THESIS

NON-PERENNIAL STREAMFLOW & GEOMORPHIC PATTERNS IN A SEMI-ARID RANGELAND SLATED FOR DEVELOPMENT

Submitted by

Dixie L. Poteet

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2023

Master's Committee:

Advisor: Aditi Bhaskar
Co-Advisor: Ryan Morrison

Stephanie Kampf
Neil Grigg

ABSTRACT

NON-PERENNIAL STREAMFLOW & GEOMORPHIC PATTERNS IN A SEMI-ARID RANGELAND SLATED FOR DEVELOPMENT

Urbanization has widely recognizable impacts on stream morphology and flow patterns. Predicting and quantifying these impacts can be difficult, especially for non-perennial streams in semi-arid rangelands. Non-perennial streams tend to lack long-term stream measurements to provide historical baseline records of streamflow presence and absence. A historical pre-development baseline allows for determining how urbanization affects these streams, information that can inform development and infrastructure decisions. This project focuses on a non-perennial stream channel in West Stroh Gulch, located in Parker, Colorado south of Denver, U.S.A. This historically semi-arid rangeland area is slated to undergo housing development in the next few years, providing a unique opportunity to establish a historical baseline for a non-perennial stream that will be impacted by urban development. Streamflow presence and absence was recorded at multiple locations along the stream network with time-lapse photography. Photo observations and precipitation data were reviewed to determine which storm events did, or did not, trigger a flow response. After over two years of stream channel monitoring, one precipitation event with a total depth of 92-mm and maximum 60-minute intensity of 50-mm per hour triggered streamflow. Additionally, a hydrodynamic model was developed in SRH-2D to compare the impacts of predicted flows through a reach of interest. Topographic pre-development data and Storm Water

Management Model (SWMM) generated peak flows were used to simulate impacts of different sized storms. Peak flows varied both by storm and development scenario: existing undeveloped, traditional centralized post-development detention, and post-development distributed detention. Boundary shear stresses were used to compare the different simulations. Overall, the pre-development existing scenario had the lowest flows shear stresses for the two smallest storm scenarios (water quality capture volume and 2-year storms). For the 5-, 10-, 50-, and 100-year storms, the proposed post-development scenarios that incorporated distributed detention had the lowest flows and shear stresses. The traditional centralized detention post-development stormwater strategy had the highest flows, shear stresses, velocities, and water depths for all storm sizes. The simulation results indicate that the post-development distributed detention strategy will be more effective at reducing stream channel stresses and erosion for larger storm events than the more traditional post-development centralized detention strategy.

ACKNOWLEDGEMENTS

Acknowledgements begin with Dr. Aditi Bhaskar, my advisor and the incredible mentor who brought me on to this project. Her oversight and encouragement were constant touchstones throughout this journey. My thanks to Dr. Ryan Morrison, my co-advisor, for guiding me through the hydrogeomorphology side of this project and the learning curve that came with hydraulic modeling. Gratitude to Dr. Stephanie Kampf for being a member of my committee and first introducing me to Dr. Bhaskar years ago. Thank you also to Dr. Neil Grigg for serving on my thesis committee and providing valuable insights. I would also like to extend my gratitude to the many team members who supported this project including: Stacy Wilson and Chris Olson at Wright Water Engineers, Sara Johnson, Katy Shaneyfelt and Jim Wulliman from Muller Engineering, Brik Zivkovich at Mile High Flood District, and Michael Grabczyk with City of Parker. Thank you to the following for their expertise and assistance in building a hydraulic model: Danny White, Jack Derbique, Nicholas Christensen, Santiago Ramirez, and Cameron Turnbow. I especially want to acknowledge the support and assistance of Dr. Peter Nelson in providing access to technological resources. Many thanks also to the following for their assistance with the many field trips: Amber Boyle, Danielle Lewis, Liam Milton, Samuel Carles-Pedroza, and Eric Sanchez.

My family and numerous friends formed a valuable support network throughout my time on this project. Their belief in my ability to carry through provided much needed support through the dry spells and at the end of long weeks.

This material is based on work supported in part by the National Science Foundation under Award Number 2115169.

TABLE OF CONTENTS

1. INTRODUCTION

Water is an important resource continually subjected to various pressures, including the hydrogeomorphic impacts of urbanization. Just as the existing climate and environment makes every watershed unique, the challenges each watershed faces can vary greatly depending on a combination of factors including natural water scarcity, water allocation, increasing population demands, and landscape urban and rural development patterns. In addition to physical and environmental factors that shape each watershed, watershed management can be unique to the specific socio-economic, institutional, and legislative situation that comes with the area (Booth et al. 2016). Recent stormwater management techniques have begun to focus on incorporating nature-based green infrastructure solutions to mitigate and treat stormwater runoff (Turner et al. 2022). While sustainable-focused stormwater control measures are being implemented more widely, there are not many studies monitoring the effects of these measures on suburban and urban watersheds (Hopkins et al. 2020). Stormwater management control measures may not be able to preserve a watershed's pre-development state. Instead, stormwater management practices tend to mitigate the urban development's effects and reduce resulting negative impacts when compared to what is usually observed in traditional development plans (Jefferson et al. 2017).

1.1 Urbanization & Stream Impacts

Urbanization transforms the landscape and changes the dynamic interactions between water and land within a watershed. Tracking the changes in these dynamic interactions is challenging but essential to effectively managing the health and supply across watersheds. Major water inputs and outputs in water balances are continually affected by changes to topography, land use, and land management within the watershed (Baffaut et al. 2020). Urban and suburban areas that have been “people modified” or anthropologically affected require particular considerations unique to each watershed. Water supply can be piped in, combustion and urban heat contribute to daily heat fluxes, and the mechanisms driving infiltration, runoff, and evapotranspiration change (Grimmond and Oke 1986). For example, tap water sources such as lawn and landscape irrigation have recently been shown to contribute to increases in urban baseflow in the Denver area (Fillo et al. 2021). Consistent stream impacts following urbanization has become recognizable enough to result in the term, “urban stream syndrome” (Walsh et al. 2005). Urban stream syndrome is a term used in reference to the commonly observed symptoms of streams being impacted by development efforts (Meyer et al. 2005; Walsh et al. 2005). These symptoms include increased overland flows, higher erosive flows, flashier hydrographs, decreased channel complexity (channelization), and higher sediment loads (Walsh et al. 2005).

Despite the recognizable effects urbanization has on existing streams, urbanization’s impacts are not always well-documented. Documenting the effectiveness of management strategies for protecting stream ecosystems requires coordination and cooperation efforts between multiple partners spanning multiple years or even decades (Hopkins et al. 2022). Stream flow monitoring has been carried out for many decades since the 1800s in the United States by the USGS (Eberts et al. 2019). Historically, stream flow monitoring efforts have focused on perennial bodies of water that continuously flow year-round (Jaeger et al. 2021). Establishing a historical baseline and recording how a stream channel is impacted over time allows for better understanding of how urban development activities are tied to watershed impacts.

Drier regions with historically non-perennial streams often lack complete records on streamflow presence or absence. Non-perennial streams are typically dry most of the year and only have streamflow presence in response to larger precipitation events or wet periods of the year. When a watershed in a semi-arid region undergoes urbanization, the increase in impermeable surfaces and lawn irrigation sources facilitates an increase in runoff into the stream channel (Fillo et al. 2021). Due to this, a stream channel that once ran dry for most days of the year in a pre-development setting becomes more likely to have streamflow presence more frequently post-development.

Quantifying stream impacts over time in developing landscapes is problematic for stream channels lacking a historical pre-development baseline for comparison. Additionally, a growing number of case studies indicate that urbanization and resulting urban stream syndrome symptoms differ greatly from watershed to watershed (Booth et al. 2016). The uniqueness of the impacts of urbanization highlights the need to continually monitor existing stream channels within watersheds throughout the stages of development.

1.1.1 A Need for Sustained Streamflow Monitoring in Semi-Arid Regions

Persistent and consistent stream flow monitoring is needed to track the unique responses of watersheds undergoing the stages of urbanization in semi-arid regions. Hydrologic responses to urbanization tend to vary more in semi-arid regions than regions with historically perennial streams. Differences in hydrologic responses in semi-arid regions begin to be apparent between watersheds before development even begins.

A study compared hydrologic responses to rainfall simulations for several shortgrass prairie sites (Weltz et al. 2000). Sites grouped by soil type did have similar patterns for rising limb slopes in the runoff hydrographs and time-to-peak. Using measurable factors such as vegetation cover was not found to be effective for predicting hydrologic function across sites. While hydrologically similar patterns were found for sites grouped by soil type, a general pattern for equilibrium runoff that applied to all the sites was not found.

Another study demonstrated the difficulty of modeling hydrologic responses by examining rangeland and grassland sites across the western United States (Pierson et al. 2002). Quantifiable factors such as soil type and vegetation state are known to impact infiltration and erosion. Despite the known link, the interactions between landscape characteristics are complex enough to result in hydrologic responses unique to each watershed. This results in a general algorithm or model being unable to perform well in predicting hydrologic responses across different rangeland sites.

Diversity among hydrologic responses continues to be observable for semi-arid watersheds subject to urban development. A study examining watersheds in Arizona found that increased levels of urbanization did not necessarily lead to increased hydrograph flashiness (McPhillips et al. 2019). Instead, observations indicated increased days with flow and decreased flow variability and decreased rise and fall rates, or ‘flashiness’ for the examined desert streams. A recent study of urbanized watersheds in the Denver area found that the watersheds clearly exhibited some, but not all, of the expected urban stream syndrome responses (Wilson et al. 2022). Patterns of changed runoff volume, runoff ratio, and time to peak were not clearly exhibited across the urbanized watersheds examined in this study. Confirmed trends in these urbanized watersheds included greater peak flow magnitudes and an increased number of streamflow triggering precipitation events. Precipitation threshold and days with no streamflow presence had a pattern of decreasing as imperviousness increased. Consistent streamflow monitoring spanning pre-development to post-development is needed to better capture patterns and compare how semi-arid watersheds change in response to urbanization.

1.1.2 Urbanization Effects on Stream Channelization & Sediment Loads

Urban impacts can include incised channels where increased runoff concentrates (Bledsoe et al. 2002). Faster flow velocities and increased shear stresses in urban streams exacerbate channel erosion. These mechanisms (increased runoff, concentrated runoff, faster flow velocities, increased shear stresses) drive the increased sediment loads associated with urban stream syndrome. Increases in impervious area due to urbanization have been linked to increased channel instability for decades (Bledsoe and Watson 2001). Over time, incised channel morphology can alter enough through bed and bank erosion to lead to channel instability and bank failure (Bledsoe et al. 2002).

Understanding how to mitigate sediment loads is a focus of many sustainable efforts including stream restoration (Earles et al. 2020). Increased sediment loads have a negative impact on water quality, especially for downstream receiving waters. This is of particular concern along Colorado's Front Range where phosphorous containing sediments can result in eutrophication in lakes and reservoirs. Strategies for mitigating the increased drivers on sediment loading following stream urbanization emphasize stream restoration when needed and natural stream preservation where possible.

2. PROJECT

2.1 West Stroh Gulch

This research focuses on a non-perennial stream within West Stroh Gulch, a 1.5 km^2 semi-arid rangeland undergoing housing development. West Stroh Gulch is located in Parker, a municipality south of Denver, Colorado U.S.A. that receives approximately 500 mm of annual precipitation. Historically, West Stroh Gulch has been utilized as a rangeland with a non-perennial stream network. Development plans for West Stroh Gulch incorporate stream based best management practices (BMPs), green infrastructure (GI), and low impact development strategies (LID). These practices include Distributed Full Spectrum Detention (DFSD) ponds and preserving the natural stream channel network when possible in the development design process (Earles et al. 2018). West Stroh Gulch is a unique opportunity to monitor impacts to streamflow patterns for a non-perennial stream channel in a historically semi-arid rangeland slated for housing development.

