

Article

The Hydrologic Mitigation Effectiveness of Bioretention Basins in an Urban Area Prone to Flash Flooding

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Abstract: The hydrologic performance and cost-effectiveness of green stormwater infrastructure (GSI) in climates with highly variable precipitation is an important subject in urban stormwater management. We measured the hydrologic effects of two bioretention basins in San Antonio, Texas, a growing city in a region prone to flash flooding. Pre-construction, inflow, and outflow hydrographs of the basins were compared to test whether the basins reduced peak flow magnitude and altered the metrics of flashiness, including rate of flow rise and fall. We determined the construction and annual maintenance cost of one basin and whether precipitation magnitude and antecedent moisture conditions altered hydrologic mitigation effectiveness. The basins reduced flashiness when comparing inflow to outflow and pre-construction to outflow hydrographs, including reducing peak flow magnitudes by >80% on average. Basin performance was not strongly affected by precipitation magnitude or antecedent conditions, though the range of precipitation magnitudes sampled was limited. Construction costs were higher than previously reported projects, but annual maintenance costs were similar and no higher than costs to maintain an equivalent landscaped area. Results indicate that bioretention basins effectively mitigate peak flow and flashiness, even in flash-flood-prone environments, which should benefit downstream ecosystems. The results provide a unique assessment of bioretention basin performance in flash-flood-prone environments and can inform the optimization of cost-effectiveness when implementing GSI at watershed scales in regions with current or future similar precipitation regimes.

Keywords: flood duration; flow flashiness; green infrastructure; hydrology; stormwater; urbanization; water retention



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1. Introduction

Stormwater management infrastructure is now applied worldwide to mitigate urban impacts to watershed processes [1–4]. The urban development of natural landscapes reduces infiltration and increases surface runoff, causing increased flashiness and higher peak flood levels in stream and river channels [5–8]. Urban development can also impair water quality in aquatic environments due to an increased runoff of pollutants from impervious surfaces during storm events [9–11]. Constructed facilities such as green rooftops, bioretention basins, cisterns, and rain gardens, also referred to as green stormwater infrastructure [12], are commonly applied to urban landscapes to recover processes lost during urban development, particularly stormwater retention and natural water filtering processes [13–16].

The previous monitoring of green stormwater infrastructure has generally found individual infrastructure projects effective at recovering natural processes [17–20]. In particular, retention basins have in many cases reduced runoff volume, mitigated peak flows, and improved water quality [21–23]. However, the performance of individual features does vary, due to multiple factors associated with storm events, basin design, and the timing of

runoff [20]. The most commonly cited cause of variability in the hydrologic mitigation effectiveness of individual green stormwater infrastructure features is the magnitude, intensity, and duration of precipitation events, with less proportional runoff captured in large magnitude events of high intensity or long duration due to finite basin storage volume [24–29]. The storage capacity of the basin relative to the size of the drainage area and amount of impervious cover in the drainage area is also a source of performance variability, since features with larger relative storage capacity can retain greater amounts of runoff [30–35]. The other properties of a feature, including the permeability of media or underlying soils for unlined systems, vegetation, and age can also affect performance [36–40]. Antecedent conditions at the time of runoff influence retention effectiveness, with wetter conditions generally reducing retention due to having some basin capacity already filled [41–43]. Seasonality also affects performance, with some studies finding reduced performance in cold seasons when soil freezing reduces storage capacity or in dry seasons due to the need to irrigate vegetation [44–47]. With climate change altering precipitation patterns in many regions, there is also a concern about the performance of green stormwater infrastructure under highly variable precipitation and runoff patterns [18,48–50]. For example, projects may be less effective when long periods without precipitation are punctuated with high-intensity runoff events, conditions often encountered in arid, semi-arid, or tropical climates.

In addition to the potential variability of hydrologic performance under different climatic patterns, most assessments of the hydrological effectiveness of green stormwater infrastructure have focused on downstream peak flow magnitude and total runoff volume [51,52]. Although runoff volume and peak flow magnitude are important from a flood mitigation perspective, there are other elements of runoff and streamflow patterns which are important ecologically [53,54]. Ecosystem functioning and aquatic biota in streams are also impacted by the frequency of flood events, the duration of floods, flood predictability (i.e., whether floods regularly occur at a specific time of year), and flood flashiness, defined as the rate at which streamflow increases and decreases [55]. Several studies have shown that bioretention basins and other green stormwater infrastructure can increase the lag time, defined as the time period between the start of precipitation and the start of runoff or between the centroid of precipitation and runoff peak flow [56–59]. Increases in lag time tend to decrease flow flashiness, since the routing of precipitation to streamflow is delayed. Previous research has also found lower flood frequency and longer duration flows, with lower peak flow when green stormwater infrastructure is present compared to untreated impervious cover [36,60–62]. Nonetheless, examinations of the effects of bioretention basins on multiple aspects of runoff and streamflow remain rare, and some elements of flow, such as the average rate of increase and decrease in flood events, have not been examined.

The potential benefits of green stormwater infrastructure beyond flood mitigation, such as for the protection or restoration of downstream aquatic habitat or the mitigation of heat island effects, are drawing increasing interest as a way to mitigate multiple impacts of urban development [4]. Cities are also increasingly incorporating networks of green stormwater infrastructure projects to manage stormwater runoff at watershed scales [63–67]. To support the city-wide planning of green stormwater infrastructure for multiple ecological benefits, models will be needed to scale the effects of individual green infrastructure features to cumulative effects for whole watersheds [68]. To inform such models, detailed information about the effects of individual features on multiple ecologically relevant aspects of hydrology will be needed. Information on the life-cycle costs of features, from planning through to yearly maintenance, will be important for large-scale planning as cities look for the most cost-effective designs [69,70]. Investigating the performance of green stormwater infrastructure in hydrologically variable climates will also help in understanding how features perform under possible future climate scenarios [71–74].

In this study, we aimed to answer questions about the effectiveness of bioretention basins in recovering the water retention features of natural landscapes and attenuating downstream hydrologic responses. Multiple ecologically relevant aspects of hydrology were assessed, including peak flow magnitude, as well as the duration of flood events and

several metrics of flow flashiness, including the rate of rise and fall of flood events. We monitored the hydrologic effects of two bioretention basins within the city limits of San Antonio, Texas, comparing the hydrologic metrics of runoff inflow to outflow and also inflow metrics at one basin to runoff metrics from a storm channel that existed prior to basin construction. Whether precipitation magnitude and antecedent moisture conditions affected the hydrologic performance of both basins was also assessed. Construction and maintenance costs and the applicability of individual bioretention basin projects for recovering natural hydrology in the region are discussed. The results provide unique information about the impact of bioretention basins on multiple hydrologic aspects and can be used in future watershed modeling that aims to inform the planning of green stormwater infrastructure for downstream ecological benefits at the watershed scale. In addition, because San Antonio is a climatological region naturally prone to intense precipitation events and flash flooding, the results can help inform how similar green stormwater infrastructure might perform under future climate scenarios with increasingly variable precipitation.

