Urban Hydrology Restoration: Proof of Concept Modeling

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Abstract

Urban development without the benefit of stormwater controls degrades stream structure and function, often referred to as the urban stream syndrome. Regulations that apply controls to development are in place in most cities, but there is often a large and costly legacy of dysfunctional stream systems with water quality, erosion and flooding problems and limited areas for economically feasible restoration. Recent research on the connection between urban stormwater hydrology and the urban stream syndrome suggests that this efficient delivery of contaminated, highly erosive and large magnitude flows is the root cause of the degradation that plagues urban streams. In Austin, Texas, building on the international movement toward small-scale distributed stormwater controls, a watershed-scale proof of concept project is taking form that will test the hypothesis that dense, distributed stormwater control measures, on both public and private property, can significantly buffer the negative effects of legacy urban development on stream hydrology. A small, 2.8 km^2 (1.08 mi^2) urban catchment, with 46% impervious cover was selected to examine this hypothesis.

Using a recently developed Green Stormwater add-on to the Soil and Water Assessment Tool (SWAT) modeling program, and historic United States Geological Survey (USGS) gage data to calibrate the model, three implementation scenarios (Low, High and Maximum) were modeled using key hydrologic metrics as the response variables. Results show incremental hydrologic improvements corresponding to the density of stormwater control measures, with changes from current conditions in these metrics improving <1-30% in the low density scenario, 1-140% in the high scenario, and 4 – 287% in the maximum scenario. Most notably, key indicators of stream flashiness (baseflow, peak flow, rate of change) all showed improvement directly corresponding to density of stormwater control measures, which in turn predict significant improvements in stream ecological health. In the High density scenario, where approximately 42% of impervious cover is disconnected via distributed stormwater controls, the hydrology of the stream is comparable to a more suburban development level (equivalent to 20-30% total impervious area),

where overall stream health and associated co-benefits are predicted to improve substantially (up to 40% improvement over current condition). Depending on potential implementation costs and a progressive service delivery model where private property stormwater controls are a critical component, the concept of distributed small-scale distributed controls is a viable and potentially singular urban hydrologic restoration solution to a range of urban stream stressors and municipal water quality and quantity burdens.

Introduction

In urban watersheds in Austin, Texas, where the majority of development occurred before environmental regulations were in place, impacts on hydrological function are severe, causing erosion, loss of baseflow, water quality degradation and flooding impacts (Walsh et al. 2005, Chadwick et al. 2006, Hawley and Bledsoe 2011). Furthermore, in dense urban areas, opportunities to build regional structural stormwater controls are often scarce and may be challenging from a cost/benefit perspective due to high land values. Increasing emphasis is now being placed on smaller-scale heavily distributed projects that rely heavily on soil, vegetation, and ecological processes to manage stormwater (Bernhardt and Palmer 2007, Roy et al. 2009, Kaushal et al. 2015, Pennino et al. 2016). Distributed stormwater control measures (SCMs) have been recognized as having the potential to address the hydrological drivers of the urban stream disturbance regime (Walsh et al. 2015, Hawley and Vietz 2016, Vietz et al. 2016).

Controlling impervious cover is frequently used as a regulatory tool to limit degradation of aquatic and other ecological systems. Although there is no agreed upon single limit on impervious cover that will protect all streams, values in the 10 – 20% range are persistent in both municipal code and in studies worldwide (Booth and Jackson 1997, Paul and Meyer 2001, Center for Watershed Protection 2003, Miltner et al. 2004, Walsh 2004, Frazer 2005).The City of Austin has impervious cover limits that have been in place since 1986 (City of Austin 1981) that have helped prevent degradation in a range of streams during an extensive period of growth in population and development (Duncan et al. 2010, Gilroy and Richter 2010, Scoggins and Richter 2010, Duncan and Wagner 2011). In Austin, water quality studies have found degradation responses correlating to a range of impervious cover levels, ranging from 5-30%, suggesting that protecting and/or restoring watersheds at or below these levels would be protective of aquatic ecosystem integrity (Scoggins 2000, Glick et al. 2010, Herrington 2010, Richter 2011, King et al. 2016).

The Imagine Austin Comprehensive Plan calls for the use of green infrastructure to enhance environmentally sensitive areas and integrate nature into the city as a priority program (City of Austin 2012). Imagine Austin targets improving the health of our watersheds, tree cover, and the connection between people and the environment while also emphasizes the need for close coordination across existing efforts and departments to achieve these goals.

