr, > 5 ≤ 9 mm/hr, and > 9 mm/hr. Correlations of metrics with maximum intensities of 5-, 10-, 15-, 30-, and 60-minutes suggested 60-minute intensity had the strongest correlation with most metrics.

We applied methods presented in previous studies to determine threshold precipitation intensity producing a streamflow response in each of our watersheds (Wilson et al., 2018). In previous studies, 60-minute rainfall intensities have been found to be most predictive for streamflow responses (Kampf et al., 2018). Again using the rain gauge with the Thiessen polygon with greatest area, we first calculated the precipitation intensity that maximized the number of streamflow events and non-events correctly predicted using the following formula from Wilson et al. (2018):

$$F = \frac{TP+TN}{P} \tag{1}$$

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.

We evaluated the strength of agreement between our observed responses and predicted responses based on the precipitation threshold using the kappa statistic, K (Viera & Garrett, 2005):

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

Where p_o is the maximized fraction of true positives and negatives, F, calculated in equation (1). The expected chance agreement, p_e, is calculated as follows:

$$p_e = R_o{*}R_e + NR_o{*}NR_e \tag{3}$$

where R_o is the fraction of rain events producing an observed streamflow response, R_e is the fraction of events producing a response expected based on the threshold 60-minute 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).

CHAPTER 3—RESULTS

West Stroh Gulch

No streamflow was seen at our monitoring location in West Stroh Gulch over the one year period of our study. Forty-three precipitation events were recorded from June 7, 2020 to May 27, 2021. The maximum depth rain event occurred on 05/02/2021 and continued into 05/03/2021 with a recorded depth of 30 mm. A light dusting of snow can be seen part-way through the event but melts quickly, creating no ponding or runoff. The highest maximum 60-minute intensity event we observed was 5 mm/hr. Higher intensity events were recorded. However, photos of these events were not taken due to issues with the camera that occurred on these dates.

Analysis by Rainfall Depth

Watersheds with greater percent imperviousness exhibited fewer measurements of zero flow, where percent zero flow considered the entire period of analysis (i.e., not just storm periods) (Figure 9). Spearman's ρ correlation indicated a strong negative relationship between zero flow and percent imperviousness, although the relationship between zero flow and drainage area was also negative and had a stronger correlation (Table 2) (Figure A2, in appendix). Zero flow decreased with imperviousness for watersheds with <10% imperviousness whereas watersheds above 10% imperviousness nearly always had flow. Watersheds with greater imperviousness produced a higher number of streamflow responses to rain events (Figure 10). Strong positive correlations between number of events and percent imperviousness were evident in all event categories. Number of events also correlated positively with drainage area.

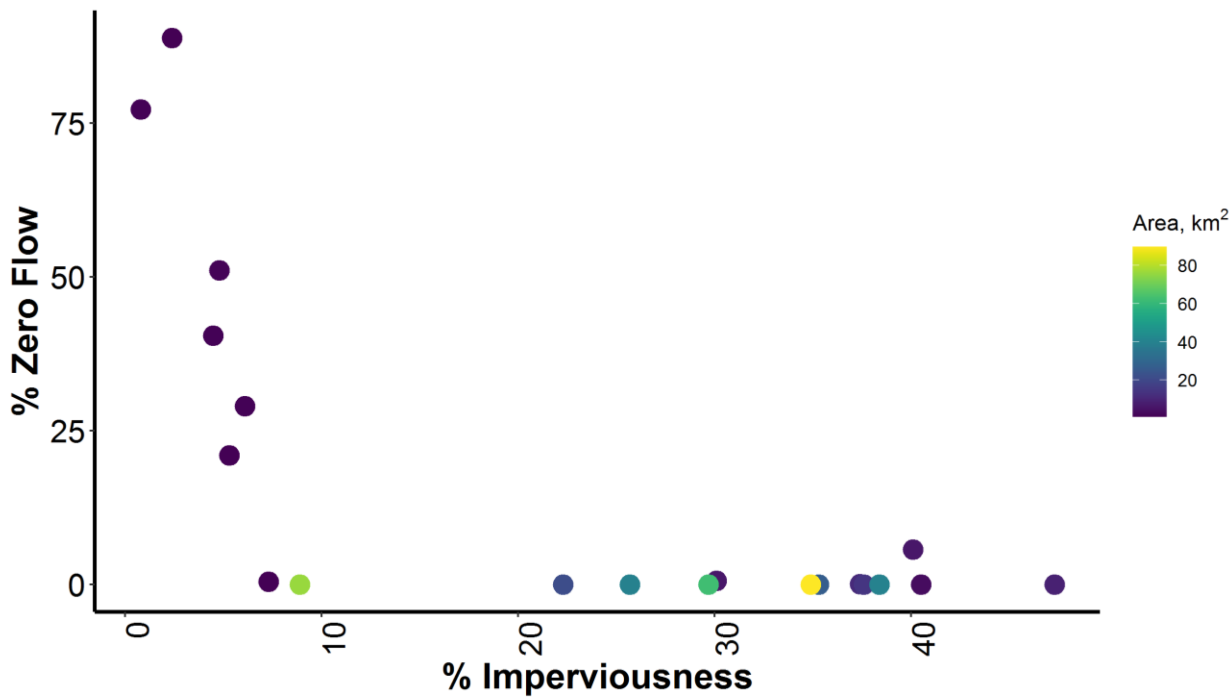

Figure 9. Percent zero flow plotted against imperviousness with points color-coded based on watershed area (km^2).

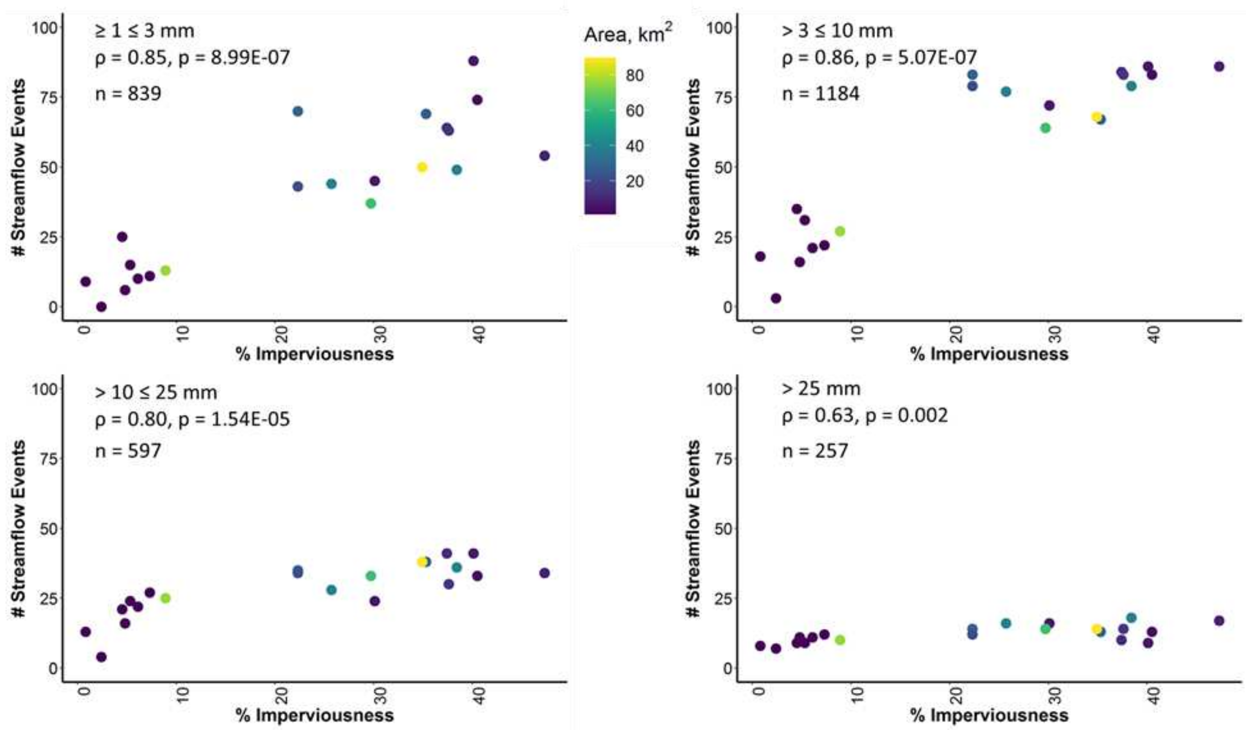

Figure 10. Number of streamflow events plotted against imperviousness and binned by rainfall event depth. Points are color-coded by watershed area (km^2). The number of rainfall events decreases as depth increases, as larger storms occur with less frequency.

Table 2. Spearman's ρ correlation results for each metric and binned by rainfall event depth. Correlations with p ≤ 0.05 are indicated in red, and p ≤ 0.10 are blue.