2. Materials and Methods

2.1. Study Site

We studied two bioretention basins on the University of Texas at San Antonio main campus (UTSA), on the northwest side of San Antonio, Texas (Figure 1). The climate of San Antonio is sub-tropical, with an annual average rainfall of approximately 800 mm. The UTSA campus is located over the Edwards Aquifer recharge zone, a narrow region of faults and fractures where runoff from surrounding landscapes percolates into the Edwards Aquifer, an important drinking water source for San Antonio and surrounding communities. The recharge zone marks a transition from the Edwards Plateau ecoregion to the north and northwest of San Antonio to Blackland Prairie and coastal plain ecoregions, and is a region prone to flash flooding due to a combination of topography and weather patterns that mix cold air masses from the north with abundant moisture from the Gulf of Mexico [75].

One of the basins was completed in November 2020 and is located near the center of campus, hereafter referred to as the central campus basin. The second basin was completed in February 2022. The second basin is located on the western edge of the campus and is hereafter referred to as the west campus basin. The central campus basin is larger, with an estimated maximum capacity of 1,520,000 L, whereas the west campus basin capacity is estimated at 100,000 L. The central campus basin is divided by an earthen berm into two sub-basins connected by an overflow pipe (Figure 1). Both basins had similar construction designs, which followed local guidelines [76], and consisted of an excavated pit lined with an impermeable liner and filled with a base layer of 0.4 m of washed gravel, a barrier layer of sand, and approximately 1 m of soil media mix. The soil media mix was covered with a layer of mulch and planted with native vegetation including Texas frogfruit (*Phyla nodiflora*), inland sea oats (*Chasmanthium latifolium*) and sedges (*Carex* sp.). Both basins are underlain by perforated PVC piping, which drains infiltrated water downslope. In the central campus basin, water that filters through both sub-basins drains to a concrete sump and is pumped over an earthen berm into a downstream open storm channel. In the west campus basin, water exits the basin underpiping via gravity into an underground stormwater pipe.

The central campus basin was constructed in and around a previously existing grass-lined drainage channel (Figure S1) and receives runoff from 5.5 hectares, including 3.8 hectares of impervious surface consisting of rooftops, campus walkways, and parking lots. The west campus basin was constructed in an open field and receives runoff from 0.4 hectares of parking lots (Figure S2).

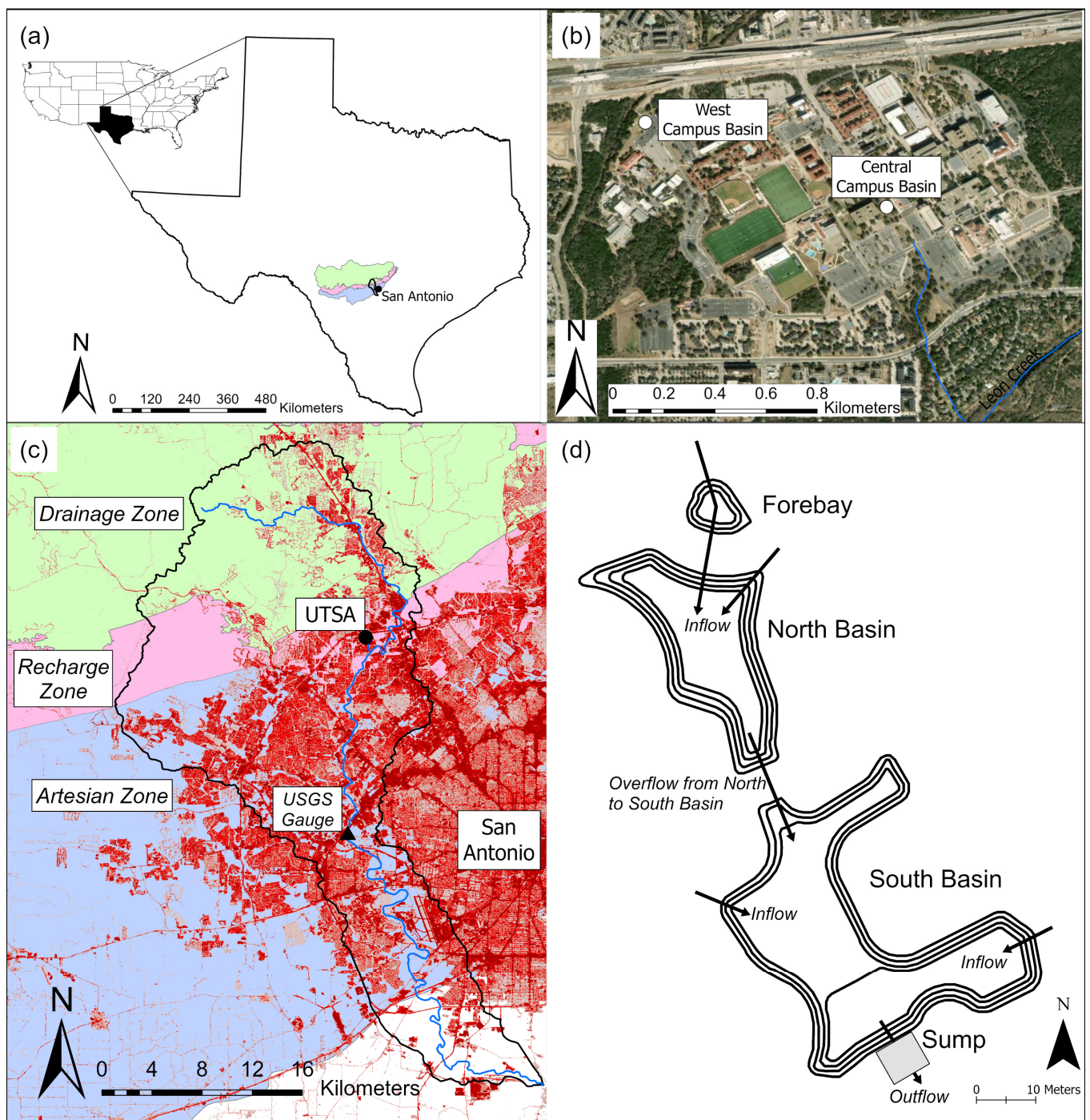


Figure 1. Map showing (a) the location of the Leon Creek watershed, San Antonio, and the Edwards Aquifer zones within the state of Texas, (b) the location of the central and west campus bioretention basins on the UTSA campus, (c) the UTSA campus and Leon Creek watershed along with the Edwards Aquifer zones, and (d) schematic diagram of the central campus basin showing the north and south basins divided by an earthen berm and connected by an overflow pipe from the north basin to the south basin. The red areas in (c) show urban developed land in and around the city of San Antonio. Also shown in (d) are major inflow points and the sump housing where water is pumped out of the basin as outflow. The contour lines in (d) are 0.3 m.