2.2 Project Objectives

This study had two primary objectives. The first objective was to monitor stream channel responses to precipitation events to establish a pre-development baseline of streamflow presence. Streamflow monitoring efforts began with a field camera installation in June 2020 by S. Wilson and A. Bhaskar (then Colorado State University) in partnership with the Mile High Flood District, Town of Parker, Wright Water Engineers, and Muller Engineering (Wilson 2021). Expanding on this work, additional field game cameras were installed along the semi-arid rangeland stream channel network to establish a pre-development baseline of streamflow presence. Precipitation data was analyzed and reviewed with time-lapse observations to investigate the relationship between streamflow presence and absence to storm event intensity and storm event duration.

The second objective was to model predictions of how the existing stream channel would be impacted by flow changes in response to watershed urbanization. Impacts of development on stream channel hydrology and sediment transport were assessed by combining stormwater management model (SWMM) generated post-development flows with a hydrodynamic model. Based on a soils test and field work, sediment was assumed to be comprised of mostly medium-sized sand particles. Boundary shear stress values calculated from the hydrodynamic model were compared to the assumed critical shear stress for medium sand.

3. METHODOLOGY

3.1 Time-Lapse Photography

SpyPoint Link-S-Dark field cameras were deployed to record spot observations of streamflow presence and absence along the stream network. Five total cameras were deployed, with one deployed in June 2020, two deployed in December 2021, and two more cameras deployed in April 2022. Camera locations are shown in Figure 1 with installation dates in Table 1.

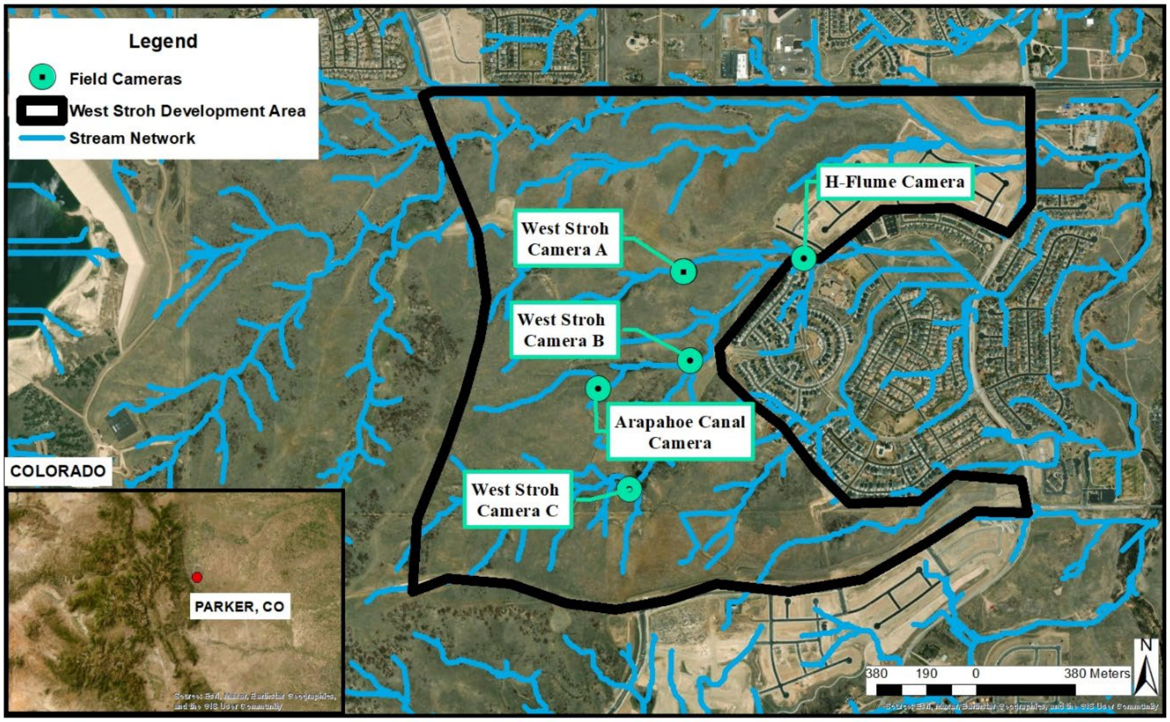


Figure 1. Camera monitoring locations in Parker, CO.

Camera B, the longest running camera location, was installed along the main stem of the West Stroh Gulch tributary. Camera A was installed along the northern tributary of the watershed, referred to as West Stroh Tributary 1. Camera C was installed just upstream of an existing stock pond in the southern part of the watershed. Overflow from this stock pond drains along the main stem towards the Camera B location. A camera was installed to monitor a location on the Arapahoe Canal that is breached on both sides and drains towards the main stem of the stream network. An additional camera was placed to monitor a location for an H-Flume installation near an existing storm drainage structure.

Table 1. Camera Monitoring Locations and Deployment Dates

Monitoring Location	Start Date	Coordinates
"Camera A"	12/15/2021	39.4866, -104.7901
"Camera B"	06/07/2020	39.4836, -104.7898
"Camera C"	12/15/2021	39.4792, -104.7926
"H-Flume Camera"	04/02/2022	39.4872, -104.7848
"Arapahoe Canal Camera"	04/02/2022	39.4791, -104.7966

Each camera was secured to a t-post and positioned to take a photograph with a view ranging from the bottom of the stream channel to part of the staff gauge. A staff gauge was installed across from the camera with the bottom of the staff gauge resting on the bottom of the stream channel. While discharge measurements were outside the scope of this study, the staff gauge served as a visual cue or reference when repositioning the camera and as an approximation for flow depth. A photo example of the field camera setup is shown in Figure 2.

Figure 2. Field camera setup. Camera A July 29th, 2022.

3.1.1 Photo Processing & Review

After retrieval, camera images were copied to a hard drive and processed for upload to the cloud. Camera images were renamed to include identifying information in the photo prefix including:

- Year, Month, Date photo was originally taken in the field.
- Camera identifier
- Original file naming from the SpyPoint Software

Camera images were reviewed and classified based on visual observations (Figure 3, Table 2). For days without a precipitation event, the camera image taken closest to noon for that day was reviewed and logged. When a precipitation event occurred, every camera image spanning from thirty minutes prior to event start to twelve hours after event end was reviewed and logged. Photos were reviewed for visually observable soil moisture and flow. Other observations that were noted included snow, animal presence, and heavy vegetation. While this study focuses on stream flow responses to rain events, observations through the winter months did capture snow events. Photos where there is snow present in the channel, but soil moisture/accumulation/flow is observable do not have this classification. Partial snow presence may still be noted in the "Observations/Other Notes" column of the Photo Log.

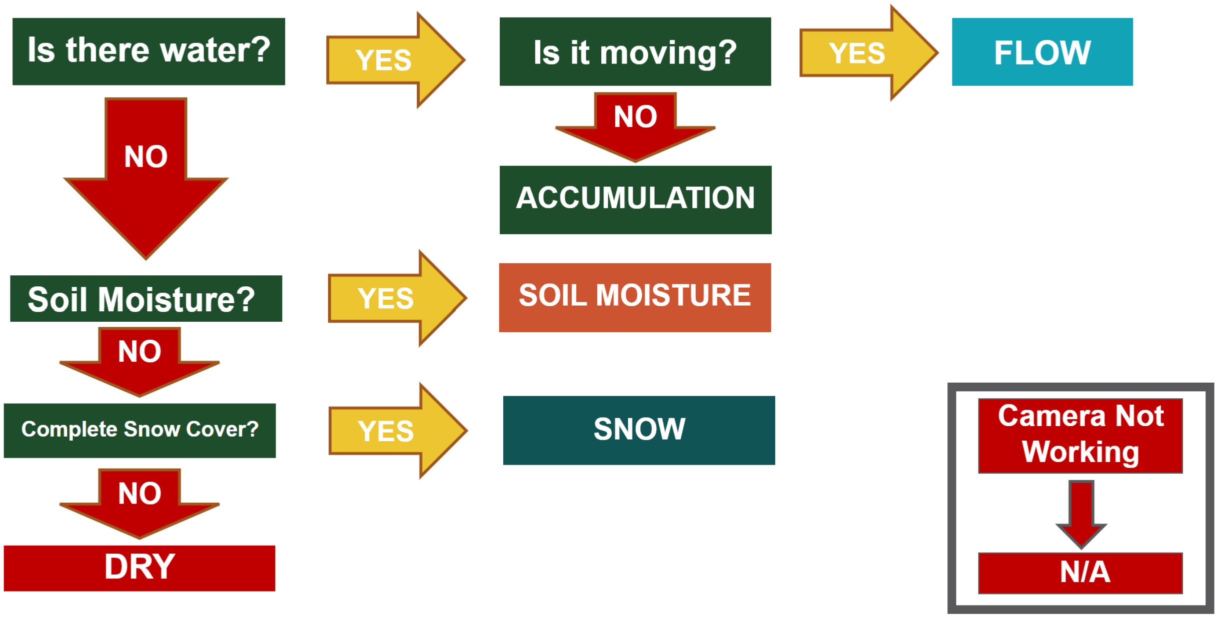


Figure 3. Photo Processing SOP Workflow

Table 2. Photo Review Classifications

Observation Classification	Description
FLOW	Water is present in the channel and changes photo to photo, indicating movement.
ACCUMULATION	Water is present in the channel but is not moving. Usually looks like a puddle.
SOIL MOISTURE	Soil moisture is visually discernible. Typically presents as a darker color due to saturation.
SNOW	Snow cover entirely blankets the channel to where characteristics such as flow, accumulation, or soil moisture are not observable.
DRY	No discernible soil moisture or characteristics to the channel.
N/A	There are multiple possible causes for this classification. **No Photos Taken:** Camera malfunctioned and did not record photos. **Camera Askew:** Camera view may be blocked or no longer on the channel due to animal interference, high winds, thick vegetation, or debris, or even snow/moisture obstructing the lens view.

3.2 Precipitation Data

Tipping bucket rain gage data sourced from the Mile High Flood District was processed to identify precipitation events that occurred in the area that would have affected the West Stroh Watershed. Data was pulled from three rain gauges: 2730 Salisbury Park, 2860 Cherry Creek at Stroh, and the 100820 FP-S1 Dam rain gauge (Table 3). The 2860 Cherry Creek at Stroh was the primary rain gauge with the other two rain gauges serving as backup for cases when the main gauge was not recording precipitation measurements.

Table 3. Rain gage information.

Rain Gage	**Operating Times**	**Location (Coordinates)**	
2730 Salisbury Park	Seasonal	39.497724	-104.773241
2860 Cherry Creek at Stroh	Year-Round	39.480469	-104.769662
100820 FP-S1 Dam Rain Gauge	Year-Round	39.480652	-104.746777

Precipitation data was analyzed using the USGS-R/Rainmaker code (https://rdrr.io/github/USGS-R/Rainmaker/) to identify rain events. Information about each rain event including total depth, event duration, and intensities were calculated using the Rainmaker code. A rain threshold of 5.1 mm and inter-event period of 6 hours was used (Wilson et al. 2022).

3.3 SWMM Models

Three Stormwater Water Management Model (SWMM) Scenarios for the watershed were provided by Muller Engineering: a pre-development model based off existing conditions, a comparison development scenario utilizing more traditional, centralized detention, which for a watershed of this size would be downstream of the watershed, and a distributed detention development model to represent proposed post-development conditions. Input storm files were created using the Colorado Urban Hydrograph Procedure (CUHP 2005 Version 2.0.1, https://mhfd.org/resources/software/) by the Mile High Flood District (MHFD). Each SWMM Model scenario was set up to run six different scenarios: 2-year storm, a 5-year storm, a 10-year storm, a 50-year storm, a 100-year storm, and finally an event that produces enough runoff for a Water Quality Capture Volume (WQCV).