The potential flood, erosion and water quality effects of a suite of stormwater controls were examined in a previous modeling study of the Brentwood/Grover tributary of Shoal Creek (Geosyntec 2014) referred to as the Brent Study. This older urban drainage system experiences frequent flooding caused by a combination of an undersized stormwater conveyance system as well as structures in close proximity to the creek. The Brentwood Study evaluated a maximum build-out of stormwater control measures (SCM) and a combination of both green and traditional grey stormwater structures. The primary response variables of the modeling focused on reduction of peak flows and total volumes. Although the results showed significant reductions in smaller storm peak flows and volumes (~30% for 1-5 year recurrence interval storm events), benefits for larger events were quite a bit smaller (~10% for 10+ year recurrence interval events). Pollutant load reductions were estimated based on volume reductions (~26%), and erosion potential benefits estimated based on lowering shear stress (30-50%). However, beyond the results for peak and volume control, the benefits to groundwater recharge and stream baseflow hydrology were not thoroughly assessed. The Brentwood Study recommended that further modeling work be done in these areas and suggested a "block-scale pilot implementation project to verify or adjust model estimates".

The modeling effort described in this report follows the framework of the Brentwood Study recommendations but proposes the use of a watershed with longer-term gaged flow data (2007-present, USGS gage 08156910). Using the newly available green stormwater modules in SWAT, we examine the potential for catchment scale distributed SCMs to improve current stream hydrological measures, primarily focusing on baseflow metrics, in a relatively small (~1 mi^2) headwater section of a fully developed urban creek (Waller Creek Segment 3 also known as WLR3). We propose three SCM distribution scenarios (maximum, high and low) to test the hypothesis that distributed storage and infiltration of stormwater in this basin will positively affect a range of hydrologic metrics associated with stream health (Scoggins 2000, Glick et al. 2010, Richter 2011).

Methods

Study Area

WLR3 is the most upstream headwater reach of the Waller Creek watershed, encompassing approximately 2.79 km^2 (1.08 mi^2) bound to the south by Koenig Lane (Fig 1) where the USGS gauge is located.

The area is dominated by gentle slopes (0-8 percent) with natural topographic patterns obscured by urban development (Fig 2). Three soil groups occupy most of the area within WLR3: UsC and UtD, both urban soils with parental material from weathered chalk with overall good drainage (saturated hydraulic conductivity ranging from 0.2 to 2.0 inch/hr (0.5 to 5.0 cm/hr), and HsD, Huston Black soils derived from calcareous shale and moderately drained (saturated hydraulic conductivity ranging from 0.001 to 0.06 inch/hr (0.0036 to 0.15 cm/hr) (Fig 3).