2.2. Estimation of Construction and Maintenance Costs

We assessed the construction and annual maintenance costs of the central campus basin. The west campus basin was constructed as part of a new building and several other

green stormwater infrastructure features, including a cistern and green roof, and thus the individual cost of the bioretention basin was not separable from the overall construction budget. However, maintenance activities are similar at both basins and maintenance costs for the central campus basin also apply to the west campus basin.

The total construction cost of the central campus basin included both design and construction activities. Construction activities included the excavation of the bioretention pit, the installation of the underpiping and basin fill materials, the testing of the biomedial mix to ensure compliance with design specifications, and planting and mulching the basin and the surrounding disturbed area. Maintenance activities have included aesthetic treatments, including mowing and trimming of vegetation in and around the basin and trash removal, and performance treatments including clearing sediment and other debris from inflows and the overflow structures in the basin. Total costs and costs per basin area and per basin storage volume are reported.

2.3. Flow Monitoring

The water depth during storm events was monitored in the pre-construction storm channel at the central campus basin site, in both sub-basins of the central campus basin, in the west campus basin, and in the outflow pipe of the west campus basin. Water depth was monitored in the concrete sump at the central campus basin, but inconsistent pump operation for several months after basin construction precluded the use of the sump data for this analysis. At all sites, bubbler tubing lines were attached to flow-level loggers (Teledyne Isco Signature flowmeter) to monitor water depth every 5 min. In the pre-construction channel at the central campus basin, the bubbler tubing was affixed to a concrete slab flush with the bed in the thalweg of the storm channel. In all three bioretention basins, the bubbler tubing was attached flush with the sediment in the deepest portion of the basin. In the west campus outflow pipe, the bubbler tubing was affixed to the bottom of the outflow pipe, which measured 10.2 cm in diameter.

At the time of installation of the bubbler tubing lines, the accuracy of depth readings was tested by placing tubing lines in a bucket and ensuring depth readings from the loggers matched the known depth. Level readings were also checked periodically during periods between flow events to ensure readings were at or near zero when water was not present. In rare cases when readings were not at or near zero during periods between precipitation events, we ensured the bubbler tubing lines were free of obstructions and then readjusted level readings to zero. We accepted an error of approximately 3 mm around zero-level readings.

In the pre-construction channel at the central campus basin and the west campus basin outflow, the water depth was converted to flow rate (Q) by Manning's equation:

$$Q = A \frac{1}{n} R_h^{2/3} S^{1/2} \quad (1)$$

where A = channel cross-section area, n = Manning's roughness coefficient, R_h = hydraulic radius, and S = slope. To determine the appropriate roughness coefficient for the pre-construction channel at the central campus basin and the outflow pipe at the west campus basin, the known properties of the channel and pipe were matched with recommended coefficients from published tables [77]. A roughness coefficient of 0.025 was used for the pre-construction channel, which was a mostly straight, uniform earthen channel with mowed grass. A roughness coefficient of 0.01 was used for the west campus basin outflow polyvinyl chloride (PVC) piping.

In both sub-basins of the central campus basin and the west campus basin, the known geometry of the constructed basins was used to convert water depth to water volume. The change in volume of the basins over time during the rising limb of storm events was used to calculate an inflow rate to the basins. The inflow rate to the basins is equivalent to the stormflow that would have occurred in a storm channel if the basins were not present to capture the stormflow, and is hereafter referred to as the without-basin hydrograph

(Figure 2). In the central campus basin, the change in volume over time during the falling limb of a storm event was used as the flow that actually did occur downstream of the central campus basin, because the receding water drained through the basin soils into the perforated PVC underdrain and was eventually pumped out of the basin into a downstream channel. This recession rate, plus an average recession rate added during the time of the rising limb of the stormflow event, was considered the with-basin hydrograph. Several runoff events in the main campus basin occurred before a previous event had completely drained from the basin. In these cases, the end of the previous event was marked at the start of the new event, and the existing water depth was used as the starting depth for the new event. However, of the flow metrics calculated (Table 1), only the duration of the with-basin hydrograph was affected in such cases.