3.4 Hydrodynamic Model

3.4.1 Reach of Interest (ROI)

This project focused on a single reach of interest (ROI) along the main stem of the stream network (Figure 4). The selected reach is defined and stable in its pre-development state and has been slated for minimal regrading and reconstruction in proposed development plans. Examining this section of the stream network is an opportunity to model impacts on a stable pre-development channel by predicted post-development flows. Simulating both proposed post-development scenarios allow for comparison of the potential impacts for using distributed or non-distributed (downstream, centralized) detention basins when developing a watershed.

3.4.2 Structure from Motion: Physical Surface of the Model

Fine resolution topographic data was required to build the hydrodynamic model. This data was obtained by conducting a drone flight, collecting aerial imagery of the site of interest. A flight boundary was created by combining the watershed and development boundary polygons and excluding the existing residential neighborhoods (Figure 4). Aerial imagery of the West Stroh development area in the pre-development stage was captured in September 2022 with a WingtraOne Gen II drone. Images were processed using structure from motion (SFM) techniques in AgiSoft Metashape to construct an initial point cloud of the West Stroh development area.

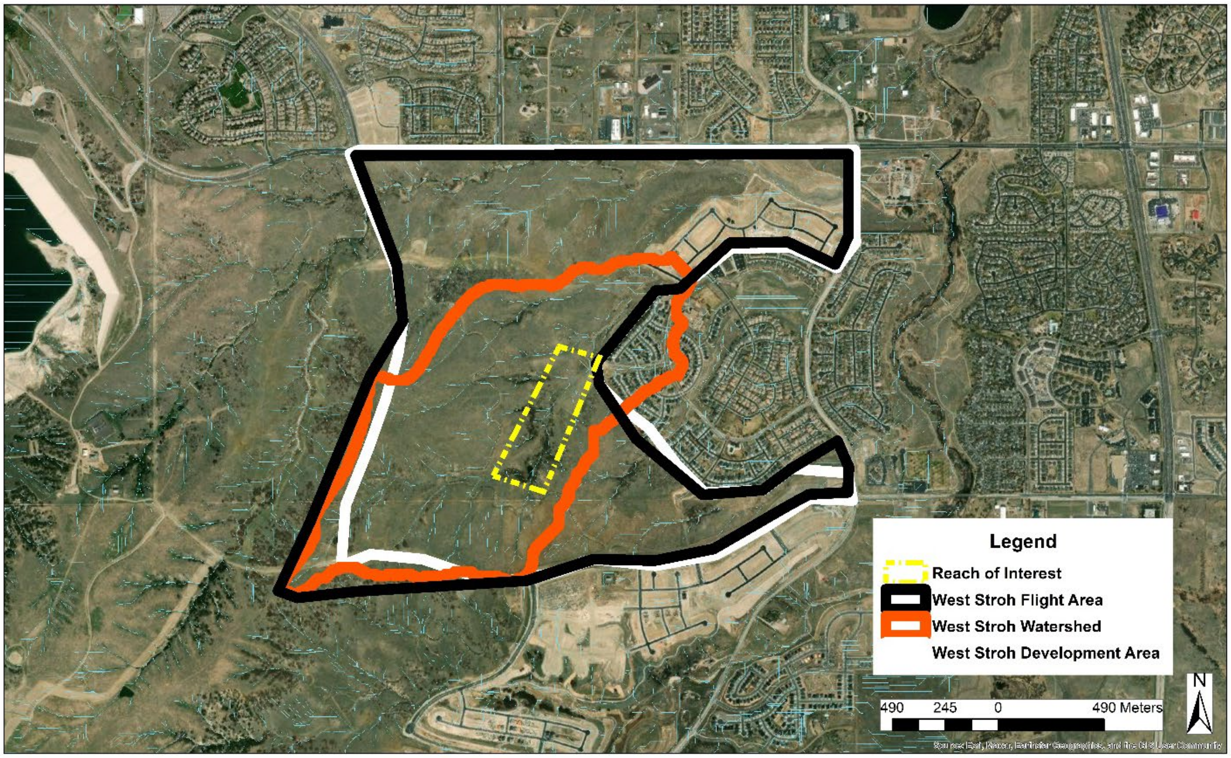


Figure 4. Drone Flight area covered in September 2022.

After the reach of interest (ROI) was determined, a polygon boundary encompassing the reach of interest and surrounding area was created. An orthomosaic and unfiltered digital elevation model (DEM) was exported from this initial point cloud. The point cloud of the smaller section around the reach of interest was exported, then processed using default ‘Steep Slope’ settings for the Cloth Simulation Filter plugin (Zhang et al. 2016) in CloudCompare (https://www.danielgm.net/cc/) to filter out vegetation. The vegetation filtered point cloud was then reprocessed in AgiSoft Metashape. A DEM was generated based on the processed point cloud. The orthomosaic and vegetation filtered DEM were used as inputs to create physical coverages in SRH-2D. All physical coverages in the SRH-2D model were in the WGS 1984 ARC System Zone 13 global projection.

A mesh was created to define the active channel and surrounding floodplains within the area. The active channel polygon was drawn based on a combination of visual imagery observable in the orthomosaic, topography from the DEM, and field experience with walking along the stream channel. The inlet boundary condition was drawn at the drainage pipe connecting the upstream pond to the main stem of the stream network. The outlet boundary condition was drawn prior to where a tributary meets the main stem. Peak flows for the upstream node of the ROI from the SWMM model scenarios were run through the SRH-2D stream channel at a steady state condition (Table 4). The materials coverage channel roughness in the model used a Manning's n of 0.05 based on the SWMM model parameters. While Manning's n would vary with flow in actual conditions, a constant value was used for all scenarios compared in the hydrodynamic model.

Table 4. Peak flows (cms) by SWMM Scenario

Design Storm	Pre-Development Conditions	Proposed with Distributed Detention	Proposed with Centralized Detention
Water Quality Capture Volume Event (WQCV)	0.004	0.200	0.616
2-year Event	0.030	0.400	1.323
5-year Event	0.501	0.464	2.118
10-year Event	0.917	0.500	2.975
50-year Event	2.873	0.600	6.508
00-year Event	4.077	0.630	8.145

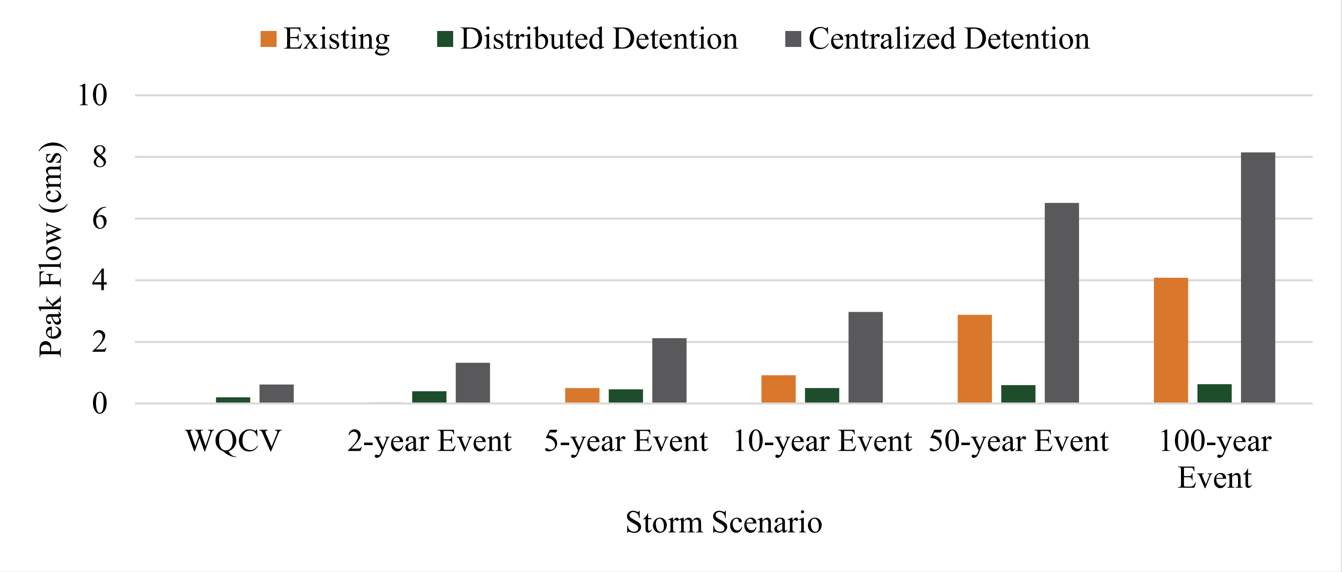


Figure 5. Peak flows (cms) by SWMM Scenario

4. RESULTS

4.1 Stream Monitoring Results

Monitoring results discussed in this paper include observations logged and reviewed until February 14th, 2023. The majority of visual observations indicated a dry stream channel with 57% of all stream channel observations recording streamflow absence. Camera C captured the most visually observable days with flow and accumulation. This is attributed to Camera C being located just upstream of an existing pond where the ground is consistently wet or muddy. Water seeps from this area and feeds into the nearby pond.

Table 5. Number of Days per Observation Type, per Camera.

Days per Observation Category						
Camera	**Flow**	**Accumulation**	**Soil Moisture**	**Snow**	**Dry**	**N/A**
A	-	-	2	121	210	82
B	1	3	98	191	534	224
C	3	129	2	127	46	114
H-Flume	-	-	3	46	120	70
Arapahoe Canal	-	-	-	51	125	138

Both Camera B and Camera C captured visually observable flow in response to one precipitation event. The streamflow triggering event had the longest duration, largest total storm depth, and highest intensities out of all examined events (Figure 5, Table 6). Based on streamflow observations, the pre-development precipitation threshold storm depth for runoff is between the flow event depth of 92 mm and next largest observed event storm depth of 40 mm. Similarly, the pre-development precipitation threshold for maximum 60-minute intensity is between 50-mm/hour and 34-mm/hour. This is consistent with prior findings indicating that storm depth would need to exceed 30-mm and a 60-minute maximum intensity of 5 mm/hour to generate runoff in West Stroh Gulch's pre-development rangeland state (Wilson 2021).