		All events			
Zero flow vs. Imperviousness	Spearman's ρ	-0.683			
	p-value	0.001			
Zero flow vs. Area	Spearman's ρ	-0.819			
	p-value	5.90E-06			
	Rainfall bins	**≥ 1 ≤ 3 mm**	**> 3 ≤ 10 mm**	**> 10 ≤ 25 mm**	**> 25 mm**
Number streamflow events vs. Imperviousness	Spearman's ρ	0.853	0.862	0.797	0.626
	p-value	8.99E-07	5.07E-07	1.54E-05	0.002
Number events vs. Area	Spearman's ρ	0.448	0.420	0.607	0.606
	p-value	0.043	0.058	0.003	0.004
Mean area-normalized peak flow vs. Imperviousness	Spearman's ρ	0.680	0.650	0.803	0.346
	p-value	0.001	0.001	1.18E-05	0.124
Mean area-normalized peak flow vs. Area	Spearman's ρ	-0.149	-0.130	0.106	-0.403
	p-value	0.530	0.573	0.645	0.071
Area-normalized peak flow vs. Precipitation depth	Spearman's ρ	0.087	0.178	0.016	0.283
	p-value	0.012	6.56E-10	0.702	4.20E-06
Mean area-normalized runoff vs. Imperviousness	Spearman's ρ	0.453	0.265	0.507	-0.196
	p-value	0.045	0.245	0.019	0.398
Mean area-normalized runoff vs. Area	Spearman's ρ	-0.200	-0.253	-0.088	-0.557
	p-value	0.396	0.267	0.703	0.010
Area-normalized runoff vs. Precipitation depth	Spearman's ρ	0.231	0.341	0.263	0.507
	p-value	1.19E-11	< 2.2e-16	6.91E-11	< 2.2e-16
Mean runoff ratio vs. Imperviousness	Spearman's ρ	0.489	0.271	0.616	0.199
	p-value	0.029	0.234	0.003	0.387
Mean runoff ratio vs. Area	Spearman's ρ	-0.114	-0.127	-0.004	-0.357
	p-value	0.631	0.581	0.989	0.113
Runoff ratio vs. Precipitation depth	Spearman's ρ	-0.040	0.018	0.005	0.080
	p-value	0.251	0.535	0.900	0.203
Mean time to peak vs. Imperviousness	Spearman's ρ	-0.326	-0.100	-0.104	-0.038
	p-value	0.163	0.668	0.656	0.874
Mean time to peak vs. Area	Spearman's ρ	0.134	0.397	0.339	0.453
	p-value	0.573	0.075	0.133	0.040
Time to peak vs. Precipitation depth	Spearman's ρ	0.181	0.079	0.135	0.203
	p-value	1.40E-07	0.007	0.001	0.001
Mean duration vs. Imperviousness	Spearman's ρ	-0.621	-0.603	-0.626	-0.631
	p-value	0.004	0.004	0.002	0.002
Mean duration vs. Area	Spearman's ρ	0.117	0.086	0.077	0.073
	p-value	0.621	0.711	0.741	0.754
Duration vs. Precipitation depth	Spearman's ρ	0.214	0.268	0.313	0.393
	p-value	3.64E-10	< 2.2e-16	5.43E-15	6.43E-11

There were 2,877 total events identified, with 14-224 in each watershed (Table 3). A total of 839 streamflow events occurred in response to rain events of ≥ 1 ≤ 3 mm depth (Bin 1), 1,184 streamflow events occurred in response to rain events of > 3 ≤ 10 mm depth (Bin 2), 597 streamflow events occurred in response to rain events > 10 ≤ 25 mm depth (Bin 3), and 257 streamflow events occurred in response to rain events > 25 mm depth (Bin 4). To present these events, we show boxplots for each watershed, grouped by rainfall bin and metric. Mean area- normalized peak flow increased significantly with imperviousness, with the relationship weakening in the largest event category (ρ = 0.346, p = 0.124) (Figure 11). No significant relationship between area-normalized peak flow and area was noted. Area-normalized peak flow significantly increased with precipitation depth in all the bins except the > 10 ≤ 25 mm bin.

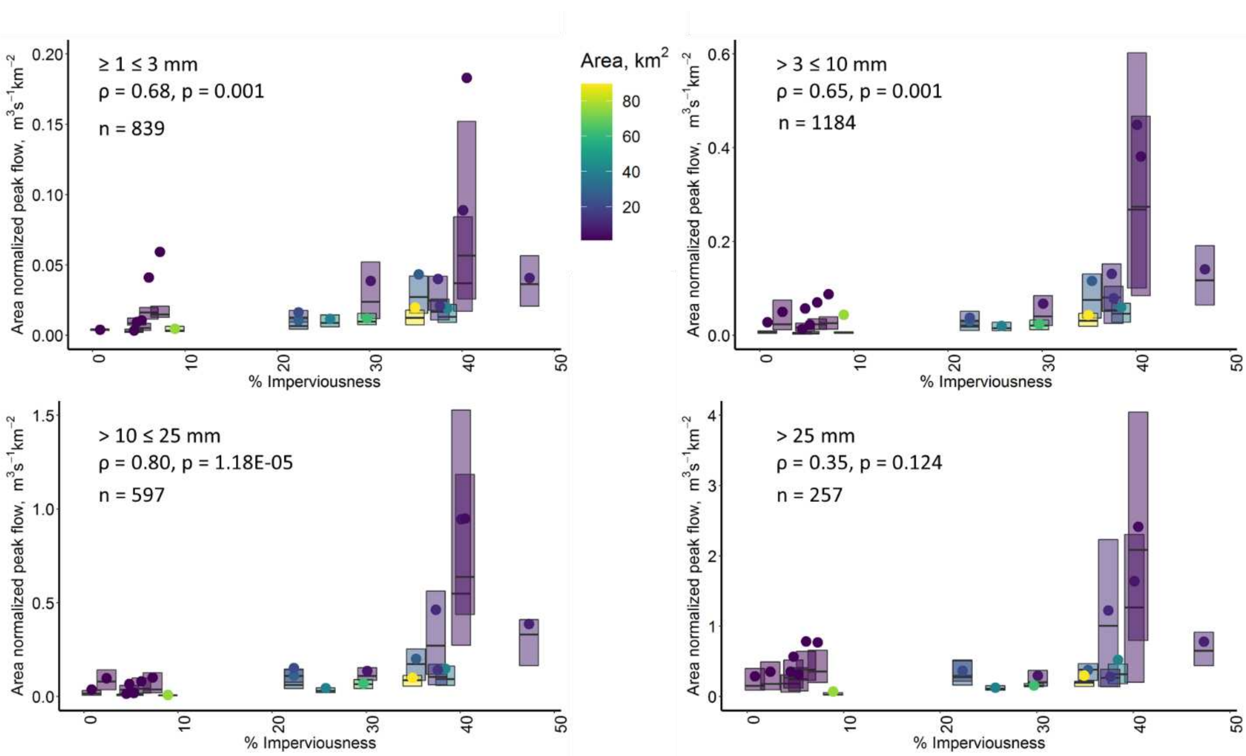

Figure 11. Area-normalized peak flow vs. percent imperviousness, where the spread in each watershed is shown by a boxplot (first quartile, median, and third quartile; whiskers and outliers have been removed for simplicity) and the mean (point). Boxes and points are colored by watershed area. Note that the peak flow scale increases with precipitation class.

Table 3. Number of streamflow responses to rain events which occurred in each watershed during the period of study 06/07/2013—09/30/2020, binned by precipitation depth.

			Precipitation Depth Bins (mm) Bin 1: ≥ 1 ≤ 3, Bin 2: > 3 ≤ 10, Bin 3: > 10 ≤ 25, Bin 4: > 25				
Station Name	% Imp	Drainage area (km^2)	# Events Bin 1	# Events Bin 2	# Events Bin 3	# Events Bin 4	Total Events All Bins
Dry Gulch	47.3	8.63	54	86	34	17	191
Little Dry Creek Arapahoe	40.5	3.3	74	83	33	13	203
Harvard Gulch CO Blvd	40.1	5.84	88	86	41	9	224
Lakewood Gulch	38.4	40.18	49	79	36	18	182
Weir Gulch	37.6	14.35	63	83	30	14	190
Harvard Gulch Harvard Park	37.4	11.18	64	84	41	10	199
Little Dry Creek Westminster	35.3	26.86	69	67	38	13	187
Toll Gate Creek	34.9	89.61	50	68	38	14	170
Lee Gulch Littleton	30.1	6.03	45	72	24	16	157
Little Dry Creek Englewood	29.7	62.4	37	64	33	14	148
Dutch Creek	25.7	39.55	44	77	28	16	165
Big Dry Creek C-470	22.3	28.84	70	83	35	14	202
Lena Gulch	22.3	21.17	43	79	34	12	168
First Creek Bel Buckley	8.9	76.06	13	27	25	10	75
SW093	7.3	0.83	11	22	27	12	72
GS13	6.1	1	10	21	22	11	64
GS10	5.3	0.87	15	31	24	9	79
GS12	4.8	1.41	6	16	16	11	49
B5INFLOW	4.5	1.13	25	35	21	9	90
SW027	2.4	0.73	0	3	4	7	14
GS33	0.8	1.16	9	18	13	8	48

Depth of runoff (mean, area-normalized) exhibited a significant positive correlation with imperviousness in Bins 1 and 3, but not 2 and 4 (Figure 12). Only the > 25 mm events demonstrated a significant negative correlation between mean area-normalized runoff and area. No relationship was demonstrated in the other three bins. A positive relationship between area-normalized runoff and precipitation depth was evident in all categories. A similar pattern was seen in correlations between mean runoff ratio vs. imperviousness, with Bins 1 and 3 showing a positive correlation with imperviousness, but not Bins 2 and 4 (Figure 13). No relationship between mean runoff ratio and area was seen in all bins. Runoff ratio and precipitation depth showed no correlation in any bin.