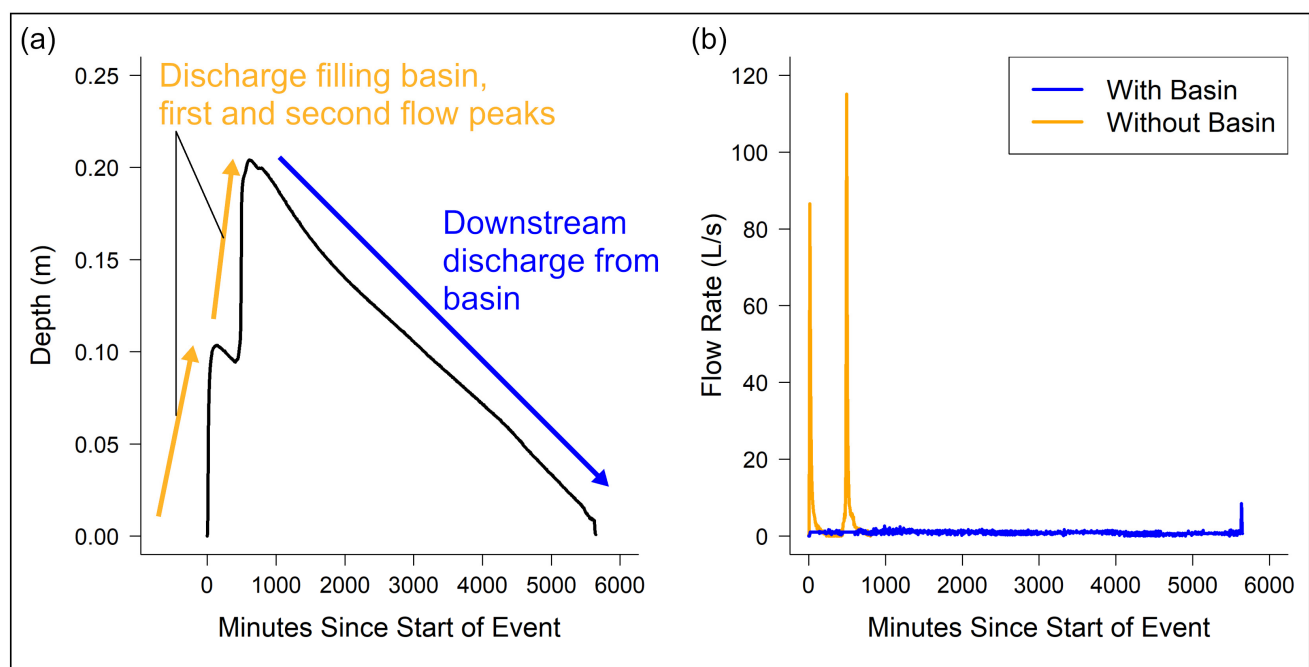


Figure 2. Example showing how with- and without-basin hydrographs were constructed from changes in water depth over time in the bioretention basins. Panel (a) shows the recorded changes in depth (black line) in the south basin during a runoff event on 3 November 2021. An increase in depth represents an inflow to the basin (highlighted by orange arrows), which would have passed downstream as flow without the basin in place. The decrease in depth represents the draining of the basin (highlighted by blue arrow), which was pumped downstream out of the basin. Panel (b) shows the resulting flow rate that would have occurred downstream of the basin without the basin (orange line) and the actual flow rate with the basin in place (blue line).

Table 1. Flow metrics calculated from hydrographs. For rise time and fall time, the first and last peaks of a storm event were sometimes different than the overall peak flow for multi-peaked events.

Metric with Units	Description
Peak flow rate (L/s)	Maximum discharge level during a storm event
Duration (Minutes)	Length of time between start and end of a storm event
Rise time (Minutes)	Length of time between start and first peak of a storm event
Fall time (Minutes)	Length of time between last peak and end of a storm event
Average rate of increase (L/s/minute)	Mean slope of periods of increasing flow during a storm event
Average rate of decrease (L/s/minute)	Mean slope of periods of decreasing flow during a storm event

2.4. Hydrograph Comparison and Statistical Analysis

To assess the effect of the central campus basin on peak flow levels and flow flashiness, for each flow event recorded, we calculated six metrics from the pre-construction, without-basin, and with-basin hydrographs, and tested whether flow metrics differed significantly between hydrographs (Table 1). Shapiro–Wilk tests were used to check normality assumptions for the six metrics within the pre-construction, without-basin, and with-basin dataset. The Shapiro–Wilk tests rejected the null hypothesis that metrics were normally distributed for all metrics in the with-basin, without-basin and pre-construction data except for without-basin fall time. Due to the mostly non-normal distributions, non-parametric Wilcoxon signed rank tests were used, rather than parametric *t*-tests, to determine the significance of the differences between with-basin, without-basin, and pre-construction metrics. Paired tests were performed to determine the significance of the differences between with- and without-basin metrics, because these two datasets have matched sample events (i.e., the with- and without-basin datasets have the same sample dates and number of samples, $n = 25$). Unpaired Wilcoxon rank-sum tests were performed to determine the significance of the differences between the with-basin and pre-construction datasets and between the without-basin and pre-construction datasets, because the pre-construction dataset had more samples ($n = 82$) and was sampled on different dates than the with- and without-basin datasets.

We conducted a similar analysis to assess the effect of the west campus basin on peak flow levels and flow flashiness. Shapiro–Wilk tests of normality showed that all metrics except duration from the with-basin hydrograph were normally distributed, but all metrics from the without-basin hydrograph had non-normal distributions. Due to the non-normal distributions for the without-basin hydrograph, Wilcoxon signed rank tests, as opposed to parametric *t*-tests, were used to compare metrics from the with-basin hydrograph to the without-basin hydrograph. Further, a paired test was used, because there were matched samples for every storm event from the with-basin and without-basin hydrographs.

To examine whether precipitation magnitude and antecedent conditions affected hydrologic performance of the basins, we first quantified precipitation magnitude and antecedent conditions for each storm event. Precipitation magnitude was quantified as the daily total precipitation for each event as measured at the nearest precipitation measurement station (GHCND:USW00012921, San Antonio International Airport, TX, USA). Antecedent moisture condition was quantified as the number of days since surface water was last detected in each basin. Using these metrics, we conducted two analyses. First, we identified storm events which overtopped the basin capacity and ranked the precipitation magnitude and number of days since surface water was detected to determine if events that overtopped basin capacity had the highest precipitation magnitudes or fewest number of days since surface water was detected of all storm events. Second, we calculated the percent reduction in peak flow, rate of increase, and rate of decrease and the percent increase in duration, rise time, and fall time from inflow to outflow for each storm event at each basin. For each metric at each basin, we then performed a simple regression analysis to determine whether the variation in metrics was explained significantly by precipitation magnitude or antecedent moisture conditions. All analyses were conducted using the R programming language with the tidyverse (version 2.0.0) and ggplot2 (version 3.4.3) families of packages as well as base R (version 4.3.1) functions [78].

3. Results

3.1. Construction and Maintenance Costs

The total construction cost of the central campus basin, including design planning, was \$2.34 million (Table 2). Approximate annual maintenance costs are \$13,200, primarily labor for vegetation management, which occurs approximately 18 times a year, and inlet sediment clearing, the frequency of which is dependent on amount of precipitation events. Annual maintenance activities at the central campus basin to date have been similar to

activities that occurred prior to bioretention basin construction, because similar landscaping and vegetation management occurred in the pre-construction grassy channel.

Table 2. Total construction and annual maintenance costs for the central campus basin and costs standardized by basin area, area of treated impervious cover, and volume capacity.

Cost Type	Total (\$Million)	Per Basin Area (\$/m ²)	Per Area of Treated Impervious Cover (\$/m ²)	Per Volume Capacity (\$/m ³)
Construction	2.34	1175	62	1539
Annual Maintenance	0.013	6.6	0.35	8.68

3.2. Hydrologic Performance

Known and potential sources of error in hydrographs, and thus calculated flow metrics, include errors in depth readings and errors in translating depth readings to flow rates. The estimated error in depth readings was 3 mm, and this error is small relative to flow depths during runoff events. For example, the minimum peak flow depth recorded during a runoff event was 14.7 mm on 23 October 2018 at the pre-construction channel at the central campus basin site. Using the known error estimate of 3 mm, peak flow rate could have varied from 2.3 to 4.8 L/s, or 30–40% of the estimated peak flow. The main source of uncertainty in translating depth to flow rate in the pre-construction channel at the central campus basin and in the outflow pipe of the west campus basin was the roughness coefficient. However, varying the roughness coefficient by 10% would only change peak flow estimates by an estimated 5%, since the flow depth is the main source of variability in peak flow estimates. No other metrics besides peak flow depended on the exact flow rate estimate, but instead depended on changes in flow rate from one time point to another or depended on the timing or ending of runoff or the timing of peak flow, which are less dependent on precise estimates of flow rate magnitude and thus have less error than peak flow estimates. Finally, our main comparisons were whether inlet and outlet flow metrics, and the pre-construction flow metrics at the central campus basin, were different relative to one another for each event, which is also less affected by exact estimates of flow rate beyond whether one is higher or lower than the other.