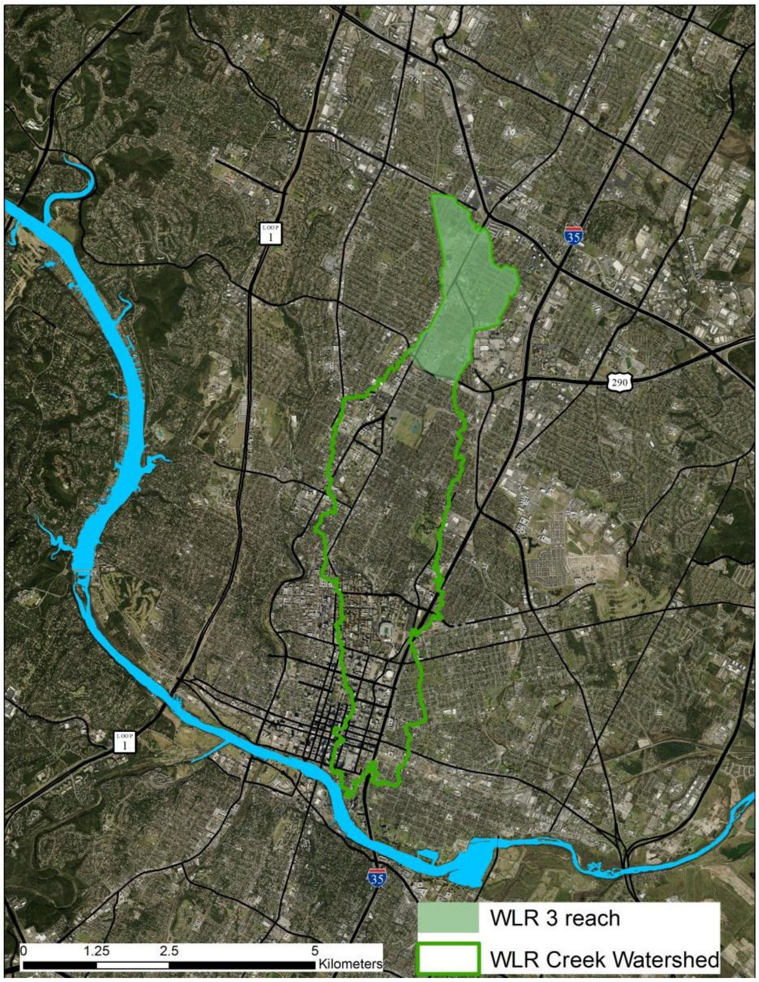

Figure 1. Waller Creek Watershed and WLR3 reach (green shaded area), Austin TX

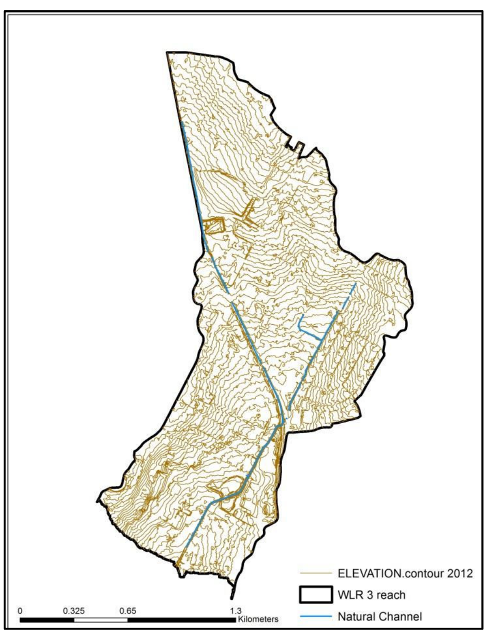

Figure 2: WLR3 reach topography

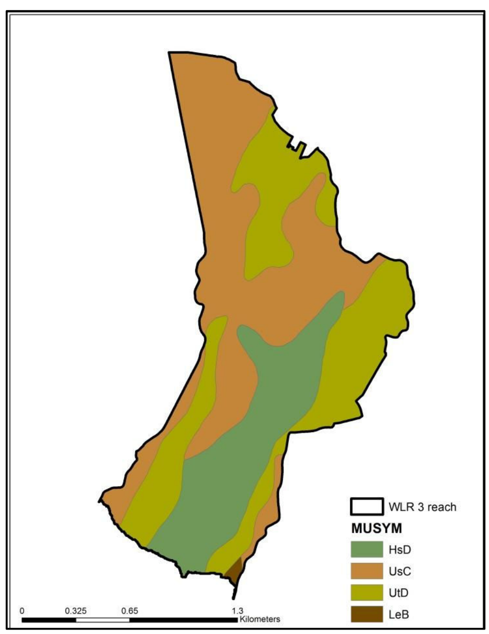

Figure 3: WLR3 reach soils

The historical aerial photographic record for the study area shows that in 1940 most of the area was cropland with initial residential development beginning in early 1950's and industrial/commercial uses appearing in the early 1960's (Fig 4, 5, 6). The overall development footprint has been in place since at least the late 1990's (Fig 7, 8) with most additions in impervious cover occurring in the northwest portion of the watershed.