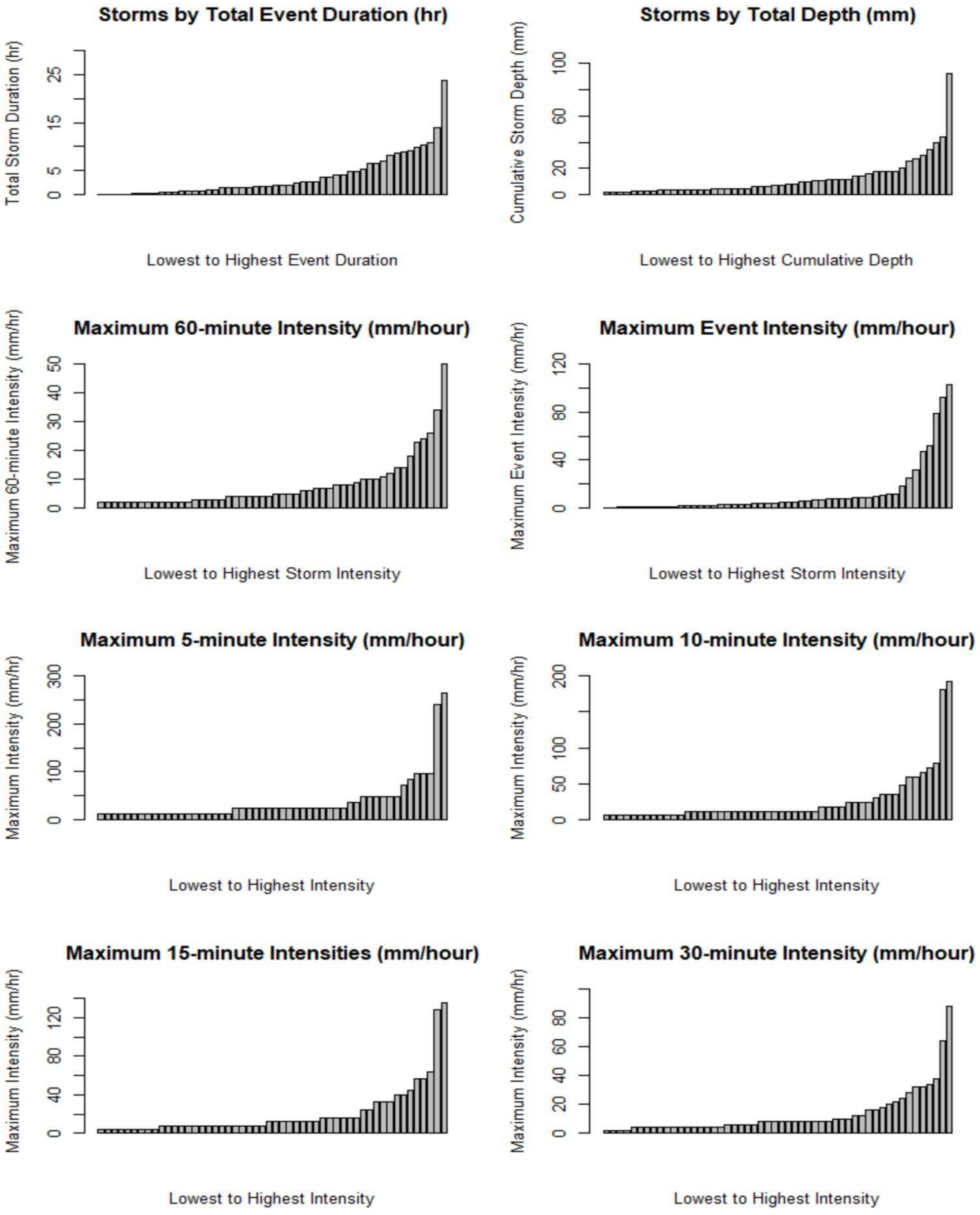


Figure 5. Events sorted by total duration, total storm depth, and maximum intensities. The highest bar in each sub-plot is the August 15th, 2022, flow triggering event.

4.1.1 August 2022 Flow Event

Photo observations of one flow triggering event were documented by West Stroh Camera B and West Stroh Camera C. The precipitation event lasted from 14:59 MDT August 15th, 2022, to 0:54 MDT August 16th, 2022. A summary of event depth and calculated event intensities are shown in Table 6. Cumulative precipitation depth over the course of the flow event is show in Figure 6. Photos taken prior to, during, and after the event are shown in Figure 7.

Table 6. Total storm depth and maximum event intensities.

	Maximum Intensities (mm/hour)					
Total Depth (mm)	Event Intensity	5-minute Intensity	10-minute Intensity	15-minute Intensity	30-minute Intensity	60-minute Intensity
92	9.28	240	192	136	88	50

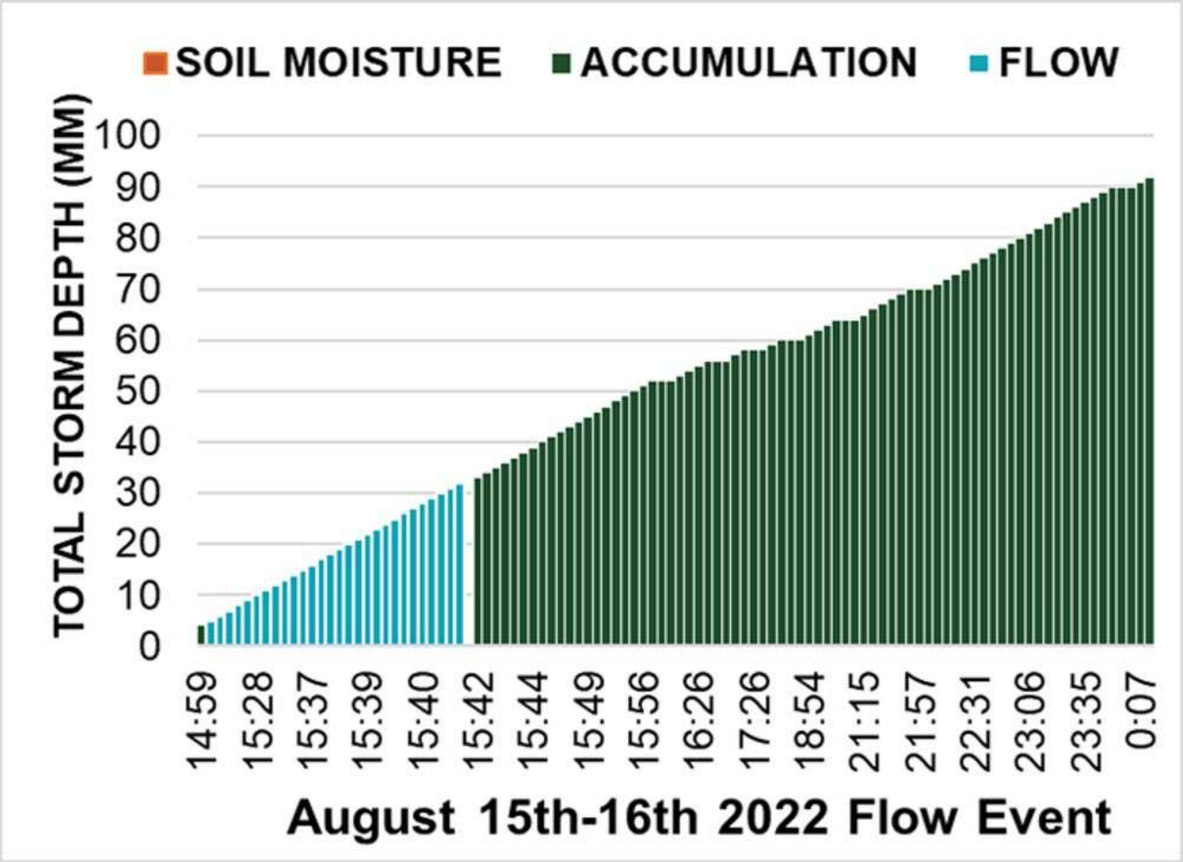


Figure 6. Cumulative precipitation depth over the flow event.

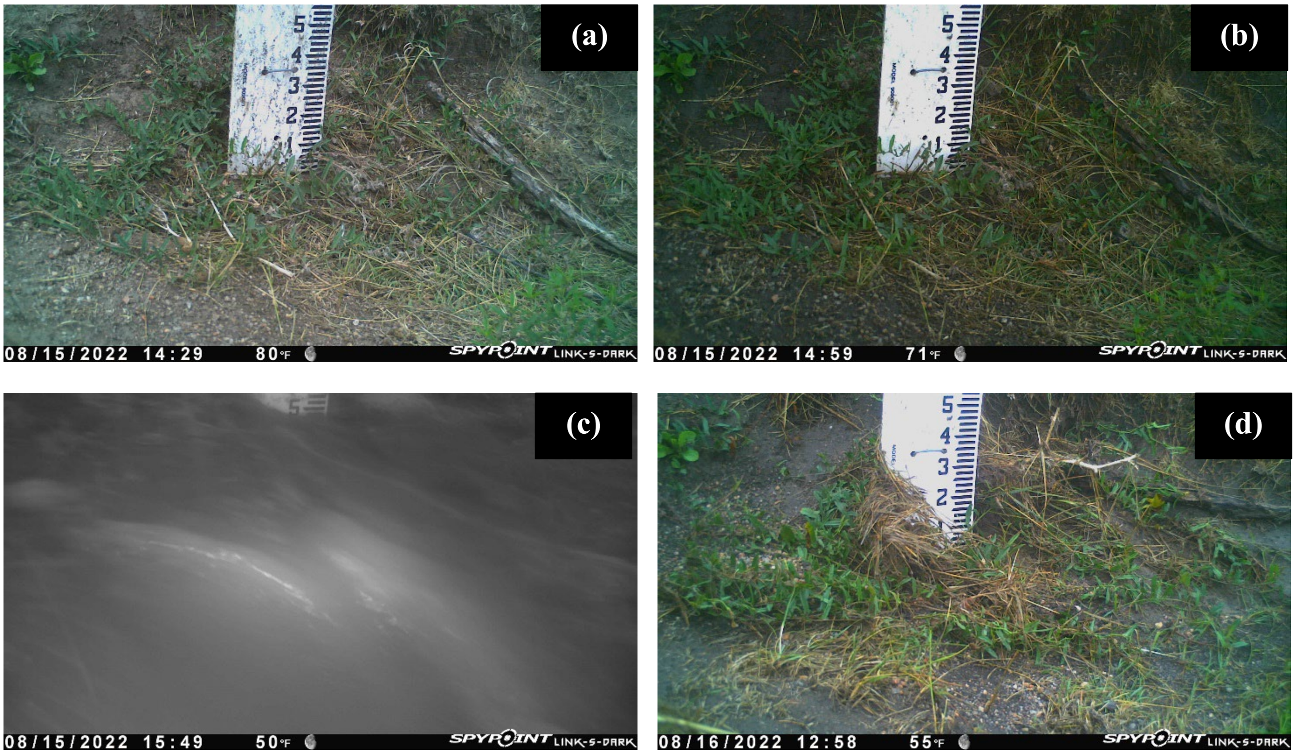


Figure 7. Photos captured by Camera B. (a) Photo thirty minutes before event start. (b) Photo captured at start of precipitation event. (c) Peak flow captured on camera. (d) Photo with soil moisture and water accumulation twelve hours after precipitation event end.

4.2 Hydrodynamic Modeling Results

Modeling potential impacts to streamflow behavior due to urbanization and considering different stormwater management strategies is important for mitigating urban stream syndrome impacts to watershed health. Flow velocities or flow-induced shear stresses are often calculated in these models to serve as predictors for how sediment loadings in a stream channel will change. Increases in flow velocity and flow-induced shear stress indicate a potential increase in sediment movement. These changing interactions can in turn lead to increased erosion, channelization, and loss of stream complexity.

Average boundary shear stresses (Figure 8) followed a similar pattern as the magnitudes of peak flows for the different SWMM model scenarios (Table 4, Figure 5). Average boundary shear stress was lowest for the existing pre-development WQCV simulation, followed by the distributed detention and centralized detention simulations. For storm scenarios from the 2-year to 100-year storm, the distributed detention simulations had the lowest average boundary stress, followed by existing pre-development, and then centralized detention.