To further ensure the accuracy of comparisons between inlet and outlet hydrographs, we excluded several runoff events from analysis at the central and west campus basins. Runoff events were excluded whenever there was a lack of matching data at the inlet and outlet at a basin. In some cases, data for an event were missing at either the inlet or outlet due to a loss of power to the data logger during the event. In some cases, the data recorded at either the inlet or outlet were clearly inaccurate. Inaccurate data were identified by plotting a time series of the depth over the course of an event and looking for deviations from the normal increase and decrease in depth observed during runoff events (see Figure 2 for an example of a normal event). In some cases, the depth stayed at a constant level for at least an hour, and in some cases depth readings exceeded the known depth of the basin or diameter of the outfall pipe at the west campus basin. Such errors were either caused by obstructions in the bubbler tubing or malfunctioning data loggers. There was no obvious pattern as to the timing of excluded events or correlation with event magnitude, and thus no bias in comparisons is expected due to excluding events.

Flow monitoring in the pre-construction channel at the central campus basin site captured 82 stormwater runoff events between July 2018 and October 2019. Flow events in the pre-construction channel had a median duration of 278 min, with a median average rate of increase of 1.4 L/s/minute and a median average rate of decrease of −0.7 L/s/minute (Figure 3). The median peak flow rate was 79 L/s, with a maximum flow rate of 1352 L/s on 19 September 2019.

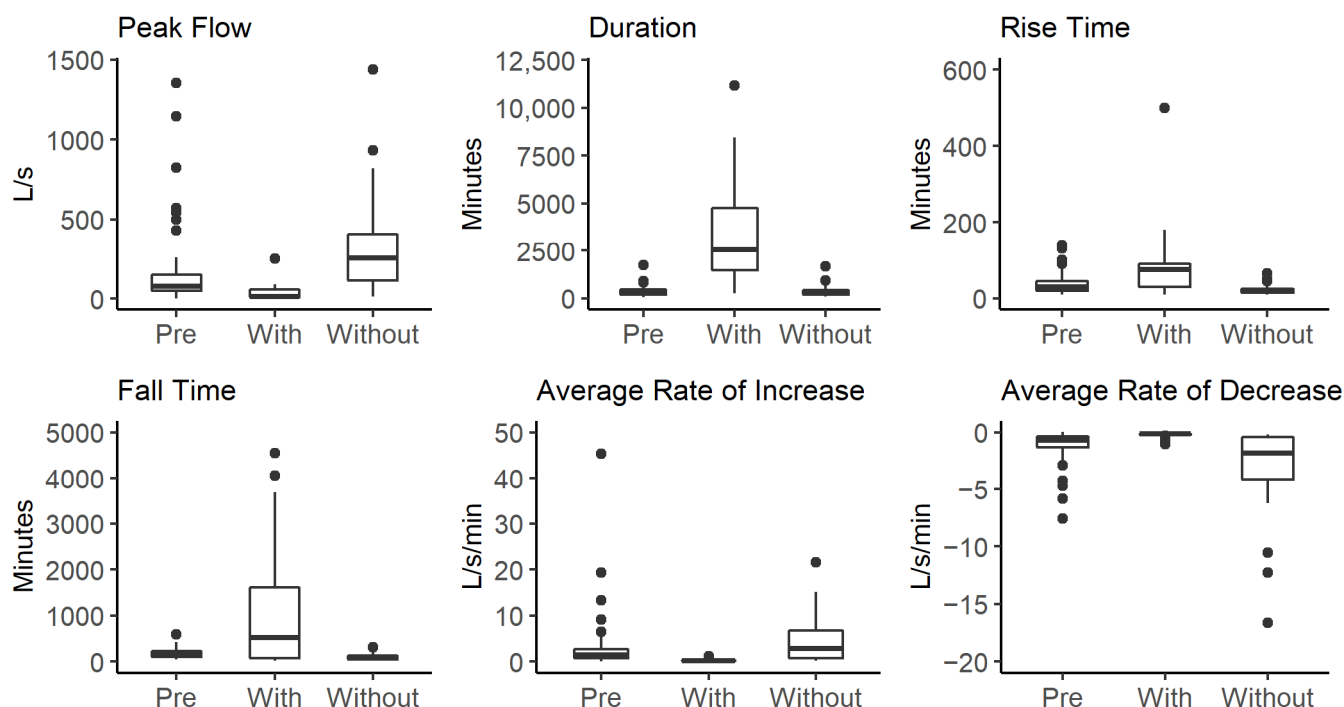


Figure 3. Box plots comparing flow metrics between pre-construction (Pre), with-basin, and without-basin hydrographs for the central campus basin. Boxes show 25th and 75th percentile (interquartile range) with the dark line indicating the median. Whiskers extend ± 1.5 times the interquartile range, with values outside whiskers indicated as individual points.

A total of 34 events occurred in the central campus basin during the monitoring period between February 2021 and February 2022. However, due to missing or inaccurate depth readings for one or both basins, we only used 25 of the events in the analysis (see Figure S3 for the hydrographs of all 25 events). Over the course of the monitoring period, eight events exceeded basin capacity, including six of the 25 events used in the analysis. The without-basin flow events had similar durations and average rates of increase compared to the pre-construction hydrographs (Table 3), though significantly higher peak flows, shorter rise times, higher fall rates (more negative), and shorter fall times (Figure 3). The with-basin flow events showed significantly longer durations, longer rise and fall times, lower peak flows, and lower average rates of increase and decrease compared to without-basin hydrographs and pre-construction hydrographs (Table 3; Figure 3). A comparison of with and without-basin flow metrics showed that the basin reduced peak flows on average by 83%, with a range of 44–98% across all monitored events. The rate of increase was reduced on average by 85% with a range of 41–99%, and the rate of decrease was reduced on average by 83% with range of 45–98%. The duration increased on average by 3000 min (2.1 days), with a range from 155 to 11,000 min (0.1–7.5 days); the rise time increased on average by 61 min with a range from –10–460, and the fall time increased on average by 1000 min with a range from –220–4400.