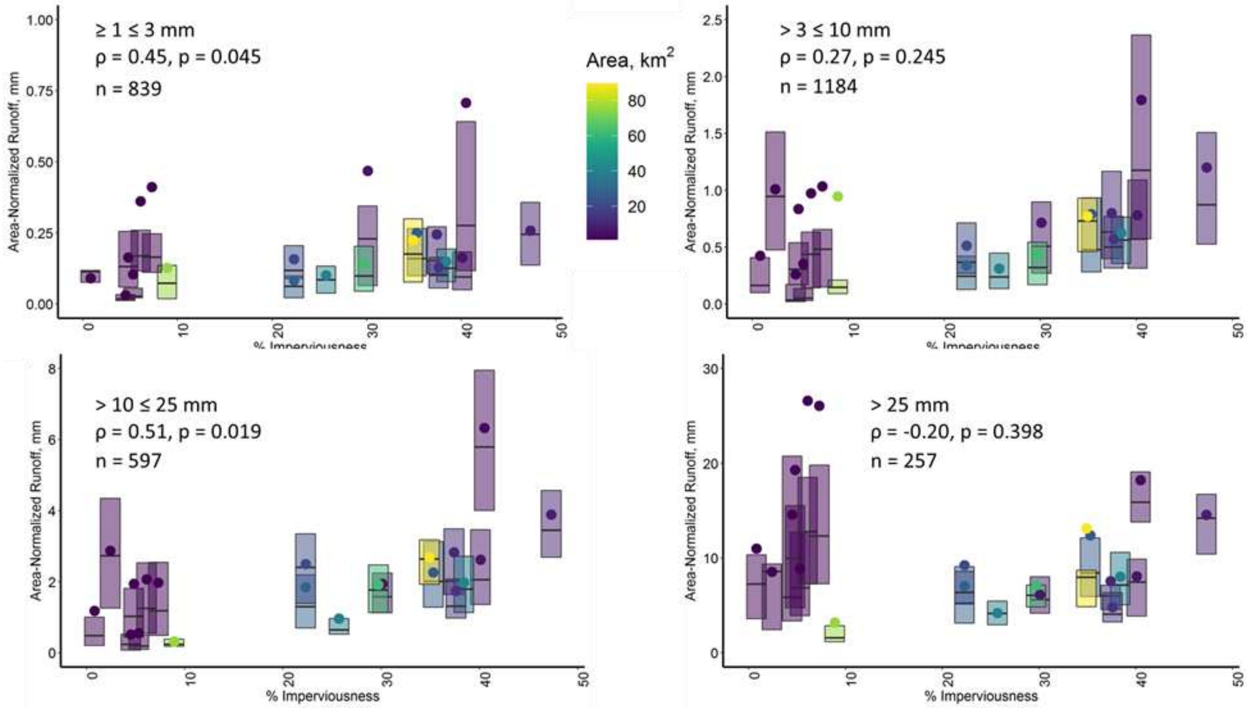

Figure 12. Boxplots showing area-normalized runoff vs. % imperviousness and color-coded by drainage area. Whiskers and outliers have been removed for simplicity. Points represent means. Note that the runoff scale increases with precipitation class.

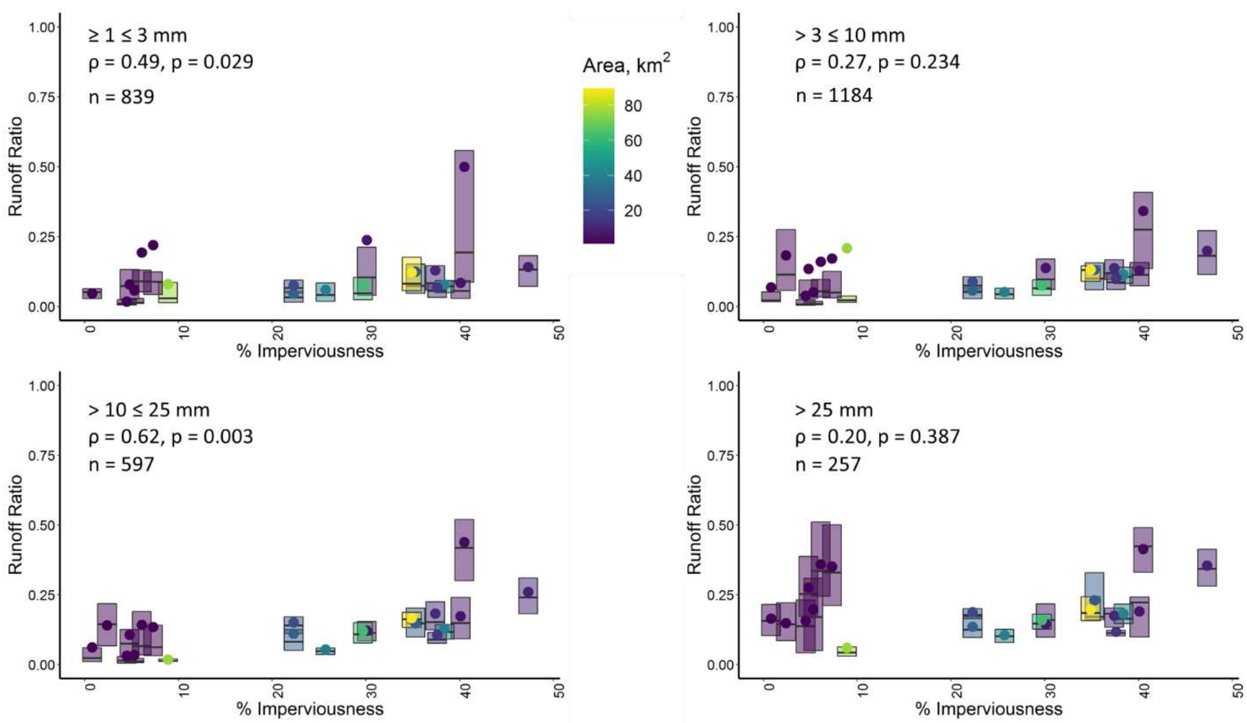

Figure 13. Boxplots of runoff ratio vs. % imperviousness. Whiskers and outliers have been removed for simplicity. Points represent means. Here, all graphs are plotted on the same scale.

No significant correlations were observed between mean time to peak and imperviousness (Figure 14). Time to peak showed a positive correlation with drainage area in Bin 4 (ρ = 0.453, p = 0.040), but not the other bins. A positive correlation was observed with precipitation depth across all bins. This indicates that smaller rainfall events produced more flashy runoff events, whereas larger, longer-duration rainfall events produced longer runoff events, including the time to peak runoff. Interactions between impervious areas and run-on to pervious areas within the study watersheds were not analyzed, but the lack of correlation with imperviousness may be due to such internal hydrologic interactions. Spatial connectivity of impervious areas (not quantified) should affect watershed responses. Significant negative correlations were observed between mean duration and imperviousness (Figure 15). No significant relationship between mean duration and area was seen. Duration and precipitation depth were positively correlated in all bins.

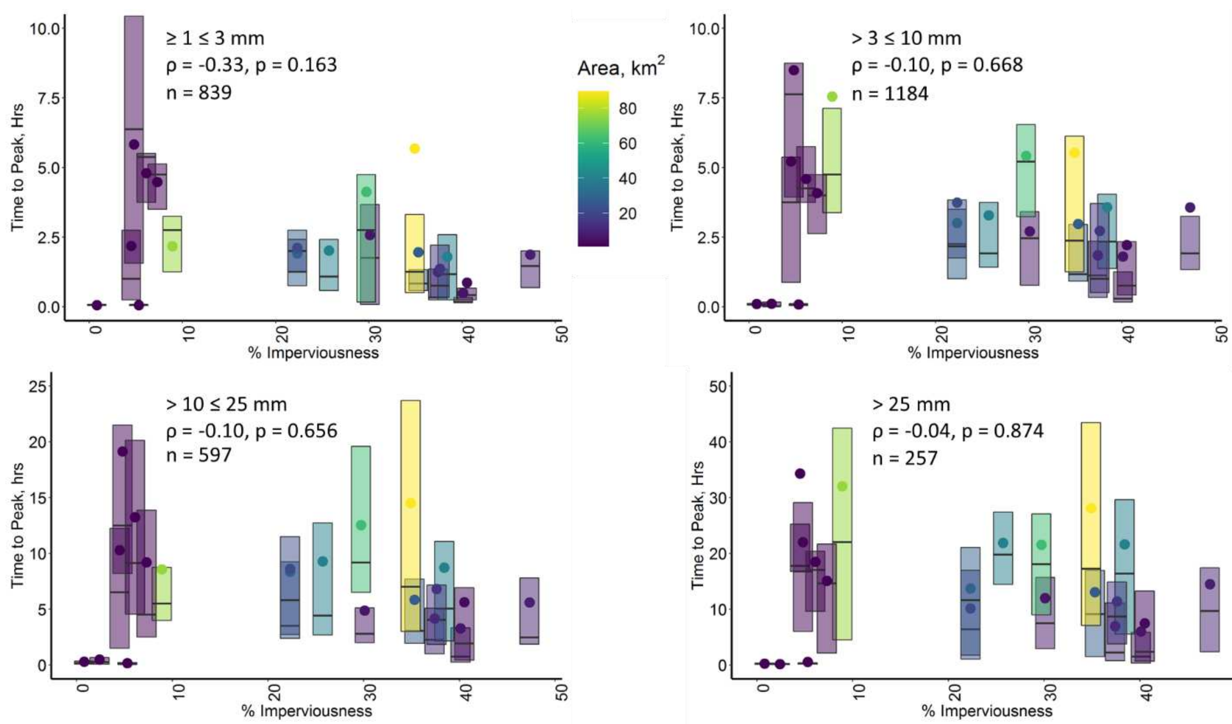

Figure 14. Time to peak vs. % imperviousness color-coded for watershed area. Whiskers and outliers have been removed for simplicity. Points represent means. Note the different scales used for time to peak.