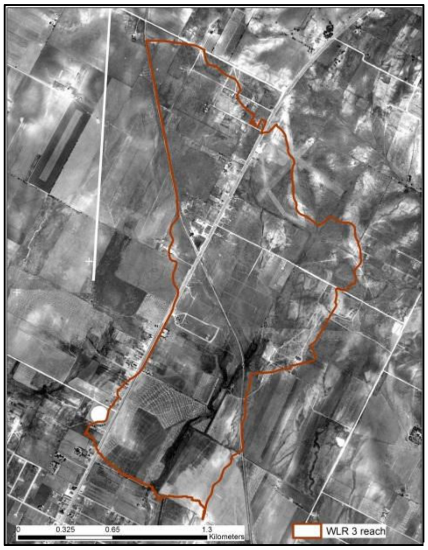

Figure 4: WLR3 reach 1940

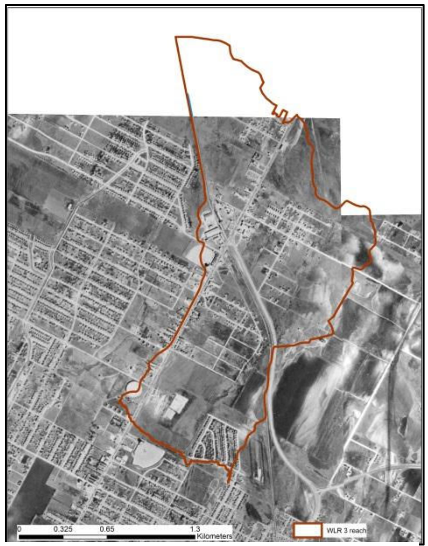

Figure 5: WLR3 reach 1951

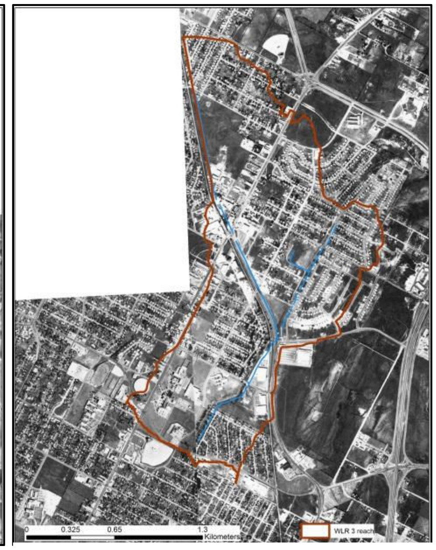

Figure 6: WLR3 reach 1964

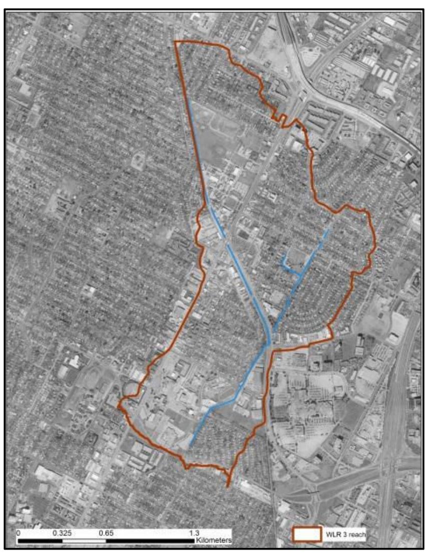

Figure 7: WLR3 reach 1997

Figure 8: WLR3 reach 2015

According to City of Austin (COA) land use data from 2012, most of the area (~40%), is dominated by residential land uses including single family, duplex and multifamily. Commercial, office and industrial land uses represent less than 20% (Fig 9, Table 1). Since 2012, the proportion of undeveloped land use has decreased with a concomitant increase in single family. Currently, impervious cover encompasses approximately 47% of WLR3.

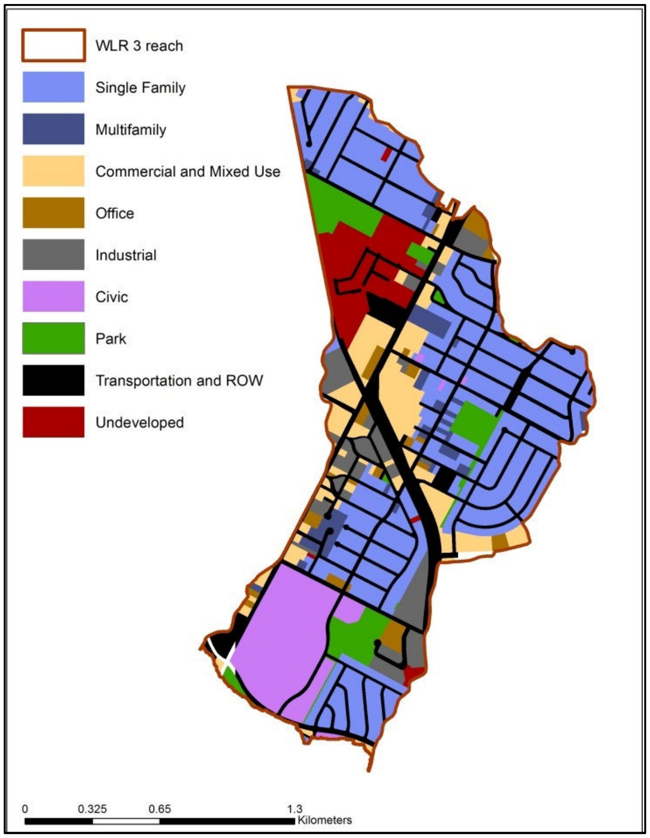

Figure 9: WLR3 reach 2012 Land Use

Table 1: Acreage and percent of the total area represented by each Land Use Category in 2012

Land Use Category	Area (2012)	Percent (2012)
Single Family and Duplex	245	35.8
Multifamily	20	2.9
Commercial	65	9.4
Office	17	2.4
Industrial	40	5.9
Civic	65	9.5
Park	42	6.1
Transportation	150	21.8
Undeveloped	43	6.2

Hydrological Model Calibration

This modeling exercise consists of a series of scenarios evaluated for the Waller Creek watershed using SWAT with different land use and SCM assumptions.