During the monitoring period of 28 June 2022 to 20 April 2023, 30 stormwater runoff events occurred at the west campus basin, of which 19 had matching inflow and outflow data (see Figure S4 for hydrographs of all 19 events). Two of the events exceeded the basin capacity. Similarly to the central campus basin, the without-basin hydrograph had significantly higher peak flows, shorter duration, shorter rise times, shorter fall times, and larger average rates of increase and decrease than the with-basin hydrographs measured in the outflow pipe (Table 4). The average percent reduction in peak flow magnitude at the west campus basin was 77%, with a range of 44–91%. The rate of increase was reduced on average by 88% with a range of 63–99% and the rate of decrease was reduced on average

by 93% with range of 80–99%. The duration increased on average by 185 min, with a range from −75–620 min, the rise time increased on average by 33 min with a range from −10–90 min, and the fall time increased on average by 181 min with a range from 0 to 585 min (Figure 4).

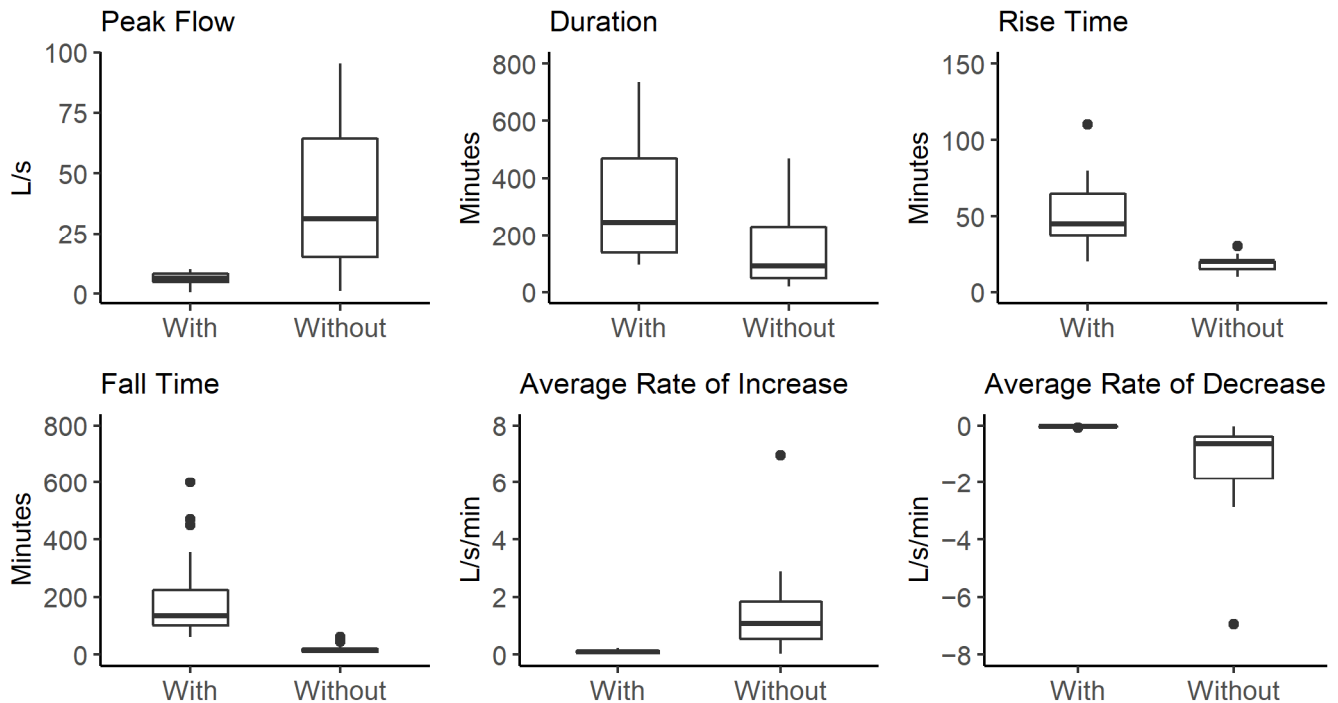


Figure 4. Box plots comparing with-basin and without-basin flow metrics for the west campus basin. Boxes show 25th and 75th percentile (interquartile range) with the dark line indicating the median. Whiskers extend ± 1.5 times the interquartile range, with values outside whiskers indicated as individual points.

Table 3. Table of comparisons between with-basin, without-basin, and pre-construction flow metrics for the central campus basin with test statistics and *p*-values. Pre-construction comparisons were conducted using unpaired Wilcoxon tests, whereas without-basin metrics were compared to with-basin metrics using paired Wilcoxon tests.

Metric	Pre-Construction vs. Without-Basin		Pre-Construction vs. With-Basin		Without-Basin vs. With-Basin	
	Test Statistic	<i>p</i> -Value	Test Statistic	<i>p</i> -Value	Test Statistic	<i>p</i> -Value
Peak flow	$W = 560$	<0.01	$W = 1658$	<0.01	$V = 0$	<0.01
Duration	$W = 949.5$	0.6	$W = 100$	<0.01	$V = 325$	<0.01
Rise time	$W = 1410$	<0.01	$W = 614$	<0.01	$V = 224$	<0.01
Fall time	$W = 1526$	<0.01	$W = 744$	0.04	$V = 286$	<0.01
Average rate of increase	$W = 803$	0.1	$W = 1889$	<0.01	$V = 0$	<0.01
Average rate of decrease	$W = 1392$	<0.01	$W = 303$	<0.01	$V = 325$	<0.01

Table 4. Table of comparisons between with-basin and without-basin flow metrics for the west campus basin with test statistics and *p*-values. Comparisons between with-basin and without-basin metrics were performed using paired Wilcoxon tests.

Metric	Test Statistic	<i>p</i> -Value
Peak flow	$V = 0$	<0.01
Duration	$V = 181$	<0.01
Rise time	$V = 188.5$	<0.01
Fall time	$V = 171$	<0.01
Average rate of increase	$V = 0$	<0.01
Average rate of decrease	$V = 190$	<0.01

Four of the six events that overtopped the central campus basin had the highest precipitation magnitudes of all storm events measured at the central campus basin, with all precipitation events >49 mm overtopping the basin. Three of the overtopping events at the central campus basin also occurred when water was still present in the basin. However, one event overtopped the basin with the third lowest precipitation magnitude and after more than a week of no water present. The two events that overtopped the west campus basin were the third and sixth highest precipitation magnitudes, and both occurred at least five days after surface water was present. Precipitation magnitude and antecedent moisture conditions did not strongly affect the hydrologic performance of the two bioretention basins. Precipitation magnitude showed a significant, or nearly significant, effect only on the rate of increase and rate of decrease at the central campus basin and the rise time at the west campus basin, measured as percent change from inflow to outflow (Table 5). Precipitation magnitude was positively correlated with percent change in all metrics, indicating that the basins had a greater effect on these flow metrics during higher magnitude precipitation events. However, the explained variance was low for all relationships ($r^2 < 0.25$ in all cases). Number of days since surface water was present in the basins did not significantly influence any metrics at either basin (Table 5).