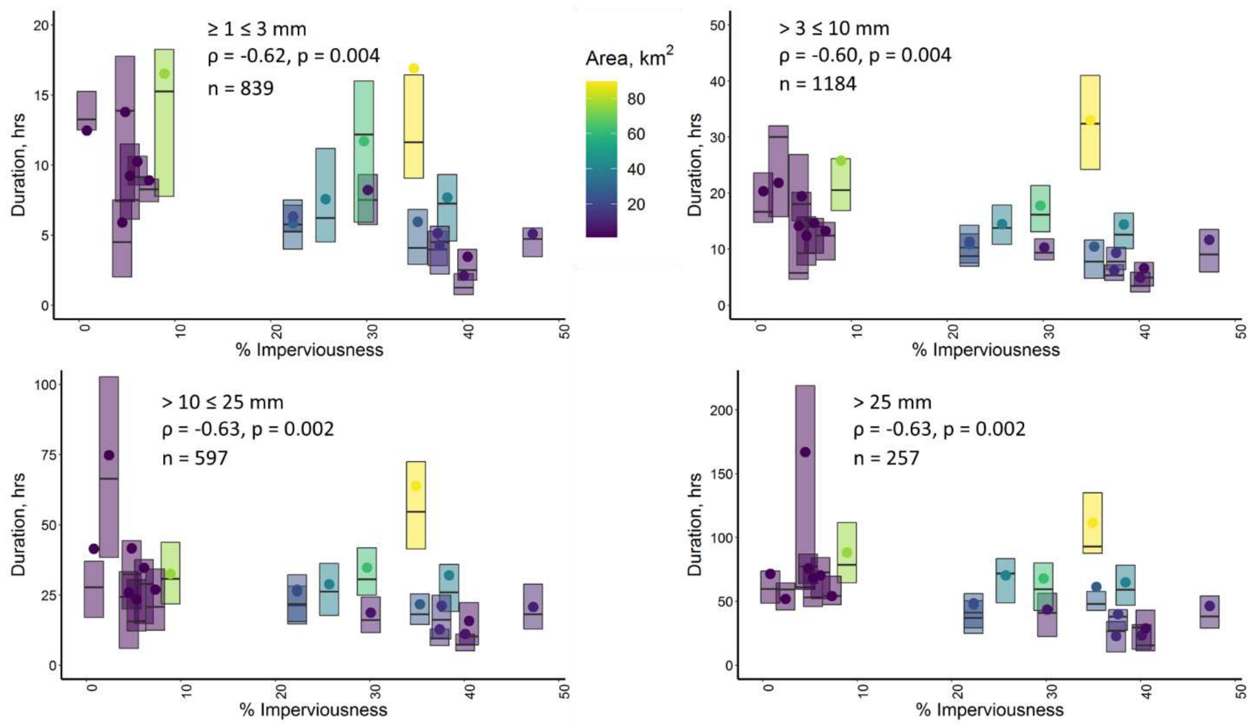

Figure 15. Duration of streamflow response to rain vs. % imperviousness color-coded for watershed area. Whiskers and outliers have been removed for simplicity. Points represent means. Note duration scale increases with precipitation class.

Analysis by Rainfall Intensity

When binned by 60-minute maximum precipitation intensity, 1103 streamflow events occurred in response to rain events with intensity of ≤ 2 mm/hr (Bin 1), 901 streamflow events occurred in response to rain events with intensity of > 2 ≤ 5 mm/hr (Bin 2), 443 streamflow events occurred in response to rain events with intensity of > 5 ≤ 9 mm/hr (Bin 3), and 385 streamflow events occurred in response to rain events with intensity of > 9 mm/hr (Bin 4) (Table A1). Number of events correlated positively with imperviousness in all bins (Figure A3) (Table A2). A positive correlation was seen between number of events and area in all bins, although Bin 2 was not significant (p = 0.075).

Mean area-normalized peak flow correlated positively with imperviousness in Bin 3. Bins 1, 2 and 4 also exhibited a positive relationship, but it was not significant (p = 0.116, p = 0.083, and p = 0.082, respectively) (Figure A4). In all four bins, mean area-normalized peak flow showed a negative relationship with area, but was only significant in Bin 2. Area-normalized peak flow was positively correlated with precipitation intensity in all bins. There was no significant relationship between mean area-normalized runoff and imperviousness (Figure A5). Runoff showed a negative correlation with area in all bins; however, only Bins 2 and 4 were significant. There was a positive correlation between runoff and intensity in all categories, although Bin 3 was not significant ($p = 0.119$). Runoff ratio exhibited a positive correlation with imperviousness in Bins 3 and 4, but Bins 1 and 2 were insignificant (Figure A6). There was no correlation shown between runoff ratio and area. Runoff ratio showed a positive correlation with intensity in Bins 2 and 4 and no correlation in Bins 1 and 3. There was no correlation between time to peak and imperviousness (Figure A7). A positive correlation was seen between time to peak and area in all bins, although Bin 2 was not significant ($p = 0.120$). There was a positive correlation between time to peak and precipitation intensity in Bin 1, but no correlation in Bins 1, 3 and 4. Duration showed a negative correlation with imperviousness in all bins (Figure A8). There was no correlation between duration and drainage area. Duration was positively correlated with rainfall intensity in Bins 1, 2, and 4, but not Bin 3.

In general, binning data by precipitation intensity did not yield stronger correlations with imperviousness than binning by precipitation depth. One exception is runoff ratio and imperviousness. When binned by precipitation depth, Bins 1 and 3 showed significant positive correlations. When binned by intensity, the correlation strengthened with greater intensity, and significant positive correlations were observed in Bins 3 and 4. 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 events, runoff ratio, and duration were mostly consistent. Correlations between peak flow and intensity were significant in all bins, while Bin 3 of peak flow vs. depth was not. Runoff and precipitation depth were positively correlated in all bins, while runoff vs. intensity was positively correlated only 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 with intensity in Bin 1. Duration and rainfall depth were positively correlated in all bins, while duration and intensity were positively correlated in Bins 1, 2, and 4. Figures and tables of results using data compiled by rainfall intensity may be found in the appendix (Tables A1-A2, Figures A3-A8).

Precipitation Threshold Analysis

Precipitation thresholds calculated using the maximum 60-minute intensity and the maximized fraction are indicated in Table 4. There was a strong negative correlation between thresholds and imperviousness (Figure 16) (Table 5). Precipitation threshold and drainage area also demonstrated a negative correlation. However, the kappa statistic for roughly half the calculated thresholds is below a reasonable confidence interval (0.41) (Table 4). The kappa statistic itself demonstrated a positive correlation with imperviousness. The kappa statistic also tends to be less reliable with fewer number of observations (Viera & Garrett, 2005). We found a positive correlation between kappa and number of streamflow events ($\rho = 0.59$, $p = 0.005$).

Table 4. Results of precipitation threshold analysis using the maximum 60-minute intensity (mm/hr).

Station Name	% Imp	Drainage Area (km^2)	Maximum 60-minute intensity (mm/hr)	Maximized fraction, F	Kappa, K
Dry Gulch	47.3	8.63	1	0.82	0.57
Little Dry Creek Arapahoe	40.5	3.3	1	0.71	0.34
Harvard Gulch CO Blvd	40.1	5.84	1	0.69	0.30
Lakewood Gulch	38.4	40.18	1	0.83	0.56
Weir Gulch	37.6	14.35	1	0.77	0.49
Harvard Gulch Harvard Park	37.4	11.18	1	0.77	0.51
Little Dry Creek Westminster	35.3	26.86	1	0.78	0.57
Toll Gate	34.9	89.61	1	0.75	0.40
Lee Gulch Littleton	30.1	6.03	2	0.79	0.54
Little Dry Creek Englewood	29.7	62.4	1	0.68	0.35
Dutch Creek	25.7	39.55	1	0.71	0.39
Big Dry Creek C-470	22.3	28.84	1	0.78	0.47
Lena Gulch	22.3	21.17	1	0.73	0.44
First Creek Bel Buckley	8.9	76.06	36	0.82	0.02
SW093	7.3	0.83	4	0.82	0.50
GS13	6.1	1	6	0.83	0.45
GS10	5.3	0.87	6	0.78	0.31
GS12	4.8	1.41	7	0.82	0.33
B5INFLOW	4.5	1.13	4	0.74	0.33
SW027	2.4	0.73	16	0.94	0.20
GS33	0.8	1.16	23	0.85	0.06