The initial SWAT model was developed using COA land use from 2003, a 10-ft Digital Elevation Model, the Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) soils data, distributed 15-minute rainfall from the Flood Early Warning System (1987-2009), supplemented by gauge-adjusted Next-Generation Radar data from the National Oceanic and Atmospheric Administration (2009-2014), Austin temperature data from the National Climatic Data Center and SWAT climate station data. The model was calibrated with SWAT-CUP using data from Waller Creek at 23rd Street at a station operated and maintained by COA (period of record 1992-present) for the years 2001-2004. The Nash-Sutcliffe model efficiency coefficient (NSE) was used to assess the success of the calibration. The NSE is a normalized statistic that measures the relative magnitude of the modeled variance compared to the measured data variance from the mean. Model simulations are considered acceptable when the NSE > 0.50 (Moriasi et al. 2007). The calibration resulted in a model with a Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) of 0.72 using a sub-hourly time and 0.91 using a daily time step. SWAT-CUP was rerun using calibration data from Waller Creek at Koenig Lane from a station maintained and operated by USGS (08156910, period of record 2007-present) for the years 2009-2012. The resulting NSE was 0.68 using a sub-hourly time step and 0.90 using a daily time for Waller Creek at Koenig Lane and 0.71 using a sub-hourly time step and 0.91 using a daily time step for Waller Creek at 23rd Street for the same period. The model incorporated existing SCMs. Landscape management (irrigation, fertilization and mowing) were also incorporated for residential and commercial lawn areas, with the exception of high slopes. The plant cover was assumed to be Bermuda and a fixed watering schedule, a fertilization schedule based on plant stress, and regular mowing during the growing season were applied and were unchanged between simulations.

The calibrated model was used to run a series of scenarios which applied impervious cover evenly distributed across the watershed that varied from 15 to 50%.
The impervious cover scenarios were run for 26 years (1989-2014, with a two year warm-up period) and flow was output at three locations in Waller Creek, Koenig Ln, 23rd St, and Cesar Chaves which correspond to the EII reaches WAL3, WAL2 and WAL1 respectively. This paper focuses on WAL3, at Koenig Lane and the SCMs are located within its approximate one square mile drainage area.

SCM Implementation Scenarios

Three SCM implementation scenarios were modeled with different saturation of two types of SCMs: cisterns receiving runoff from building roofs and raingardens receiving runoff from paved surfaces. The SWAT modules for small distributed control measures such as cisterns and raingardens act as temporary or infiltration storage. They are represented as a distributed set of controls that are physically located within the model within subbasins, and applied specific Hydrologic Response Units (HRUs, each of which have a unique combination of soil, slope and land use). Within the selected HRUs, these small scale SCMs treat only runoff from connected impervious surfaces; both pervious surfaces and disconnected impervious cover is routed overland. The SCM itself is located within disconnected impervious areas. For these simulations, land use specifically was used to apply varying levels of SCM treatment. Within a subbasin, depending on the size, the physical location of SCMs is only specified by the type of land use they are applied to; and a change of level of treatment is not specific to individual buildings or lots. Subdivision of a watershed into smaller subbasins would allow that level of specification; for this simulation, WAL3 was divided into four subbasins.

Raingarden depths varied according to the saturated hydraulic conductivity of the different soils. UtD and UsC soils had a theoretical ponding depth of 12 inches while HsD soils were only 1.5 inches, in compliance with the COA Environmental Criteria Manual (ECM) Section 1.6.7(H). Raingarden volume was calculated by SWAT to comply with the water quality volume requirements in ECM Section 1.6.2. Cisterns were sized to capture a 2 inch rainfall event from the average roof size in each land use (Table 2).

SCM modeling scenarios were simulated using actual Austin rainfall from 1987-2014 to evaluate hydrologic metrics response to SCM implementation over a variety of weather conditions. Results presented in this report do not use the 1987-1988 modeling warm-up period. Hydrologic metrics were calculated for current conditions (calibration), the different levels of impervious cover, and each of the SCM scenarios over the entire modeling period (1989-2014). Some metrics were also calculated for the wettest (1991-1995) and the driest (2008-2012) consecutive five year rainfall periods to provide further insight into variability during more extreme years.