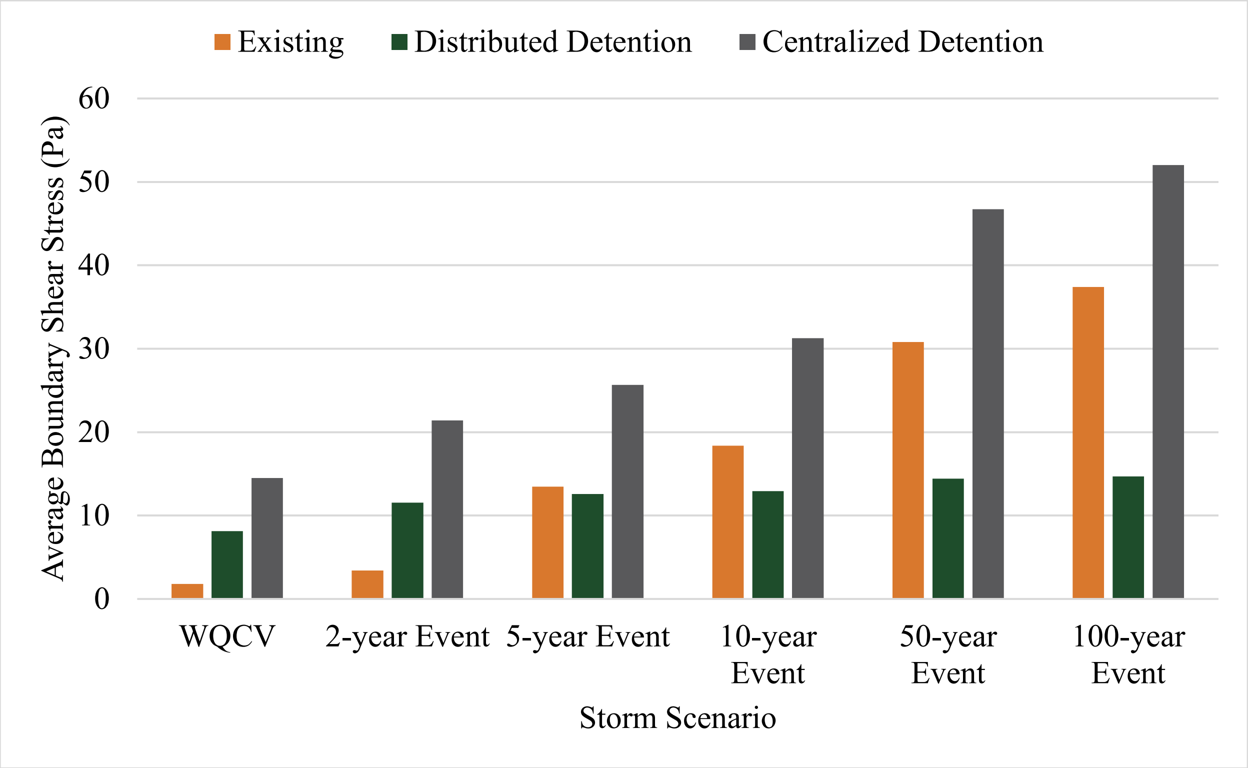
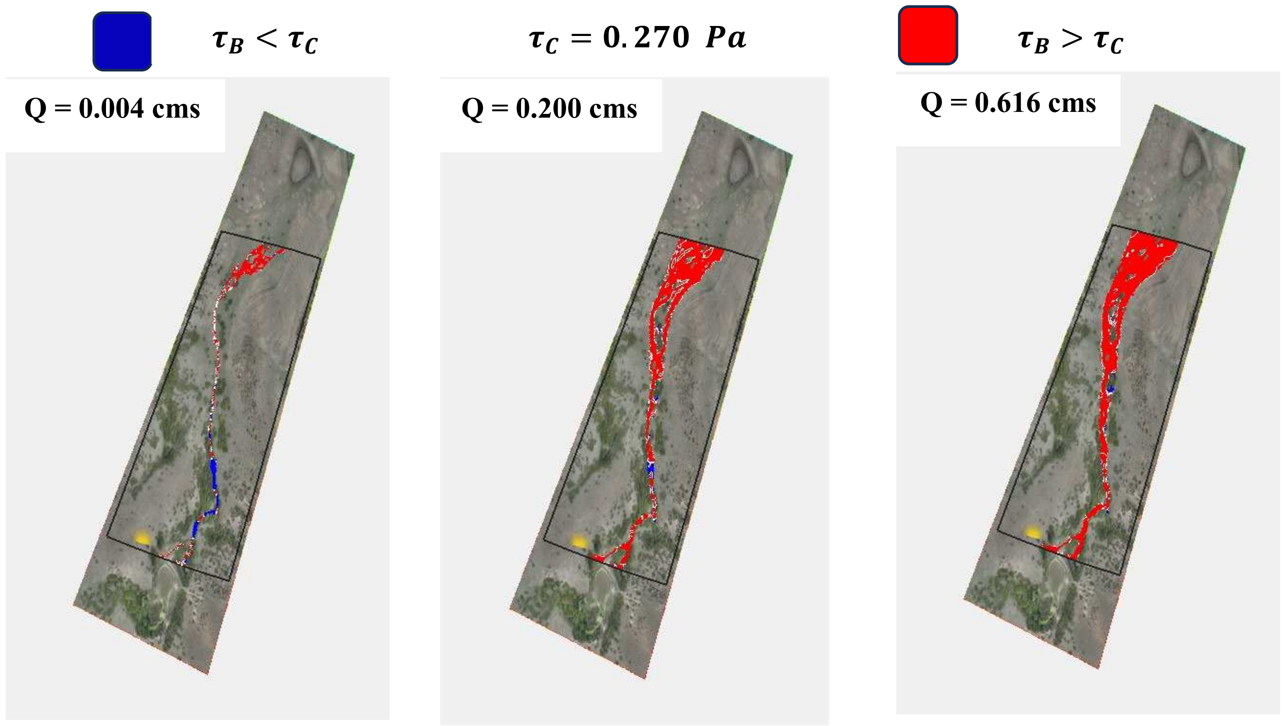


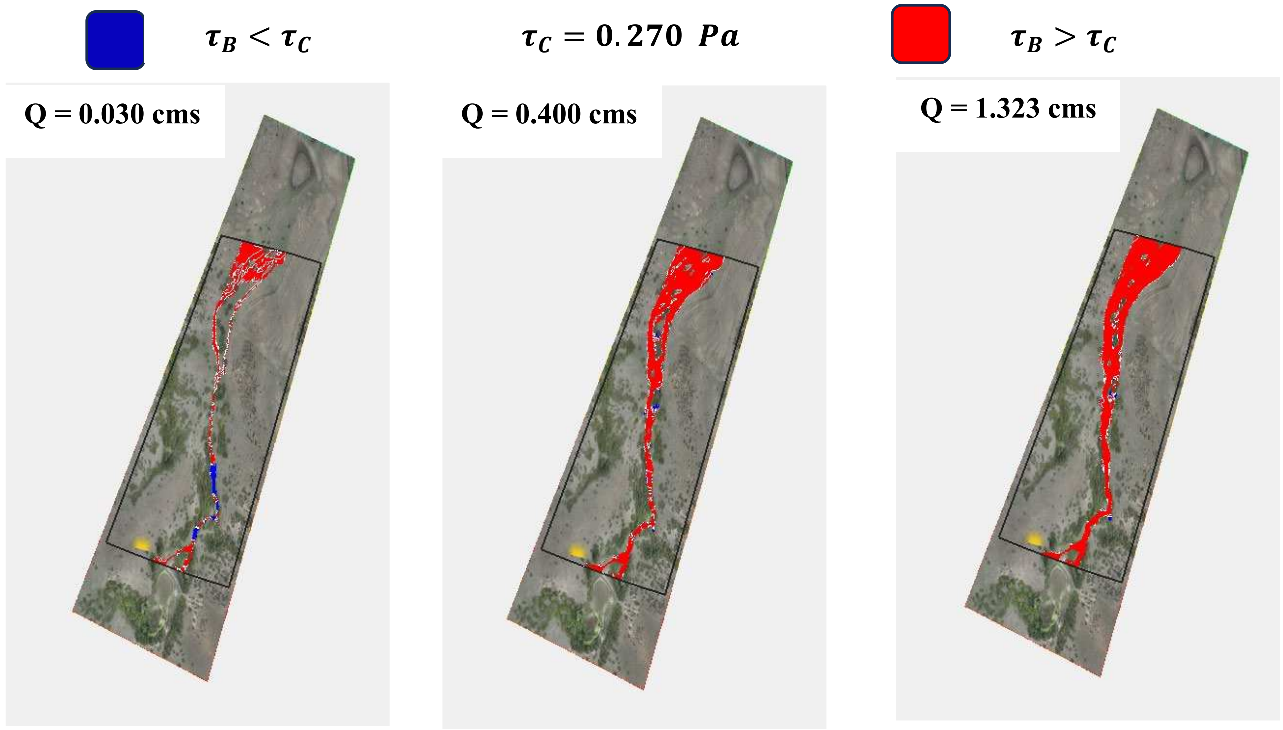
Figure 8. Summary of average boundary shear stress by storm and development scenario.

The following section for Figure 9 shows the plan view of the boundary shear stresses for each simulation at end time of 12.0 hours. Simulation plan views are grouped by storm (WQCV, 2-year, 5-year, 10-year, 50-year, and 100-year). Areas shaded in red indicate areas with boundary shear stress values greater than the critical shear stress value for coarse sand (τ_C = 0.270 Pascal). Sediment movement is predicted for these areas. Areas in blue indicate areas where the boundary stress values are less than the critical shear stress value for coarse sand (τ_C = 0.270 Pascal).



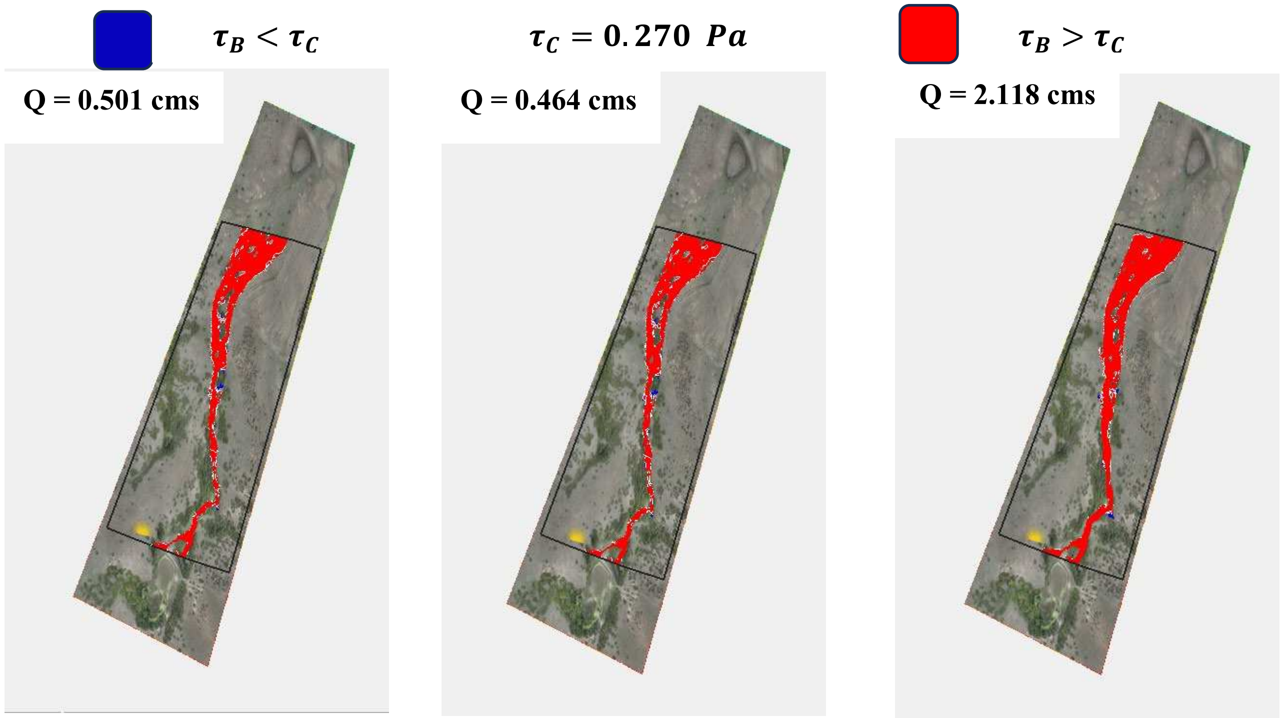
Existing **Distributed Detention** **Centralized Detention**