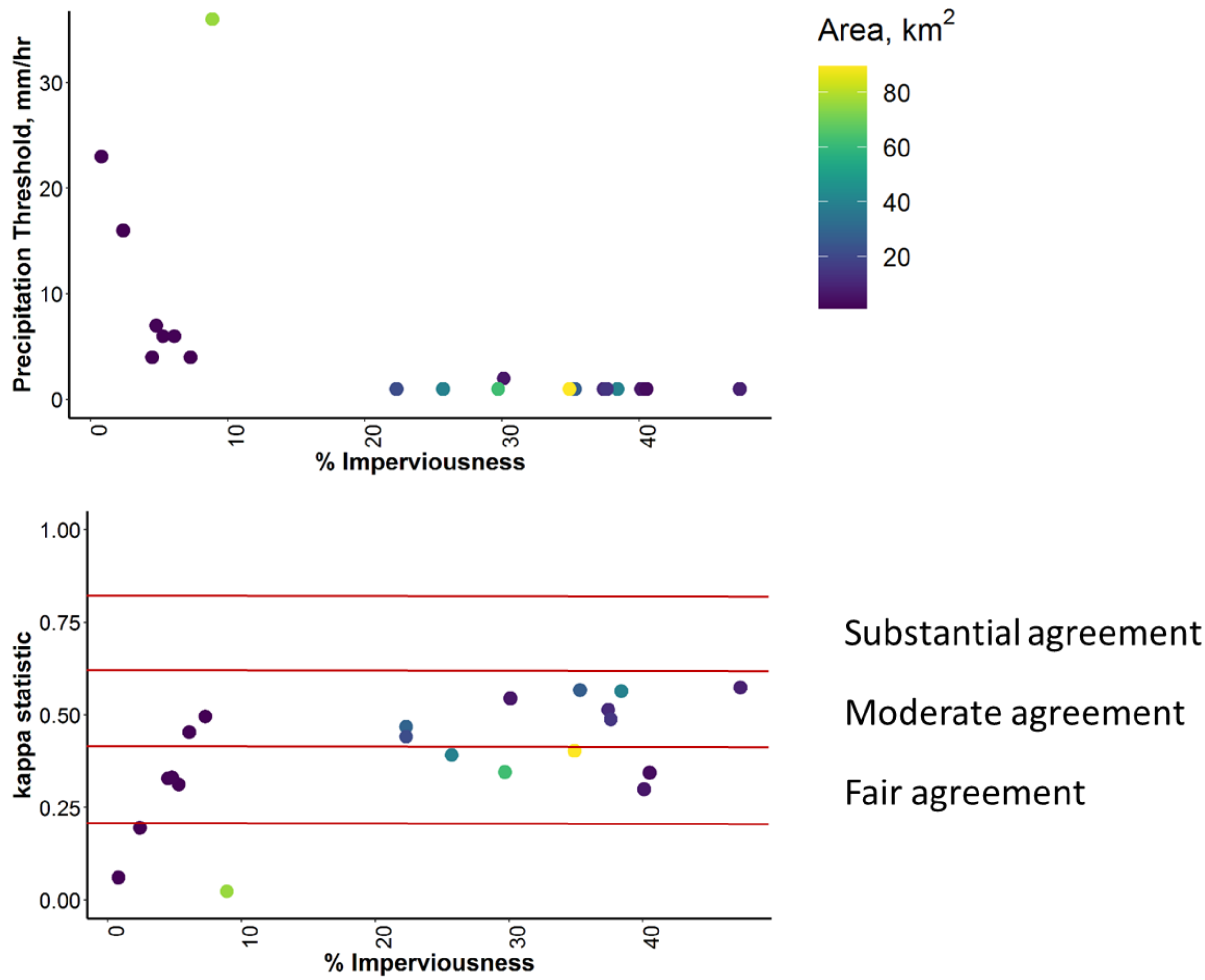

Figure 16. Precipitation threshold vs. % imperviousness (left), color-coded by watershed area. Kappa statistic vs. % imperviousness (right), color-coded by watershed area, with agreement classes indicated (Viera & Garrett, 2005).

Table 5. Correlation results of precipitation threshold analysis.

	Spearman's ρ	p-value
Precipitation threshold vs. Imperviousness	-0.81	7.64E-06
Precipitation threshold vs. Area	-0.55	0.009
Kappa vs. imperviousness	0.57	0.008
Kappa vs. number of events	0.59	0.005

CHAPTER 4—DISCUSSION

Key Findings

Our study included a large number of watersheds covering a wide range of imperviousness (0.8 – 47.3%) with 8 years of instantaneous streamflow data. The "urban stream syndrome" can manifest itself differently in different climate and geologic settings. Our analysis of Denver watersheds across a gradient of imperviousness revealed hydrologic changes specific to this semi-arid environment. Our results are similar to studies conducted in arid environments that found not all metrics conformed to the typically understood urban response of increases in flashiness. Here we discuss key findings and the relationship to previous work for changes to (1) zero flow, (2) number of streamflow events and precipitation thresholds, (3) peak flow, (4) total runoff and runoff ratio, and (5) time to peak streamflow and streamflow duration.

Zero Flow

The frequency of zero flow decreased significantly with urbanization, particularly in watersheds of less than 10% imperviousness. In our study watersheds, there appears to be a threshold of approximately 8% imperviousness above which perennial flow occurs at most stream gauges. Two possible explanations are increases to baseflow due to irrigation and leaking pipes, and increased occurrence of runoff in response to rain events. Zero flow has been previously found in an arid environment to decrease with increasing imperviousness, while number of events exceeding a moderate flow threshold increased and those exceeding a higher threshold did not (McPhillips et al., 2019). These results closely mirror our findings regarding zero flow and increasing number of streamflow events.

Frequency of streamflow events and precipitation intensity threshold to generate streamflow response

We found urbanization to increase the number of streamflow events in a watershed significantly in all size events looking at both depth and intensity (Figure 10 and A3). As more impervious surfaces replace permeable surfaces, opportunities for depression storage and infiltration decrease, impervious surfaces are often directly connected to streams, and runoff is more likely to occur, even for smaller events.

Threshold analysis results are consistent with the pattern that the number of streamflow events increased with imperviousness. We found that as imperviousness increased in our study watersheds, the intensity of rainfall needed to produce a streamflow response decreased (Figure 16). The least impervious of the Denver study watersheds (GS33, % impervious surface cover = 0.8) has an estimated 60-minute precipitation threshold of 23 mm/hr (Table 5).

Area-normalized peak flow

We found magnitude of flow (measured as mean area-normalized peak flow) to increase with imperviousness (Figure 11), with a weaker relationship in the streamflow responses to larger rain events. A California case study 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). We found a significant positive correlation between peak flow and precipitation intensity in all intensity bins and precipitation depth in Bins 1, 2, and 4. We found that watershed area was somewhat important for area-normalized peak flow (although only when binning by rain intensity, Table A2), but in most cases correlations with imperviousness were stronger (Figure A4).

Total runoff and runoff ratio

Results looking at runoff and runoff ratio were mixed. When looking at events binned by precipitation depth, we found both runoff and runoff ratio to increase with imperviousness in Bins 1 and 3, but not 2 and 4. The increase in runoff in smaller events suggests runoff is generated with increasing efficiency in more impervious watersheds in these sized storms, where opportunities for depression storage and infiltration are fewer. The lack of correlation observed in Bin 2 may reflect the effectiveness of stormwater control measures in capturing and slowing the release of runoff in rainfall events of 3-10 mm depth. Streamflow events binned by rainfall intensity did not demonstrate a significant relationship between total runoff and imperviousness. However, runoff ratio and imperviousness showed an increasingly positive and significant relationship with increasing rainfall intensity. These results suggest that as rainfall intensity increases, the amount of impervious surface in the watershed has a greater influence on the proportion of runoff generated from rainfall.

We were not able to capture a runoff event in West Stroh Gulch that might test these hypotheses, as our monitoring period encompassed only one year. It may be that current stormwater control strategies have been largely successful at reducing overall volume of runoff and attenuating flashiness. Most impervious surfaces lack the roughness and variability of undeveloped landscapes that slow flow and increase travel time to channels. In addition, stormwater systems have traditionally been designed to convey stormwater quickly and efficiently away from urban environments to receiving streams (*"Urban Stormwater Management in the United States" at NAP.Edu*, n.d.). This finding along with the peak flow results suggests that the runoff being generated in these storms, while possibly not of greater quantity, is being delivered to receiving streams more efficiently in urban settings. The lack of a clear pattern in the runoff results suggests that complex processes are involved that further analysis may help to discern.

Time to peak streamflow and streamflow event duration

Metrics indicative of timing also gave mixed results. Time to peak was not influenced by urbanization in our study. However, duration of streamflow decreased with increasing imperviousness, suggesting more efficient removal of stormwater in urbanized watersheds than in less developed ones. Time to peak would be more sensitive to complex hydrographs with multiple peaks than would streamflow duration, which may explain the differing responses observed. Exploration of the potential impact of stormwater control measures on urban hydrologic response was outside the purview of this study, but is likely a highly influential factor. McPhillips et al. (2019) found rise and fall rates (mm hr^{-1} d^{-1}) decreased with imperviousness. A study in Tucson, AZ of five watersheds ranging from 22 – 90% imperviousness found that streamflow duration and frequency of runoff increased with urbanization, while time to peak and total runoff did not (Gallo et al., 2013). These are the same patterns we found in our analysis of time to peak, while our results for total runoff were mixed. This is opposite of our finding of the effect of imperviousness on duration of flow, however, where our results indicated duration decreases with imperviousness. Overall, this supports the concept of regional or climate-specific patterns in changes to storm hydrographs with urban development.

Limitations and Future Work

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 km^2), First Creek Bel Buckley (8.9% impervious surface cover; 76 km^2), and the ongoing flow monitoring in West Stroh Gulch (0.06% impervious surface cover; 1.0 km^2). The watersheds in Rocky Flats currently have low impervious surface cover, but the soils are expected to be still 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. There are no historically monitored small, grassland watersheds in the Denver area that are available for comparison of the effect of this legacy on the hydrologic response in Rocky Flats, other than the ongoing monitoring in West Stroh Gulch. While our use of correlations is an appropriate first step in analyzing the data generated in this study, other statistical methods may be used to account for nested watersheds and the interactions of multiple variables likely affecting the hydrologic responses seen in our study watersheds. Other areas for improvement for future study are a longer study period for capturing a broader range of events (many of our study stream gauges were installed in 2013), analysis of the stormwater control measures and other landscape characteristics such as soil properties and directly-connected imperviousness across the twelve municipalities that our study areas fell into, and further evaluation of the parameters and application of the semi-automated method for event identification (Hopkins et al., 2020).

CHAPTER 5—CONCLUSIONS

Flashier hydrographs are an assumed consequence of urbanization in most watersheds, but how rangelands, both developed and undeveloped, respond to rain events has not been clearly understood. Our study demonstrated the following characteristics of semi-arid watersheds, from undeveloped rangelands through highly impervious urban watersheds:

- Twenty-four hour monitoring of an undeveloped rangeland for one year did not produce any flow events, suggesting grasslands in the Denver area require rain events in excess of the largest rain events observed (30 mm depth or 5 mm/hour intensity) to generate a channelized flow response in ephemeral stream networks. In comparison, urban streams responded to rain events with 60-minute intensities of 1.0 mm/hour.
- Our analysis of event-based elements of the hydrograph paired with rain events over an 8-year study period of 21 watersheds indicates that urbanization in this semi-arid region increases magnitudes of peak flow and decreases duration of flow (Table 2).
- The 60-minute precipitation intensity required to produce a streamflow response decreases with urbanization, resulting in more streamflow events occurring in watersheds with more impervious surface (Tables 2 and 4).
- Urbanization clearly increases the responsiveness of these watersheds to even small rain events, producing a greater number of streamflow responses (Figure 10), increasing peak streamflow (Figure 11), and decreasing duration (Figure 15). We did not find volume of runoff or time to peak to change significantly with imperviousness.