SCM implementation scenarios differ only in the proportion of the roof and paved surfaces treated. All other model assumptions were constant among scenarios. None of the three SCM scenarios include treatment of transportation land use impervious surfaces beyond what treatment is currently provided by existing regional SCM already considered in the current conditions run. For all scenarios, the impervious cover treated was circumscribed to paved surfaces (exclusive of transportation land use) and roofs within the parcels of each of the considered land uses.

Table 2 Average roof (acres) and cistern volume (gallons) for different land use category evaluated in the model scenarios

Land Use Category	Average roof area (acres)	Cistern volume (gallons)
Single Family and Duplex	2,150	2,500
Multifamily	6,933	8,000
Commercial	10,522	12,500
Office	10,427	12,500
Industrial	16,688	20,000
Civic	13,605	15,500

<u>Maximum saturation SCM (Max)</u>

In the Max scenario, runoff from all directly connected impervious cover surfaces from most land uses was directed to either a cistern or a raingarden (Table 3, 4), with the exception of transportation. Although this is most likely an unrealistic scenario in terms of implementation and capture, we were interested in examining the maximum potential hydrological departure from current conditions in order to determine whether or not it was appropriate to continue with additional modeling scenarios. After results from the Max scenario were obtained, the two additional scenarios were modeled.

High saturation SCM (High)
In contrast with the Max scenario, in the High scenario the proportion of runoff directed to SCM differs between roof and paved surfaces as well as among land use categories (Table 3). It is assumed that single family land use paved surfaces, mostly in the form of driveways, are directly draining to the street and it may not be cost-effective to redirect that runoff to a raingarden. In addition, this scenario assumes that 25% of the roof surface for all land uses may not be directed to a cistern given that some roofs may have complex designs rendering gutter systems too complicated.

This scenario is optimistic about the degree of adoption by private landowners implementing SCMs in their parcels while taking into consideration some of the potential technical difficulties of treating 100% of the impervious cover within each parcel.

Low saturation SCM (Low)
This scenario was defined as being 33% of the level of treatment provided by the High scenario (Table 3). The Low scenario can be interpreted as a substantially lower adoption of SCMs by private landowners, and thus allows us to examine the potential results of the early implementation stages on the ground. Alternatively, this scenario can be interpreted as a 33% of the level of treatment provided by the High scenario within each parcel. Because SWAT does not spatially model individual SCMs, the two interpretations are equivalent.

Table 3: Percent impervious cover within each land use category treated by raingardens (RG) or cisterns (CS) in each of the three scenarios examined

Land Use Category	Max	High	Low
Single Family and Duplex	100% roof → CS 100% paved → RG	75% roof → CS 0% paved → RG	25% roof → CS 0% paved → RG
Multifamily	100% roof → CS 100% paved → RG	75% roof → CS 50% paved → RG	25% roof → CS 17% paved → RG
Commercial	100% roof → CS 100% paved → RG	75% roof → CS 50% paved → RG	25% roof → CS 17% paved → RG
Office	100% roof → CS 100% paved → RG	75% roof → CS 50% paved → RG	25% roof → CS 17% paved → RG
Industrial	100% roof → CS 100% paved → RG	75% roof → CS 50% paved → RG	25% roof → CS 17% paved → RG
Civic	100% roof → CS 100% paved → RG	75% roof → CS 50% paved → RG	25% roof → CS 17% paved → RG

Table 4: Total acreage of impervious cover within each land use category treated by SCMs in each of the three scenarios examined

Land Use Category	Total Paved IC	Total Roof IC	IC area treated			Total # Parcels
			Max	High	Low	
Single Family	18.1	61.1	79.2	45.8	15.3	1,257
Multifamily	8.0	6.9	14.8	9.1	3.1	40
Commercial	37.3	25.6	62.9	37.9	12.7	88
Office	9.2	5.7	14.9	8.9	3.0	22
Industrial	18.6	15.9	34.5	21.2	7.1	40
Civic	32.8	11.6	44.4	25.1	8.5	13
% of all IC in WLR 3 treated			71.4 %	42.2 %	14.2 %	
% of all surface area treated			26.4%	16.0%	3.4%	

In contrast with the Brentwood Study, the Max and High scenarios in this report capture a larger volume of rainfall in cisterns in the overall watershed area (approximate capture: Max~1,140 ft^3/acre, High ~855 ft^3/acre, Low ~285 ft^3/acre) (Table 5). The overall volume of water captured in the maximum green infrastructure scenario in the Brentwood Study equaled 143,000 ft^3 equivalent to approximately 400 ft^3/acre as a result of targeting implementation of cisterns at lower proportions of each land use and fewer individual lots in each planning area.