Table 5. Table showing *p*-values and r^2 -values for regression analyses between the indicated predictor variable and different hydrologic metrics for both the central campus and west campus basins. Hydrologic metrics were analyzed as percent difference between inflow and outflow.

Response Variable	Central Campus Basin				West Campus Basin			
	Precipitation Magnitude (mm)		Antecedent Condition (Number of Days since Surface Water Present)		Precipitation Magnitude (mm)		Antecedent Condition (Number of Days since Surface Water Present)	
	<i>p</i>	r^2	<i>p</i>	r^2	<i>p</i>	r^2	<i>p</i>	r^2
Peak flow	0.66	0.008	0.49	0.02	0.36	0.05	0.57	0.02
Duration	0.54	0.02	0.34	0.04	0.86	0.002	0.58	0.02
Rise Time	0.83	0.002	0.34	0.04	0.05	0.22	0.22	0.09
Fall Time	0.96	0.27	0.42	0.03	0.26	0.07	0.68	0.01
Rate of Increase	0.06	0.15	0.96	0.0001	0.18	0.10	0.15	0.12
Rate of Decrease	0.04	0.18	0.31	0.04	0.57	0.02	0.64	0.01

4. Discussion

The effectiveness of bioretention basins to mitigate flooding issues caused by increasing urban development and recover more natural flow patterns is important to address, as cities increasingly look to such green stormwater infrastructure investments to manage stormwater runoff. Understanding the costs of green stormwater features and their performance in climates with highly variable precipitation will also help inform cost-effective planning. Here, we investigated the impacts of two constructed bioretention basins on downstream flow patterns, including peak flow magnitude and flashiness. Bioretention basins effectively reduced downstream peak flows and flashiness at the small watershed scale (0.055 km²). Precipitation magnitude and length of time since previous runoff did not negatively affect basin performance, showing basins performed well under varying weather conditions, at least for small- to moderate-magnitude precipitation events, and still attenuated flows effectively, even for events that did exceed bioretention basin capacity. Thus, bioretention basins appear to work effectively as stormwater management infrastructure even in environments prone to flash flooding. The results presented here provide unique information on how bioretention basins impact flow flashiness and can be used in planning to assess the cost effectiveness of bioretention features.

Both the central campus and west campus basins significantly reduced peak flow magnitude and the metrics of flow flashiness and increased flow duration when comparing incoming hydrographs to outflowing hydrographs. Comparisons of outflowing hydrographs from the central campus basin to pre-construction hydrographs further showed that the construction of the basin reduced peak flows and measures of flow flashiness for stormwater runoff events from the local catchment. Specifically, peak flow magnitude and rates of flow increase and decrease were reduced by >80% on average. Similar average magnitudes of peak flow reduction have been found in other field investigations of bioretention basins [79–83]. However, substantial variability in peak flow reduction percent has been reported across basins and storm events, essentially ranging from 0 to 100% [1]. Peak flow reduction ranged from 37 to 96% in southeastern Australia [80], 0–100% in Ohio, USA [82], 19–100% in Virginia, USA [84], and from <0 to 99% in North Carolina and Maryland, USA, although <0 values may have represented measurement errors [21,30,40]. Other studies have reported a narrower range of variability. For example, peak flow reduction ranged from 80 to 100% in Virginia, USA [81], 86–96% in Vermont, USA [85], 63–100% in Montreal, Canada [86], 75–100% in Queensland, Australia [87], and from 86.1 to 92.3% in a study of basins built with compost and biochar-amended media in India [88]. Factors influencing peak flow reduction effectiveness have been primarily related to the size and intensity of storm events, as well as bioretention basin design, such as basin size relative to contributing impervious surface area [13,18,20,89]. The range of variability in peak flow reduction effectiveness for the basins studied here (44–98%) falls between the high and low ranges previously reported, suggesting the basins are performing similarly in the climate of south Texas, which is prone to flash flooding, compared to other regions throughout the world.

Few other studies have investigated impacts to flow flashiness [51,52]. Those that have investigated lag time usually find that bioretention basins increase lag time [13,41,89]. For example, bioretention basins delayed peak flow by a factor of two or more in Maryland and North Carolina, and by 6.7 h on average compared to untreated impervious surface cover in Montreal, Québec, Canada [21,30,86]. Lag time, defined as the time between the start of rainfall and the start of runoff, increased by 5–60 min, depending on rainfall scenario, with an average of 26 min when bioretention was combined with other green infrastructure in Shanghai, China [62]. Bioretention planters increased lag time in New Jersey, with a median increase of 77.5 min compared to untreated runoff [58]. Beyond lag time, previous studies have usually found that basins reduce metrics of flashiness such as rate of stormflow increase and decrease [90], consistent with the results of our analysis, though individual feature effects do not always translate to significant impacts at the watershed scale [91]. An increase in flashiness caused by urban development,

combined with higher peak flood magnitude, often leads to downstream channel erosion and incision [10,92]. Thus, the mitigation of urban-driven increases to flow flashiness by the bioretention basins should help prevent the degradation of channel habitat in watersheds undergoing urban development in addition to mitigating flood issues downstream.

The reduction in peak flow volume and flow flashiness and the increase in flow duration is due to the capturing of runoff by the basins during storm events, followed by a slow release of the stored water over a longer time as the water infiltrates through the basin soil and into the underdrain. Although previous work has shown this mechanism to be effective at reducing runoff volume and attenuating peak flows of small- to moderate-magnitude storm events [20], questions have been raised about whether bioretention basins and other green stormwater infrastructure may be less effective in increasingly hydrologically variable climates, as expected in many regions with climate change [50,74,93,94]. Although the largest precipitation events and several events that occurred before the complete draining of the basin did completely fill the central campus basin, precipitation magnitude and antecedent basin dryness had minimal impact on basin hydrologic effectiveness as measured by reductions in peak flow and flow flashiness. Precipitation magnitude significantly influenced flashiness metrics, including rate of rise and rate of fall, but there was a positive relationship between precipitation magnitude and percent reduction in rate of rise and rate of fall, indicating basins did better at mitigating flashiness of stormwater runoff in larger magnitude precipitation events. Our study was conducted in a region naturally prone to flash flooding, and these results suggest bioretention basins can still perform effectively in regions with similar climate or in regions where precipitation variability may increase in the future under climate change.