Despite the widespread use of stormwater control measures, urbanized watersheds in semi-arid Denver remain more hydraulically efficient (higher peak flow, shorter duration of storm responses) than their less developed counterparts. Our work suggests the design of new stormwater systems should focus on slowing the delivery of runoff and widening the hydrograph, encouraging infiltration and improving capture of small-moderate sized events.

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APPENDIX

Figures Illustrating Challenge of Automated Event ID

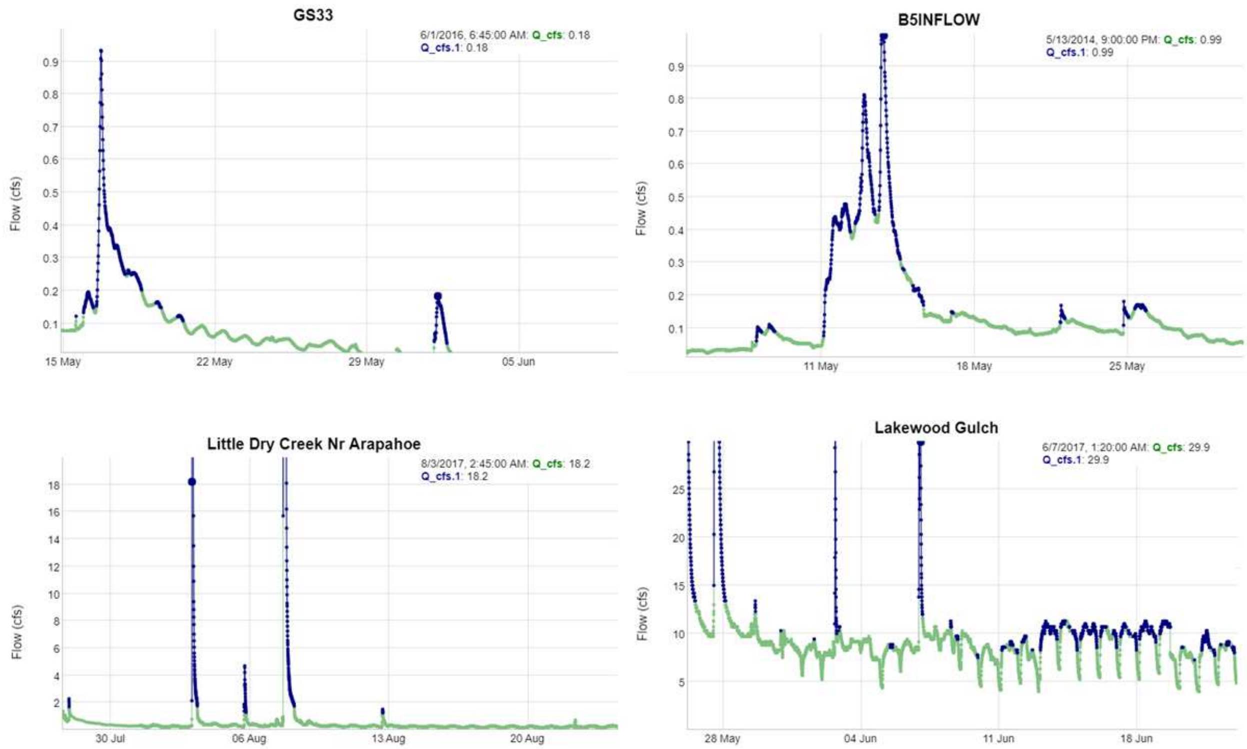

Figure A1. Output hydrographs from automated event ID in R software. Note the different scales on the y-axes.

Figures and Tables for Analysis of Zero Flow

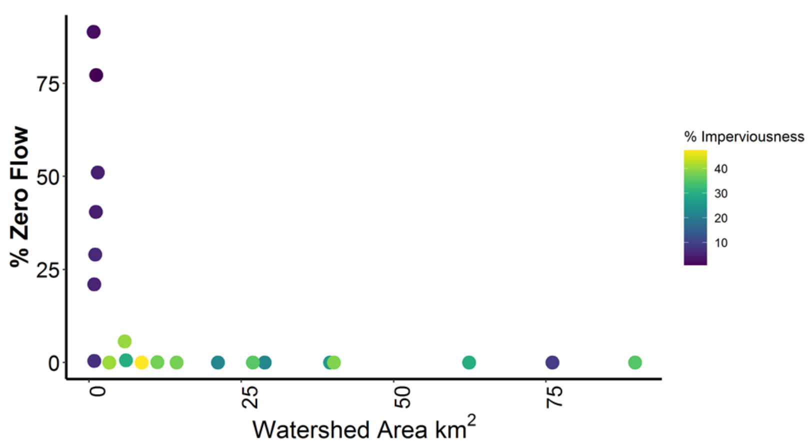

Figure A2. Percent zero flow plotted against watershed area.

Figures and Tables for Analysis by Rainfall Intensity

Table A1. Number of streamflow responses to rain events which occurred in each watershed during the period of study 06/07/2013—09/30/2020, binned by 60-minute maximum precipitation intensity.

			Precipitation Intensity Bins (mm/hr) Bin 1: ≤ 2, Bin 2: > 2 ≤ 5, Bin 3: > 5 ≤ 9, Bin 4: > 9				
Station Name	% Imp	Drainage Area (km^2)	# Events Bin 1	# Events Bin 2	# Events Bin 3	# Events Bin 4	Total Events All Bins
Dry Gulch	47.3	8.63	60	68	28	34	190
Little Dry Creek Arapahoe	40.5	3.3	102	61	23	17	203
Harvard Gulch CO Blvd	40.1	5.84	111	73	35	21	240
Lakewood Gulch	38.4	40.18	61	69	28	34	192
Weir Gulch	37.6	14.35	73	50	34	17	174
Harvard Gulch Harvard Park	37.4	11.18	75	72	34	22	203
Little Dry Creek Westminster	35.3	26.86	97	52	29	25	203
Toll Gate Creek	34.9	89.61	55	42	23	28	148
Lee Gulch Littleton	30.1	6.03	58	55	25	17	155
Little Dry Creek Englewood	29.7	62.4	62	45	18	14	139
Dutch Creek	25.7	39.55	71	54	26	18	169
Big Dry Creek C-470	22.3	28.84	89	64	24	20	197
Lena Gulch	22.3	21.17	56	59	22	16	153
First Creek Bel Buckley	8.9	76.06	18	15	14	19	66
SW093	7.3	0.83	17	22	13	17	69
GS13	6.1	1	15	19	15	14	63
GS10	5.3	0.87	28	25	12	13	78
GS12	4.8	1.41	15	14	11	12	52
B5INFLOW	4.5	1.13	32	24	13	14	83
SW027	2.4	0.73	2	5	4	3	14
GS33	0.8	1.16	9	13	12	10	44

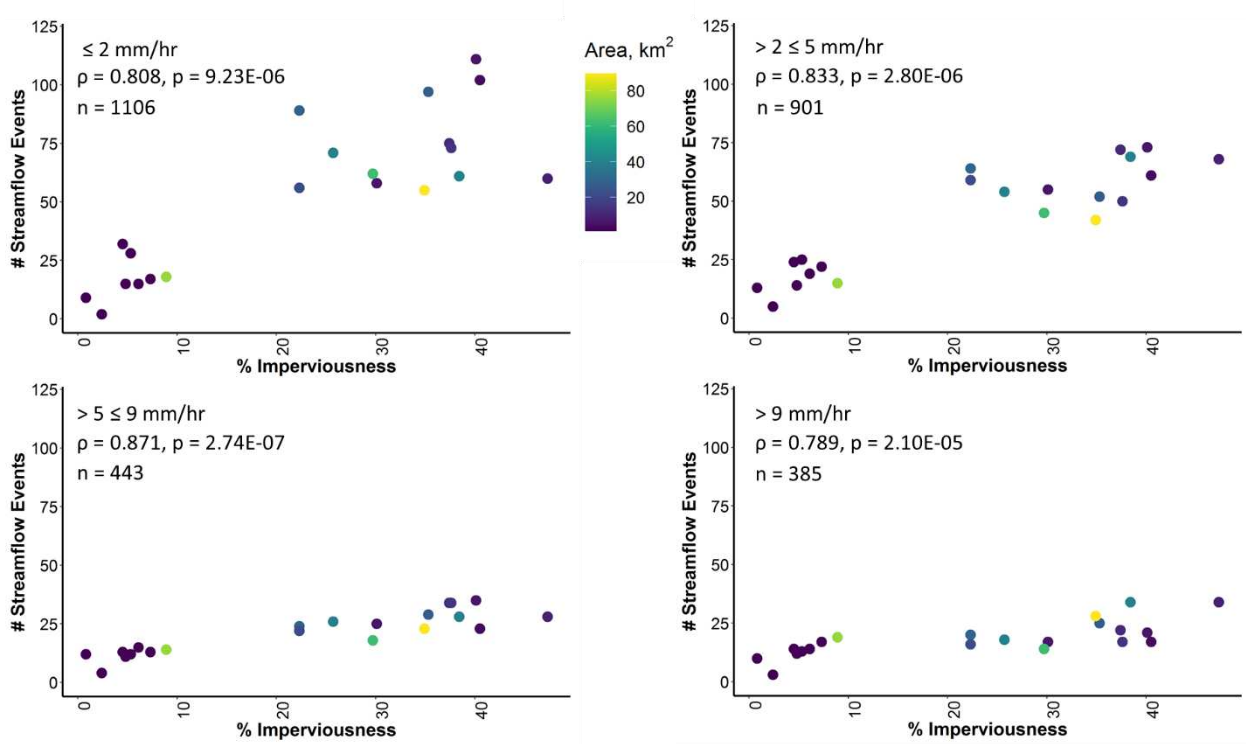

Figure A3. Number of streamflow events plotted against imperviousness and binned by rainfall event maximum 60-minute intensity. Points are color-coded by watershed area (km^2).