Figure 9a. Water Quality Capture Volume Simulations: Boundary Shear Stress



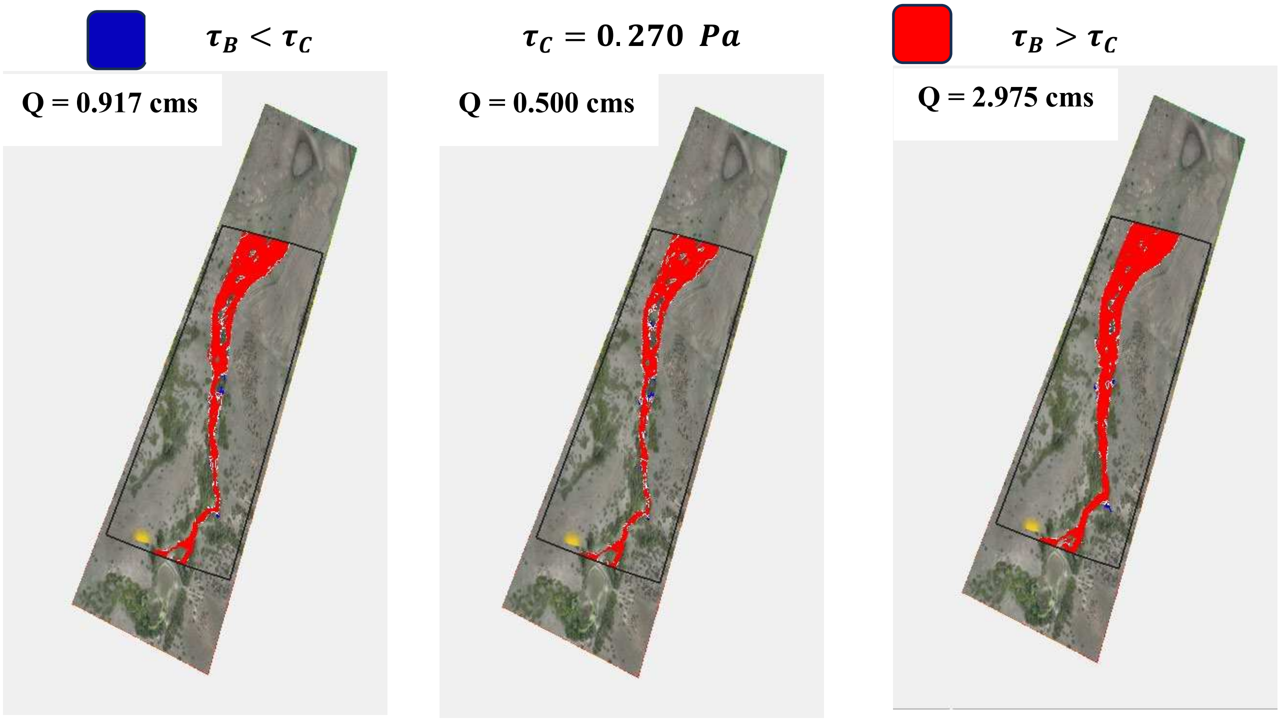
Existing **Distributed Detention** **Centralized Detention**

Figure 9b. 2-year Design Storm Simulations: Boundary Shear Stress



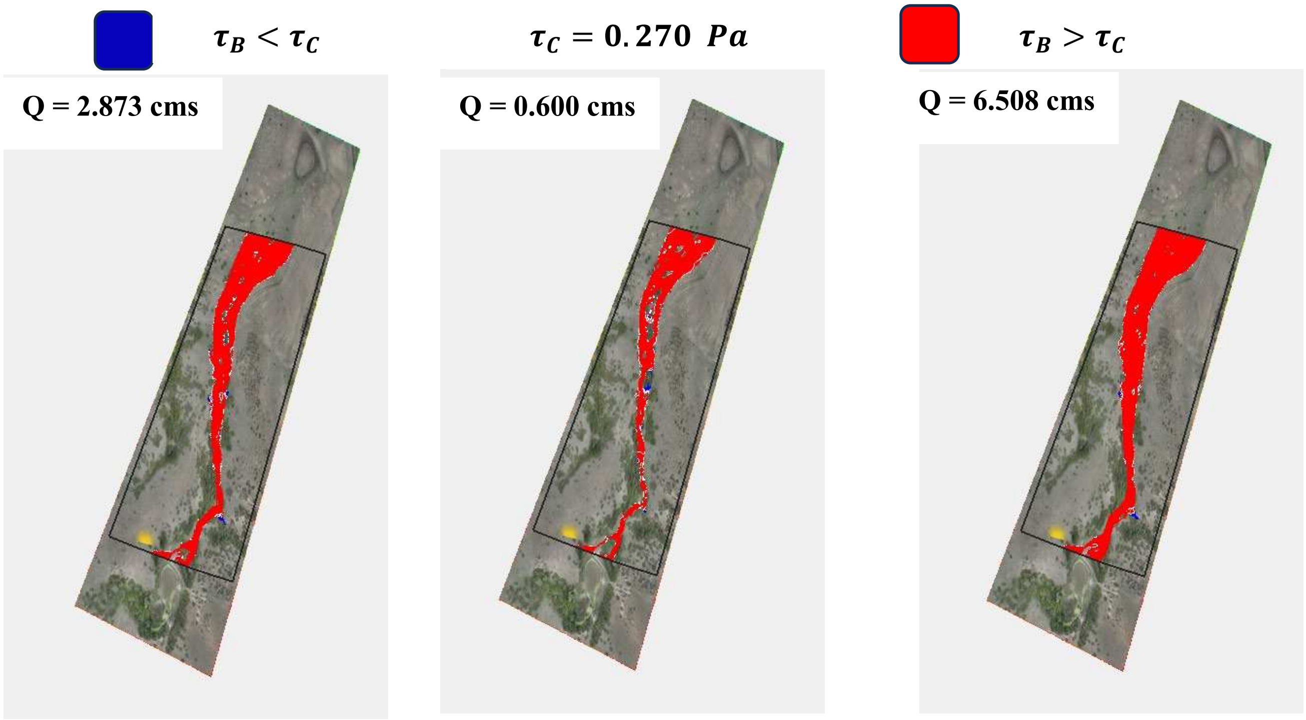
Existing **Distributed Detention** **Centralized Detention**

Figure 9c. 5-year Design Storm Simulations: Boundary Shear Stress



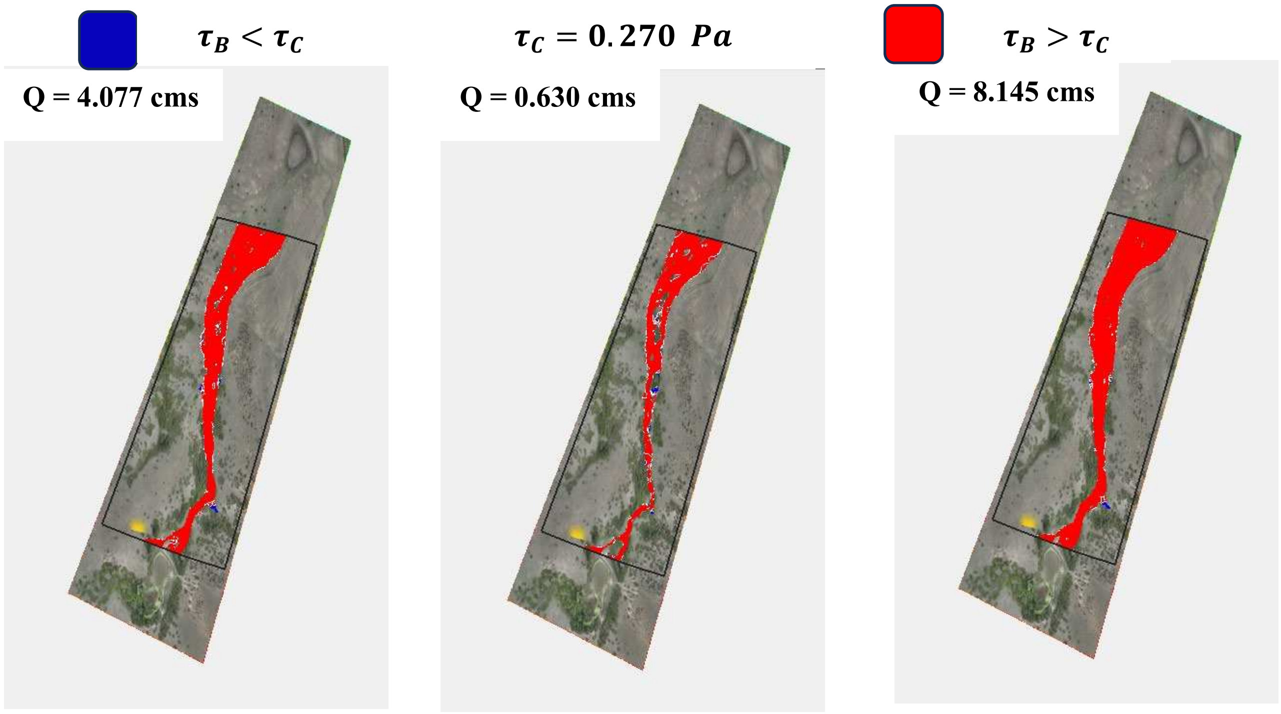
Existing **Distributed Detention** **Centralized Detention**

Figure 9d. 10-year Design Storm Simulations: Boundary Shear Stress



Existing **Distributed Detention** **Centralized Detention**

Figure 9e. 50-year Design Storm Simulations: Boundary Shear Stress



Existing **Distributed Detention** **Centralized Detention**

Figure 9f. 100-year Design Storm Simulations: Boundary Shear Stress

Figure 9. Areas of the channel with boundary shear stress (τ_B) values above the upper critical shear stress (τ_C) value for medium sand (τ_C = 0.270) are shaded in red. Areas of the channel with boundary shear stress (τ_B) values below the lower critical shear stress (τ_C) value for medium sand (τ_C = 0.270) are shaded blue.

The existing pre-development scenario had the lowest flows at the WQCV and 2-year storm events. This was reflected in this scenario having boundary shear stresses are below critical values in the upstream part of the reach for the WQCV and 2-year storm events. The distributed detention simulations showed boundary shear stresses as below critical values in the upstream part of the reach for the WQCV event, similar to the existing pre-development WQCV scenario. Boundary shear stresses for the distributed detention simulations were below critical values towards the most downstream part of the reach for the 5-year, 50-year, and 100-year storms. Out of the centralized detention simulations, only the WQCV scenario showed boundary shear stress below critical values in the most downstream part of the reach. Overall, the centralized detention simulations showed boundary shear stresses above critical values throughout the reach of interest.

5. DISCUSSION

As found in prior streamflow monitoring efforts in West Stroh Gulch, this study supports previous findings that streamflow triggering precipitation events do not occur often in the pre-development West Stroh Gulch watershed (Wilson 2021). Results from this study indicate a precipitation threshold maximum 60-minute intensity between 50-mm/hr and 34-mm/hr and storm depth between 40-mm and 92-mm for a 1.5 km^2 pre-development semi-arid watershed.

Precipitation threshold analysis in a prior study of semi-arid watersheds in the Denver area estimated a maximum 60-minute intensity precipitation thresholds for sites ranging in drainage areas between 89.61 km^2 and 0.73 km^2 and percent imperviousness between 0.8% and 47.3% (Wilson et al. 2022). In this study, a 1.16 km^2 drainage area (Station U) with 0.8% imperviousness had a maximum 60-minute intensity precipitation threshold of 23-mm/hr. Station U's precipitation threshold is lower than the 34-mm/hr maximum 60-minute intensity event that did not trigger stream flow in West Stroh Gulch. Another watershed in this study, Station R, 1.4 km^2 drainage area with 4.8% imperviousness had a maximum 60-minute intensity precipitation threshold of 7-mm/hr. Precipitation thresholds may also be affected by factors such as watershed topography, precipitation event frequency, vegetation cover, and percent impervious area.