An important limitation of our conclusions about the hydrologic effectiveness of the basins under variable precipitation magnitudes is that the range of daily precipitation sampled here (0.3–67 mm) does not capture the full range of daily precipitation that occurs in the area. For example, the estimated 100-year precipitation event for the region is approximately 300 mm [95]. Although we did find that the peak flows and flashiness of the six monitored events that exceeded the central campus basin capacity and the two events that exceeded the west campus basin capacity were still reduced by the basins, precipitation events with a very high magnitude were not monitored, and it is likely that basin effectiveness is lower during such events, as has been found in other studies [24–26,33]. Future studies that sample across a larger range of precipitation magnitudes would further help clarify whether there is a precipitation magnitude threshold above which effectiveness of hydrologic treatment starts to decline.

The effectiveness of the basins in attenuating peak flows and reducing flashiness shows that new urban developments can be effectively treated to reduce peak flows in local channels with bioretention basins. The central campus basin had a footprint of 0.23 hectares, which is 4% of the watershed area treated, showing that the treatment of stormwater from new developments can occur with relatively little land area devoted to green stormwater infrastructure [34]. Construction and maintenance costs are also important when assessing the feasibility of using any type of green stormwater infrastructure feature for stormwater management [96,97]. The construction cost of \$1175/m² for the central campus basin was higher than the previously reported costs of similar features, which have ranged between \$35–513/m² [67,97–100]. Costs were likely higher for the central campus basin due to it being a retrofit project and because significant effort and cost went into landscaping the basin for aesthetic purposes, because it is located in a highly trafficked area of the campus. However, the construction and maintenance cost relative to the impervious area treated (\$62.4/m²) is similar to the estimated cost \$87.5/m² for another bioretention feature in south Texas [34], and the estimated annual maintenance costs of \$6.6/m² were within the range of previously reported maintenance costs of \$0.23–17/m² [96,97,100,101]. We did not perform a cost–benefit analysis, but previous studies have generally found bioretention basins a worthwhile investment, especially when other benefits beyond hydrological performance are considered, though other green stormwater infrastructure features may

be more cost-effective in many scenarios [70,99,101]. Our data can be used in regions with similar climate to weigh costs against hydrologic benefits, such as costs saved by preventing flood damage or ecological degradation. However, future research into other potential benefits of the bioretention basins, such as aesthetic appeal or heat mitigation, would be important for a full accounting of the benefits of such green stormwater infrastructure projects. Similarly, the proper construction of bioretention basins, such as the installation of biomedial design specifications, influences long-term maintenance and operation and long-term performance [20], and such constraints will need to be incorporated into potential basin costs.

The bioretention basins studied here were constructed in a region with a climate typical of many arid or semi-arid and tropical climates, which often experience long periods without precipitation punctuated by high-intensity rainfall and runoff events. Our flow monitoring showed that bioretention basins are effective at mitigating hydrologic impacts of urban development locally, and even though large events can overwhelm storage capacity, peak flows and flow flashiness are still reduced compared to the untreated condition. Cities in similarly variable current or future climates looking to use similar green stormwater infrastructure for mitigating urban impacts to hydrology can use the results presented here to inform green infrastructure planning and optimization. Future research can help further inform such planning by investigating water quality performance and short-term and long-term changes in hydrological processes of basins under highly variable precipitation regimes. For example, even though high-intensity and large-magnitude events can overwhelm basin capacity, long antecedent dry periods between runoff events could be beneficial, allowing time for evaporation to increase storage capacity and water retention [43,102]. On the other hand, long antecedent dry periods may reduce effectiveness if vegetation is reduced due to drying [46,49]. Previous work has found consistent or even improved hydrologic effectiveness with basin age [40,84,103], but whether such conclusions hold in arid and semi-arid climates is still uncertain. Water quality treatment effectiveness depends on soil saturation conditions and resulting redox potentials within basins [104–106]. Water quality treatment effectiveness may also be compromised by long dry periods due to the loss of vegetation unless irrigation is supplied [46,107,108], although appropriate design guidance may alleviate this issue [31].

The monitoring of inflow and outflow hydrology of two bioretention basins showed this type of green stormwater infrastructure can effectively reduce peak flows. Unique to this study, bioretention basins were also found to reduce flow flashiness, including rate of increase and decrease in peak flows. Although other assessments of basin effectiveness, such as water quality treatment or effects on downstream temperatures, would help provide a more comprehensive analysis of overall ecological benefits, the results do provide further evidence that green stormwater infrastructure is likely to provide downstream ecological benefits wherever applied by mitigating peak flow magnitudes and flashy flows typical of urban development, likely reducing sediment erosion and channel incision [109]. Combined with the potential additional benefits of bioretention basins, especially when integrated into land-use planning [110,111], such as water quality treatment [30,37,112,113], wildlife habitat [114], groundwater recharge [115,116], promoting resilience to climate change [117–120], and green space in urban areas, which can provide cooling, recreational, education, and aesthetic benefits [4,19,121–123], green infrastructure projects are likely to be cost-effective methods for managing stormwater runoff from new developments, even in areas prone to flash flooding. The cost data reported here provide unique information needed to formally assess cost-effectiveness as part of green stormwater infrastructure planning. Research is starting to show further hydrologic benefits for individual bioretention basins of low-cost amendments such as biochar [59,88,124], and improved hydrologic effectiveness at the watershed scale through the real-time operation of networks of green stormwater infrastructure features [125–127]. Continued research in these areas will be important to further help improve cost-effectiveness.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w16182597/s1>. Figure S1: Photographs showing (a) the grassy channel prior to construction of the central campus bioretention basin and (b) the constructed bioretention basin approximately two years after construction. View is from the north end of the north basin looking south.; Figure S2: Photograph showing the west campus bioretention basin, marked by the gravel and cobbles in front of the building. The parking lot on the left of the picture drains into the bioretention basin.; Figure S3: Hydrographs of all analyzed events at the central campus basin. Each plot shows an individual storm event, with the with-basin hydrograph shown in the dotted line and the without-basin hydrograph shown in the solid line.; Figure S4: Hydrographs of all analyzed events at the west campus basin. Each plot shows an individual storm event, with the with-basin hydrograph shown in the dotted line and the without-basin hydrograph shown in the solid line.

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