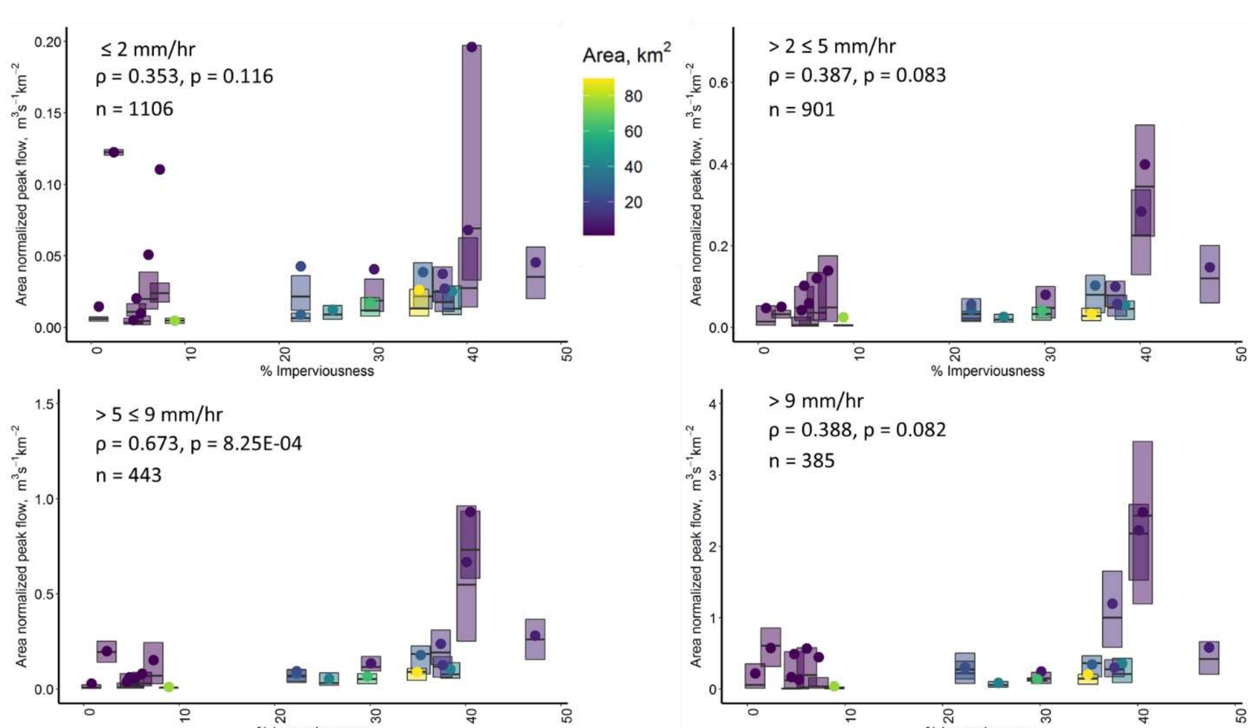

Figure A4. Area-normalized peak flow vs. percent imperviousness, where the spread in each watershed is shown by a boxplot (first quartile, median, and third quartile; whiskers and outliers have been removed for simplicity) and the mean (point). Boxes and points are colored by watershed area.

Table A2. Spearman's ρ correlation results for each metric and binned by rainfall event maximum 60-minute intensity. Correlations with $p \leq 0.05$ are indicated in red, and $p \leq 0.10$ are blue.

	Rainfall bins	**≤ 2 mm/hr**	**> 2 ≤ 5 mm/hr**	**> 5 ≤ 9 mm/hr**	**> 9 mm/hr**
Number Events vs. Imperviousness	Spearman's ρ	0.808	0.833	0.871	0.789
	p-value	9.23E-06	2.80E-06	2.74E-07	2.10E-05
Number Events vs. Area	Spearman's ρ	0.470	0.397	0.505	0.632
	p-value	0.032	0.075	0.019	0.002
Mean area-normalized peak flow vs. Imperviousness	Spearman's ρ	0.353	0.387	0.673	0.388
	p-value	0.116	0.083	8.25E-04	0.082
Mean area-normalized peak flow vs. Area	Spearman's ρ	-0.396	-0.509	-0.144	-0.384
	p-value	0.077	0.020	0.532	0.086
Area-normalized peak flow vs. Precipitation intensity	Spearman's ρ	0.119	0.228	0.101	0.354
	p-value	7.40E-05	3.98E-12	0.033	8.53E-13
Mean area-normalized runoff vs. Imperviousness	Spearman's ρ	-0.005	-0.348	0.301	-0.230
	p-value	0.987	0.124	0.185	0.318
Mean area-normalized runoff vs. Area	Spearman's ρ	-0.352	-0.753	-0.192	-0.597
	p-value	0.118	1.24E-04	0.402	0.005
Area-normalized runoff vs. Precipitation intensity	Spearman's ρ	0.228	0.297	0.074	0.367
	p-value	1.88E-14	< 2.2e-16	0.119	1.09E-13
Mean runoff ratio vs. Imperviousness	Spearman's ρ	0.182	0.314	0.531	0.547
	p-value	0.429	0.165	0.013	0.010
Mean runoff ratio vs. Area	Spearman's ρ	-0.300	-0.245	-0.155	0.004
	p-value	0.186	0.282	0.502	0.989
Runoff ratio vs. Precipitation intensity	Spearman's ρ	-0.006	0.132	-0.006	0.218
	p-value	0.852	6.63E-05	0.892	1.64E-05
Mean time to peak vs. Imperviousness	Spearman's ρ	0.012	-0.123	0.042	0.037
	p-value	0.956	0.598	0.856	0.871
Mean time to peak vs. Area	Spearman's ρ	0.512	0.351	0.469	0.557
	p-value	0.019	0.120	0.033	0.010
Time to peak vs. Precipitation intensity	Spearman's ρ	0.107	0.027	-0.037	-0.053
	p-value	3.85E-04	0.423	0.440	0.298
Mean duration vs. Imperviousness	Spearman's ρ	-0.702	-0.807	-0.586	-0.648
	p-value	4.07E-04	1.02E-05	0.005	0.002
Mean duration vs. Area	Spearman's ρ	-0.103	-0.243	0.016	0.099
	p-value	0.657	0.288	0.948	0.670
Duration vs. Precipitation intensity	Spearman's ρ	0.171	0.201	0.023	0.139
	p-value	1.12E-08	1.22E-09	0.635	0.006

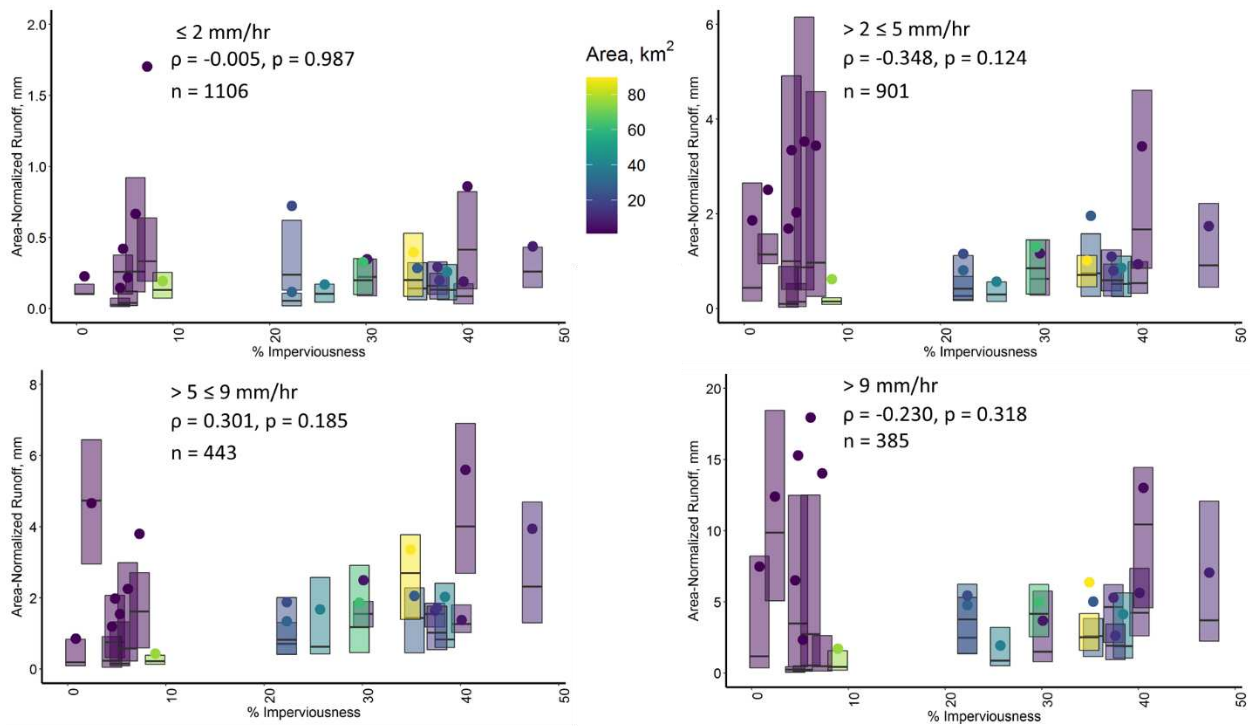

Figure A5. Boxplots showing area-normalized runoff vs. % imperviousness and color-coded by drainage area. Whiskers and outliers have been removed for simplicity. Points represent means.