Table 5: Total water volume (ft^3) capacity within each land use for cisterns (CS) in each of the three scenarios examined

Land Use Category	Max	High	Low
Single Family and Duplex	420,091	315,068	105,023
Multifamily	42,778	32,083	10,694
Commercial	147,049	110,286	36,762
Office	36,762	27,572	9,191
Industrial	106,944	80,208	26,736
Civic	26,937	20,202	6,734
Total volume	780,561	585,421	195,140

Hydrologic Metrics Selection

Building on prior studies relating creek flow to biological health, COA examined local data to identify hydrologic metrics that were regionally appropriate given the dominance of intermittent streams in the urban Austin area using daily flow statistics (Glick et al. 2010) and later using sub-daily flow statistics (Richter 2011). These analyses were undertaken to identify indirect linkages that might lead to a better understanding of the potential response of creek systems to best management practices that attempt to modify the hydrologic regime. The metrics selected were those highly correlated to a composite multi-metric Aquatic Life Score used by COA to measure the health of the diatom and benthic macroinvertebrate communities in creeks (Clamann et al. 2015), as well as additional metrics which are related to the potential for creek erosion (Table 6). Most metrics were calculated using the 15-minute time step simulated flow. Some metrics were calculated at the daily time-step if previous analyses indicated that explained a higher proportion of variation.

An analysis was conducted using WinXSPro to evaluate potential changes to erosive flows, defined in this study as those larger than 50 ft^3/s (cfs). The 50 cfs value was selected as the flow at which a median particle size (d50) of 16 mm would be mobilized on this reach of Waller Creek. The actual measured median particle size on this reach of Waller creek was much larger (64 mm), but reflects the current heavily scoured condition.

Table 6. Descriptive flow metrics utilized

Hydrologic Variable	Units	Description
Q_{mean}	cfs	Mean flow rate during the period
Q_{peak}	cfs	Peak flow rate during the period
Q_{90}	cfs	Flow rate that is exceeded 10 percent of the time during the period, the 90th percentile.
COV	--	Standard deviation of flow divided by the mean flow during the period (Poff and Ward 1989)
BFR	--	Fraction of flow considered baseflow after three passes with a digital filter
+mean	cfs	Average rise rate: mean of all positive differences between consecutive daily values (Richter et al. 1996)
-mean	cfs	Average fall rate: absolute value of the mean of all negative differences between consecutive daily values (Richter et al. 1996)
T_{Qmean}	--	Fraction of time during the period that the flow exceeds the mean flow for the period (Booth et al. 2001, 2004)
T_{dry}	--	Fraction of time during the period that the flow was less than 0.1 cfs (Richter et al. 1996)
F_{Ld}	cfs	Average duration of periods when flow remains below 0.1 cfs (Richter et al. 1996)
F_{Ln}	--	Average number of low flow periods per year, where a low flow period is flow remaining below 0.1 cfs for at least 15 minutes (Richter et al. 1996)
F_{Hd}	cfs	Average duration of high flow events during the period, with a high flow event defined as sustained flow greater than 0.1 cfs. (Richter et al. 1996).
F_{Hn}	--	Average number of high flow events per year, where a high flow event is defined as sustained flow greater than 0.1 cfs for at least 15 minutes (Richter et al. 1996)
TQE		Fraction of time during the period that the flow exceeds the erosive flow of 50 cfs
F_{En}		Average number of erosive flow events per year, where flow was above the 50 cfs erosion threshold, lasting at least 15 minutes
F_{Ed}		The average duration of erosive flow periods above 50 cfs

Results

The effects of SCM implementation can be illustrated by changes in the hydrograph among scenarios during a sample storm event. In general, peak flows are reduced more substantially with increased implementation of SCM (Fig 10). These changes in the hydrograph are quantified in the diverse array of hydrological metrics. At high levels of SCM implementation, peak flows (Q_{peak}) and flow variation (SD and COV) decrease (Table 7). This is expected since some of the runoff is detained temporarily during storm events. The baseflow ratio (BFR) increased with the increased density of SCMs as stormwater capture reduces runoff and favors slower shallow groundwater release from saturated soils and shallow groundwater.