Future streamflow patterns may be predicted based on previous research regarding similar watersheds in semi-arid regions subject to urbanization. As the area undergoes development, West Stroh Gulch is anticipated to have less days with zero streamflow. With increased urbanization and an increased percentage in impervious area, the precipitation threshold for streamflow triggering events is expected to also lower. However, West Stroh Gulch may have less sediment mobilization in the stream channel in its post-development state than similar semi-arid watersheds that utilize the more traditional centralized detention stormwater management approach. This expectation may be different for West Stroh Gulch than other watersheds due to the predicted effectiveness of distributed detention in reducing flow-induced shear stresses for the stream channel during larger storm events. Modeling results for the West Stroh Gulch watershed imply that the planned distributed detention stormwater management strategy has the potential to reduce flow magnitudes, velocity, and shear stresses. SWMM model outputs showed that the distributed detention post-development scenario had lower peak flows along the reach of interest for larger storm scenarios than even the pre-development existing conditions scenario (Table 4, Figure 5).

6. CONCLUSIONS

6.1 Streamflow Monitoring

The majority of observations were of a dry stream channel, supporting the assumption that the stream channel was non-perennial. Most responses within the stream channel following rain events were observed soil moisture, with only one event triggering observed flow within the stream channel. This case study demonstrates the need for persistent, constant monitoring of stream channels in semi-arid regions. A single event with observable flow was captured after over two years of monitoring. As the flow triggering event was far larger than all other events in the monitoring period, a specific precipitation threshold for West Stroh Gulch in its pre-development state could not be established, but that a rain depth between 92-mm and 40-mm and 60-minute maximum intensity between 50-mm/hr and 34-mm/hr is needed to trigger flow.

Continued monitoring along points of the stream network is recommended to document changes in stream channel behavior through the stages of development. Capturing future streamflow responses to precipitation events as West Stroh Gulch continues to develop may allow for better comparison to similarly urbanized watersheds in either the Denver area or other semi-arid regions. With enough monitored streamflow responses to precipitation events, a more specific precipitation threshold for a post-development West Stroh Gulch may be established in the future.

6.2 Stream Reach Modeling

Stormwater management practices have primarily focused on slowing down and controlling flows post-precipitation events. Hydrodynamic modeling may emphasize the potential benefits of slowing down and controlling stormflows by estimating parameters such as boundary shear stresses and flow patterns throughout the stream channel. Simulating different scenarios may also support stormwater management decisions from the design stage when selecting different strategies and approaches for watersheds undergoing development.

The scope of modeling for this research project focused on a single reach of the West Stroh Gulch stream network. Recommendations for future modeling include future collection of topographic data and aerial imagery of the watershed and further investigation of other reaches of interest within the stream network. Future comparison of pre- to post -development landscape will be valuable for comparing model predictions to actual stream channel changes. Sediment transport modeling and updated roughness parameters could be implemented in future simulations to predict sediment movement and physical changes to channel morphology. Additional investigation into the hydraulic model can also include smaller areas within the reach of interest for trends in water depth, velocity, or critical shear stress.

REFERENCES

Baffaut, C., J. M. Baker, J. A. Biederman, D. D. Bosch, E. S. Brooks, A. R. Buda, E. M. Demaria, E. H. Elias, G. N. Flerchinger, D. C. Goodrich, S. K. Hamilton, S. P. Hardegree, R. D. Moglen, T. B. Moorman, D. N. Moriasi, J. Okalebo, F. B. Pierson, E. S. Russell, N. Z. Saliendra, A. K. Saha, D. R. Smith, and L. M. W. Yasarer. 2020. "Comparative analysis of water budgets across the U.S. long-term agroecosystem research network." J. Hydrol., 588: 125021. https://doi.org/10.1016/j.jhydrol.2020.125021.

Bhaskar, A. S., L. Beesley, M. J. Burns, T. D. Fletcher, P. Hamel, C. E. Oldham, and A. H. Roy. 2016. "Will it rise or will it fall? Managing the complex effects of urbanization on base flow." Freshw. Sci., 35 (1): 293–310. https://doi.org/10.1086/685084.

Bledsoe, B. P., and C. C. Watson. 2001. "EFFECTS OF URBANIZATION ON CHANNEL INSTABILITY." J. Am. Water Resour. Assoc., 37 (2): 255–270. https://doi.org/10.1111/j.1752-1688.2001.tb00966.x.

Bledsoe, B. P., C. C. Watson, and D. S. Biedenharn. 2002. "QUANTIFICATION OF INCISED CHANNEL EVOLUTION AND EQUILIBRIUM." J. Am. Water Resour. Assoc., 38 (3): 861–870. https://doi.org/10.1111/j.1752-1688.2002.tb01002.x.

Booth, D. B., A. H. Roy, B. Smith, and K. A. Capps. 2016. "Global perspectives on the urban stream syndrome." Freshw. Sci., 35 (1): 412–420. https://doi.org/10.1086/684940.
Earles, A., B. Chongtoua, J. Clary, and B. Zivkovich. 2020. "Estimation of Pollutant Load Reductions from Restoration of Cherry Creek in Denver." J. Sustain. Water Built Environ., 6 (3): 02520002. https://doi.org/10.1061/JSWBAY.0000918.

Earles, A., J. Wulliman, B. Chongtoua, B. Zivkovich, S. Rogers, and S. Johnson. 2018. "Oak Gulch Green Infrastructure: Scaling and Continuity Analysis from the Lot to the Watershed Level." World Environ. Water Resour. Congr. 2018, 143–151. Minneapolis, Minnesota: American Society of Civil Engineers.

Eberts, S. M., M. D. Woodside, M. N. Landers, and C. R. Wagner. 2019. Fact Sheet. Fact Sheet. Fact Sheet. U.S. Geological Survey.

Fillo, N. K., A. S. Bhaskar, and A. J. Jefferson. 2021. "Lawn Irrigation Contributions to Semi-Arid Urban Baseflow Based on Water-Stable Isotopes." Water Resour. Res., 57 (8): e2020WR028777. https://doi.org/10.1029/2020WR028777.

Grimmond, C. S. B., and T. R. Oke. 1986. "Urban Water Balance: 2. Results From a Suburb of Vancouver, British Columbia." Water Resour. Res., 22 (10): 1404–1412. https://doi.org/10.1029/WR022i010p01404.

Hopkins, K. G., A. S. Bhaskar, S. A. Woznicki, and R. M. Fanelli. 2020. “Changes in event-based streamflow magnitude and timing after suburban development with infiltration-based stormwater management.” Hydrol. Process., 34 (2): 387–403. https://doi.org/10.1002/hyp.13593.

Hopkins, K. G., S. A. Woznicki, B. M. Williams, C. C. Stillwell, E. Naibert, M. J. Metes, D. K. Jones, D. M. Hogan, N. C. Hall, R. M. Fanelli, and A. S. Bhaskar. 2022. “Lessons learned from 20 y of monitoring suburban development with distributed stormwater management in Clarksburg, Maryland, USA.” Freshw. Sci., 41 (3): 459–476. https://doi.org/10.1086/719360.

Jaeger, K. L., K. C. Hafen, J. B. Dunham, K. M. Fritz, S. K. Kampf, T. B. Barnhart, K. E. Kaiser, R. Sando, S. L. Johnson, R. R. McShane, and S. B. Dunn. 2021. “Beyond Streamflow: Call for a National Data Repository of Streamflow Presence for Streams and Rivers in the United States.” Water, 13 (12): 1627. https://doi.org/10.3390/w13121627.

Jefferson, A. J., A. S. Bhaskar, K. G. Hopkins, R. Fanelli, P. M. Avellaneda, and S. K. McMillan. 2017. “Stormwater management network effectiveness and implications for urban watershed function: A critical review.” Hydrol. Process., 31 (23): 4056–4080. https://doi.org/10.1002/hyp.11347.

McPhillips, L. E., S. R. Earl, R. L. Hale, and N. B. Grimm. 2019. “Urbanization in Arid Central Arizona Watersheds Results in Decreased Stream Flashiness.” Water Resour. Res. https://doi.org/10.1029/2019WR025835.

Meyer, J. L., M. J. Paul, and W. K. Taulbee. 2005. “Stream ecosystem function in urbanizing landscapes.” J. North Am. Benthol. Soc., 24 (3): 602–612. https://doi.org/10.1899/04-021.1.
Pierson, F. B., K. E. Spaeth, M. A. Weltz, and D. H. Carlson. 2002. “Hydrologic Response of Diverse Western Rangelands.” 14.

Turner, V. K., K. Gmoser-Daskalakis, D. M. Costello, A. Jefferson, and A. S. Bhaskar. 2022. “Champions and Traditional Technocrats: The Role of Environmental Value Orientation in Stormwater Management.” JAWRA J. Am. Water Resour. Assoc., 58 (3): 336–354. https://doi.org/10.1111/1752-1688.13015.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. “The urban stream syndrome: current knowledge and the search for a cure.” J. North Am. Benthol. Soc., 24 (3): 706–723. https://doi.org/10.1899/04-028.1.

Weltz, L., G. Frasier, and M. Weltz. 2000. “Hydrologic responses of shortgrass prairie ecosystems.” Rangel. Ecol. Manag. Range Manag. Arch., 53 (4): 403–409.

Wilson, S. 2021. “HYDROLOGIC RESPONSES TO URBANIZATION IN DENVER WATERSHEDS AND INVESTIGATION OF PRECIPITATION THRESHOLDS FOR STREAMFLOW GENERATION IN PRE-DEVELOPMENT SEMI-ARID RANGELAND.” ProQuest Dissertations Publishing, 54.

Wilson, S., A. S. Bhaskar, B. Choat, S. Kampf, T. R. Green, and K. G. Hopkins. 2022. "Urbanization of grasslands in the Denver area affects streamflow responses to rainfall events." Hydrol. Process., 36 (10). https://doi.org/10.1002/hyp.14720.

Zhang, W., J. Qi, P. Wan, H. Wang, D. Xie, X. Wang, and G. Yan. 2016. "An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation." Remote Sens., 8 (6): 501. https://doi.org/10.3390/rs8060501.

APPENDIX

SWMM Information

Table A1. Reference Nodes and Links for the SWMM Models

SWMM Model	**Inlet Node**	**Link(s) Between Nodes**	**Outlet Node**
Existing Conditions	J_WS_4	J_WS_4	J_WS3
Proposed Detained Distributed Detention **Improved**	J_WS_9	C_WS_9 C_WS_8.5b C_WS_8.5a	J_WS_8
Proposed Undetained Centralized Detention Traditional	J_WS_9	C_WS_9 C_WS_8.5b C_WS_8.5a	J_WS_8