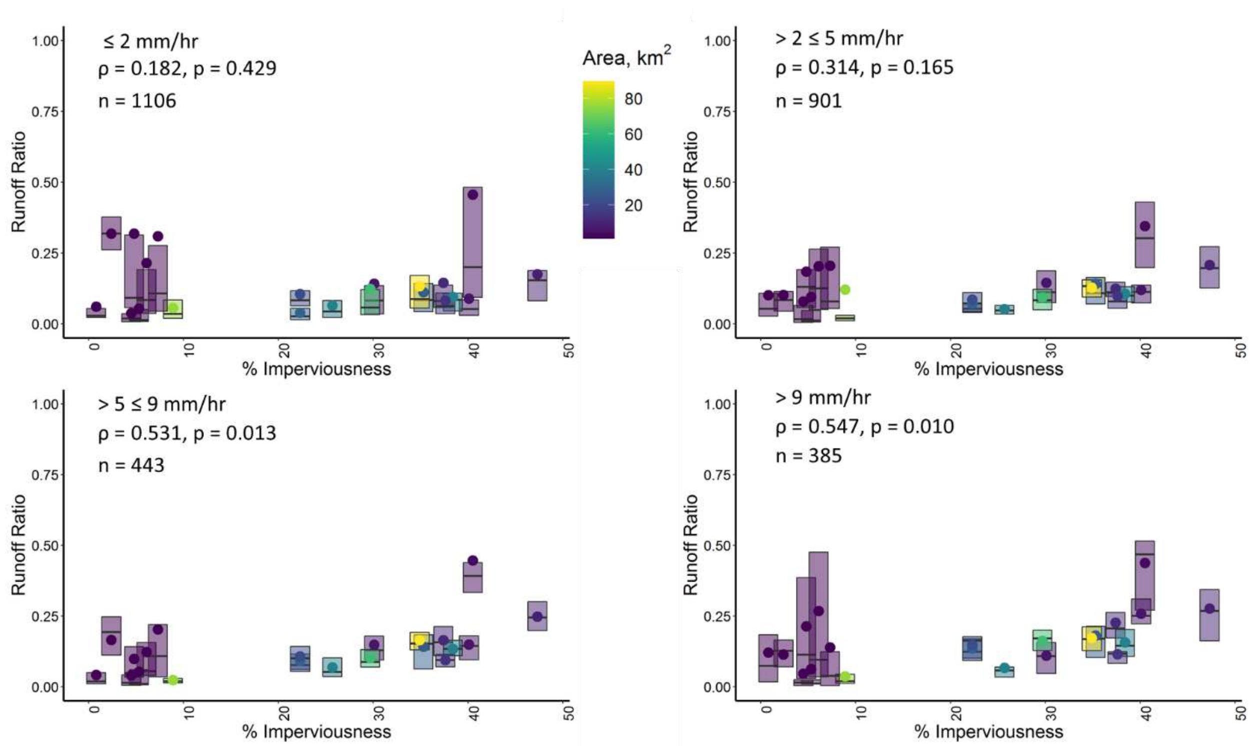

Figure A6. Boxplots of runoff ratio vs. % imperviousness. Whiskers and outliers have been removed for simplicity. Points represent means.

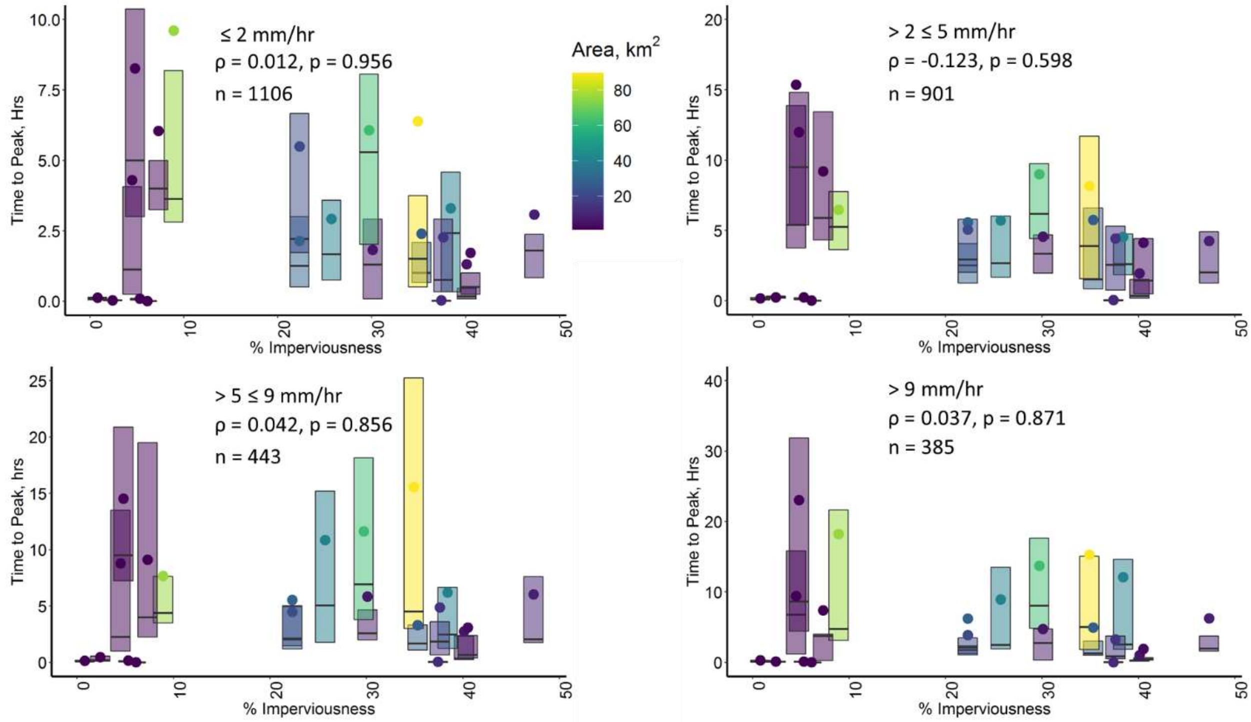

Figure A7. Time to peak vs. % imperviousness color-coded for watershed area. Whiskers and outliers have been removed for simplicity. Points represent means.

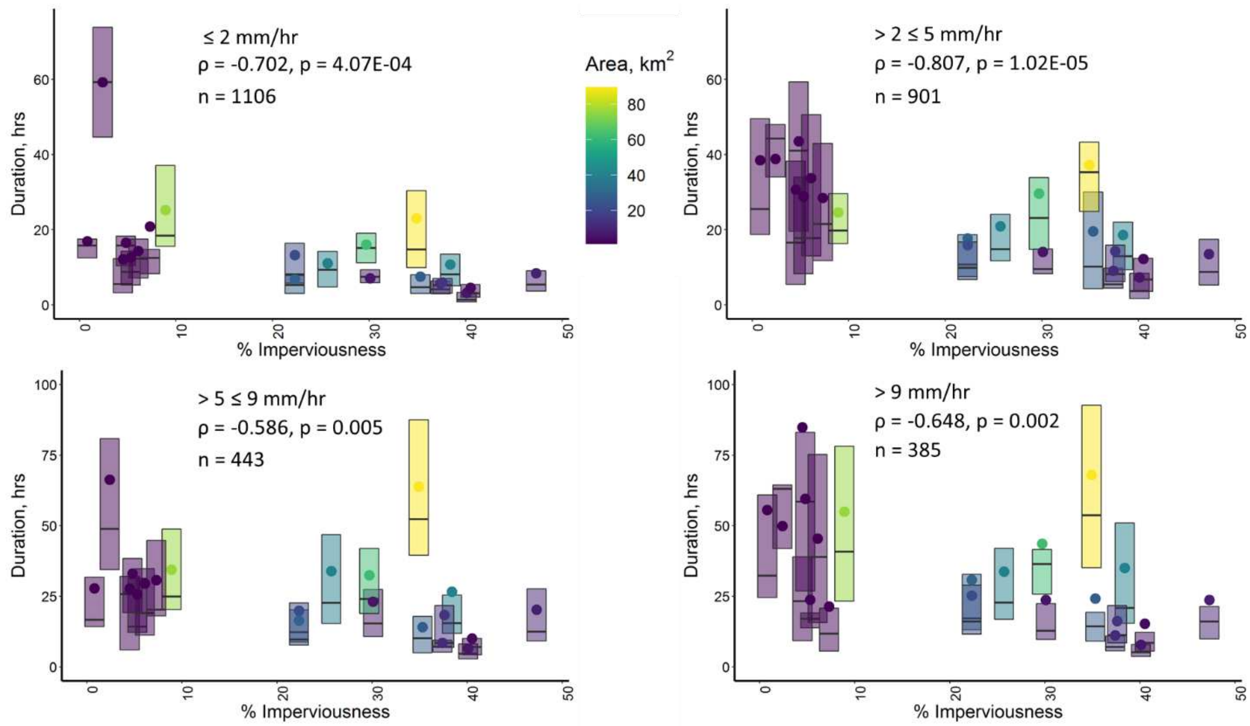

Figure A8. Duration of streamflow response to rain vs. % imperviousness color-coded for watershed area. Whiskers and outliers have been removed for simplicity. Points represent means.