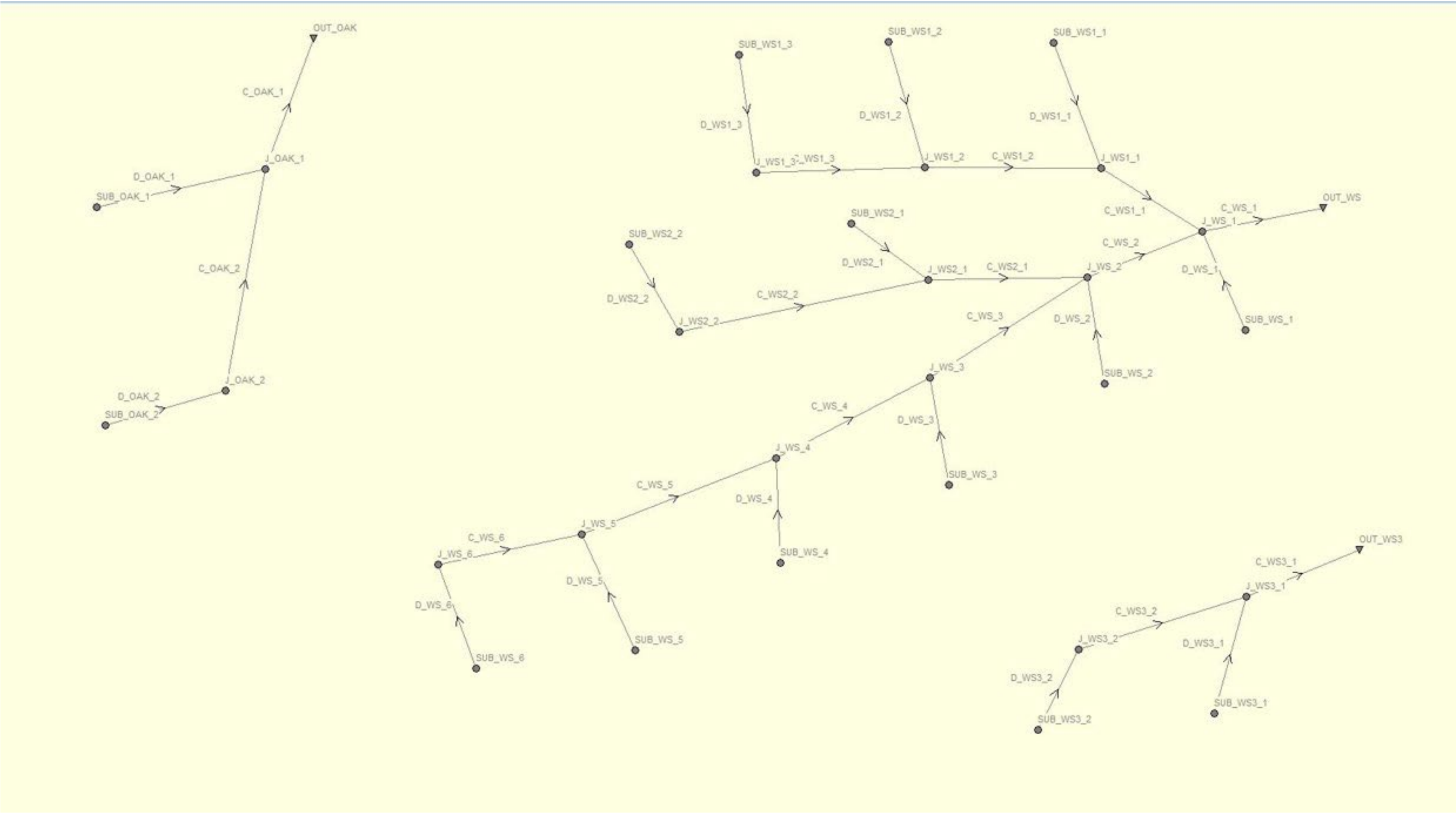


Figure A1. Existing Pre-development SWMM model layout. Provided by Muller Engineering, 2023.

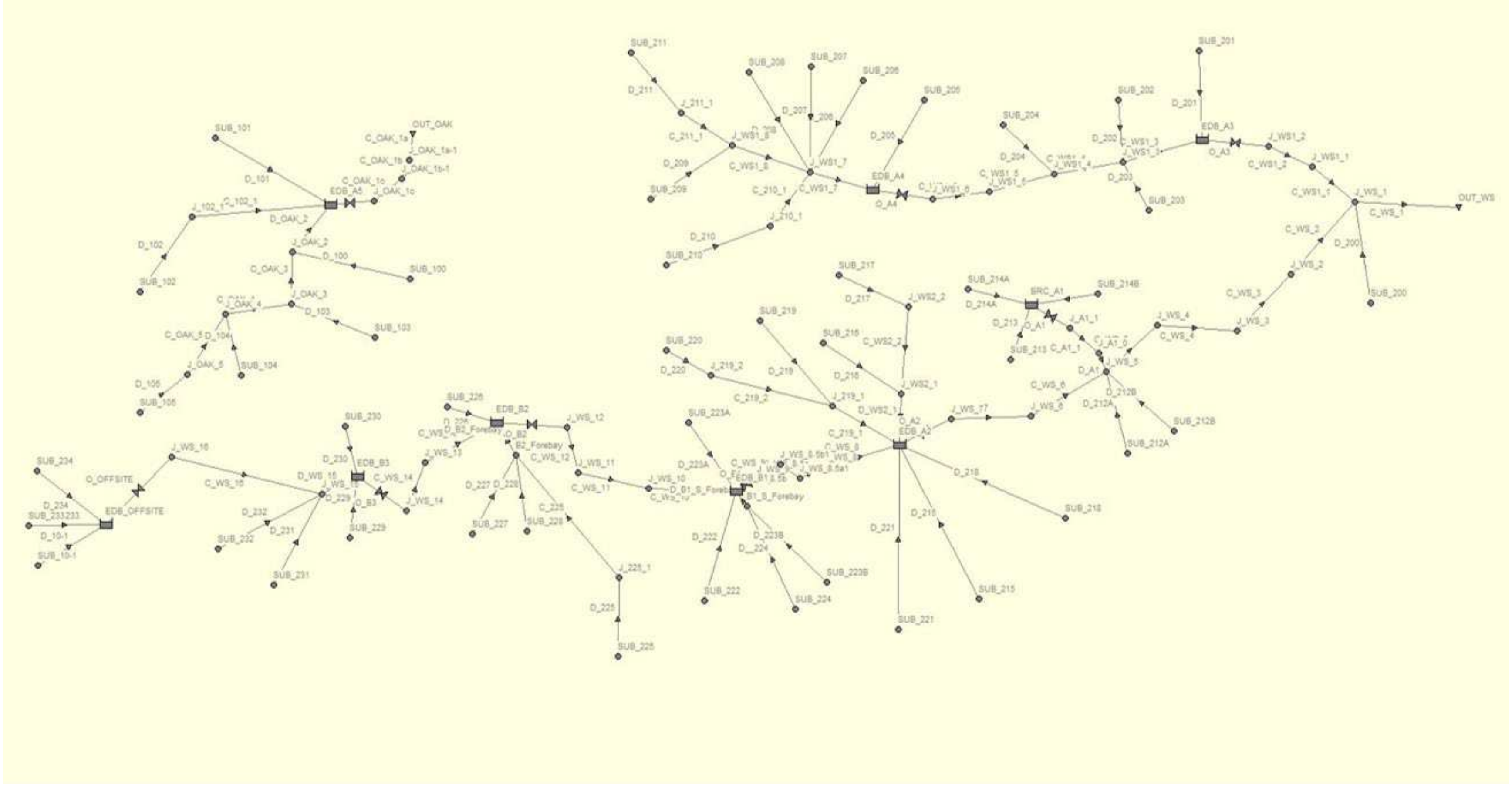


Figure A2. Existing Post-development SWMM model layout. Provided by Muller Engineering, 2023.

Velocity Magnitude Simulation Results

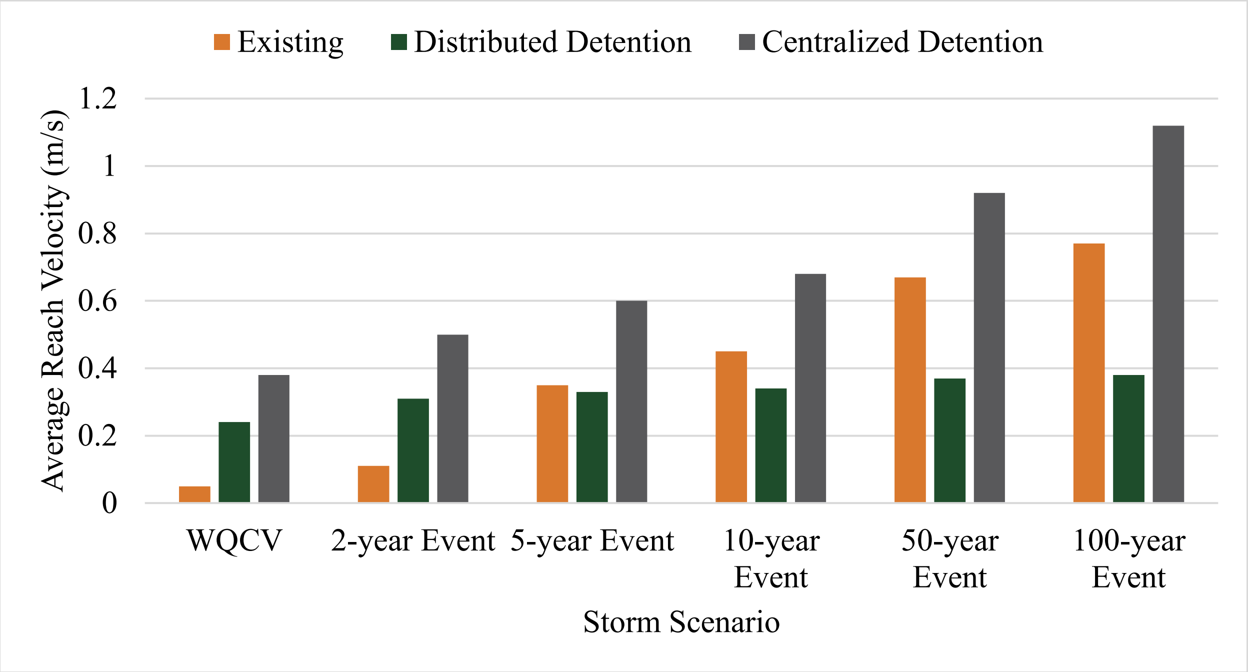


Figure A3. Summary of average velocities by storm and development scenario.

Water Depth Simulation Results

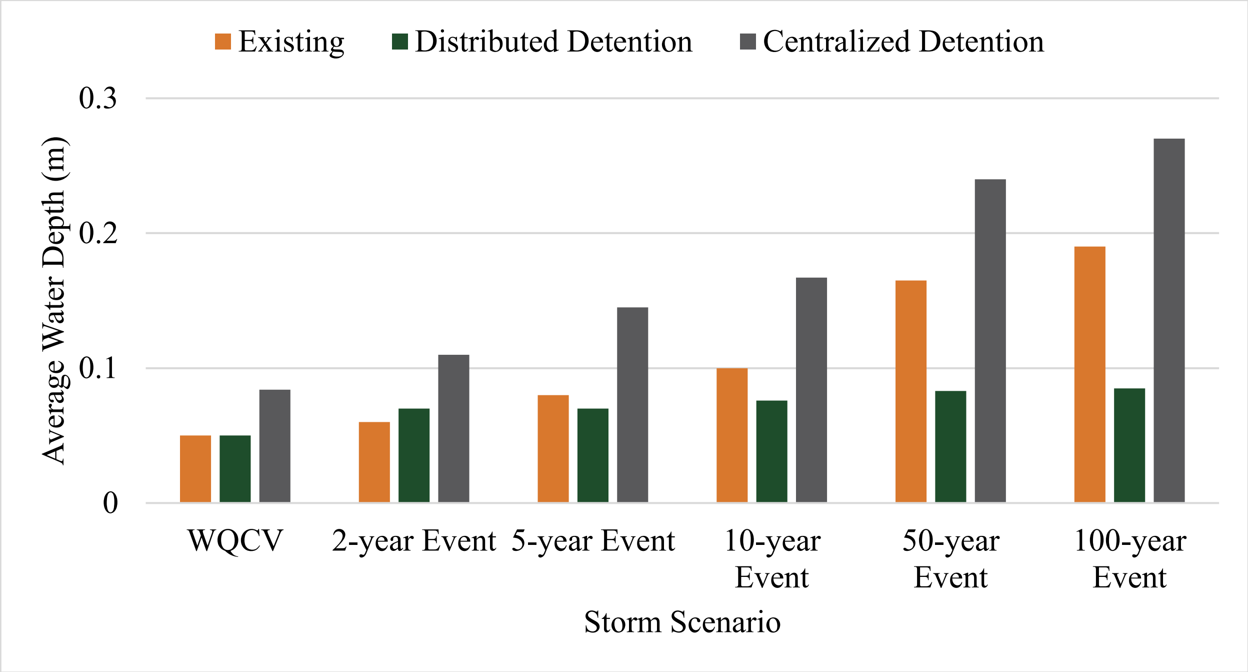


Figure A4. Summary of average water depth by storm and development scenario.