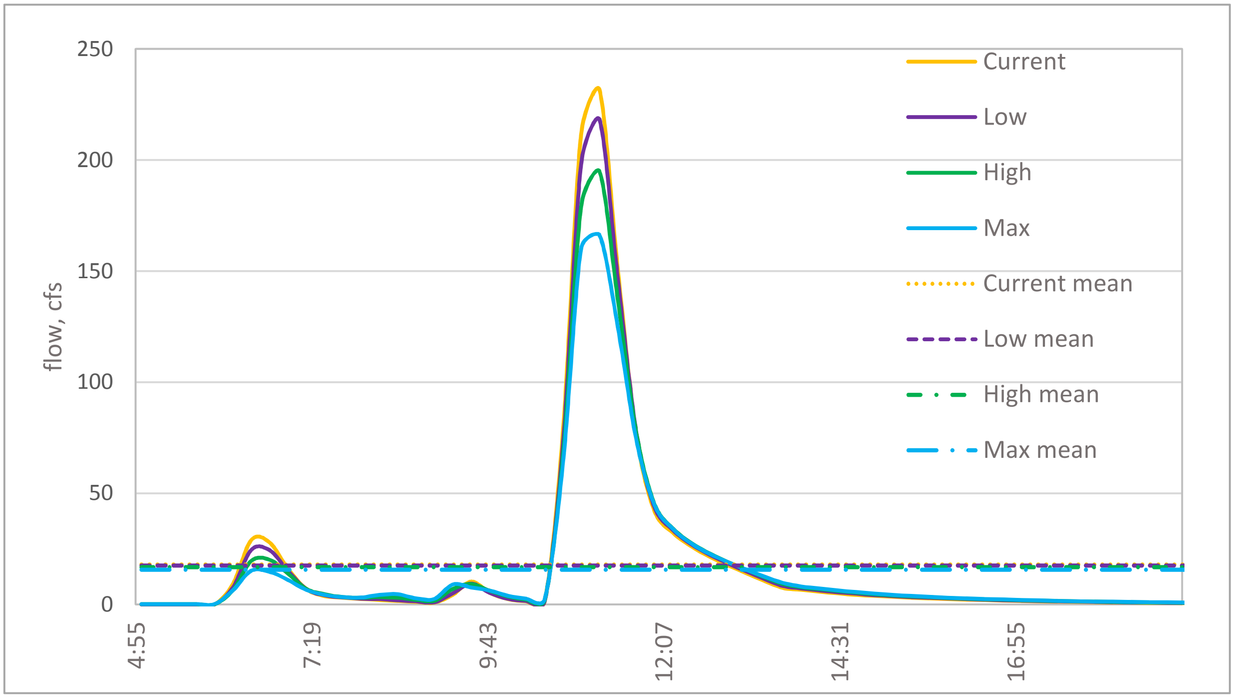

Figure 10: Snapshot hydrograph: Instantaneous flow (solid lines) and long term average flow (discontinuous lines) during a series of three storms of different magnitudes under varying SCM implementation scenarios

The degree of changes in the hydrological metrics relative to the current conditions model in response to each of the SCM scenarios varies among metrics (Table 7). Mean flow (Q_{mean}) decreased while the 90th percentile (Q_{90}) flow increased. The two metrics for the High scenario coincide roughly with the values corresponding to approximately 30% impervious cover (Fig 11).

The increase in Q_{90} with higher saturation of SCMs reflects the change in the flow regime as it redistributes stormflow peaks to baseflow. With more SCMs, the flow rate for 90% of the flows increases even though the peak is decreasing.

The range of Q_{peak} for all scenarios (900 to 1,500 cfs) compared with Q_{90} (of <1 cfs), and the fact that the Q_{mean} is higher than Q90 for all but the Max scenario, demonstrates the extreme flashiness of the flow regime in this urbanized watershed (Table 7).

Table 7. Flow statistics for the entirety of the modeling period (1989-2014) with difference (%) relative to the current conditions in parenthesis

Statistic	current	low (Δ)	high (Δ)	Max (Δ)
Q_{mean}	0.68	0.58 (-14%)	0.46 (-31.3%)	0.38 (-43.6%)
Q_{peak}	893	805 (-9.8%)	688 (-22.9%)	593 (-33.5%)
Q_{90}	0.23	0.26 (13%)	0.34 (47.8%)	0.43 (86.9%)
SD	7.98	6.81 (-14.6%)	5.36 (-32.8%)	4.28 (-46.3%)
COV	11.81	11.73 (-0.6%)	11.55 (-2.1%)	11.24 (-4.8%)
BFR	0.12	0.13 (13.9%)	0.18 (54.6%)	0.26 (122.2%)
+mean	2.10	1.72 (-18.2%)	1.24 (-41.1%)	0.85 (-59.5%)
-mean	1.55	1.26 (-18.9%)	0.9 (-41.7%)	1.07 (-30.9%)
T_{Qmean}	0.06	0.07 (4.7%)	0.08 (25.9%)	0.11 (69.5%)
T_{dry}	0.86	0.85 (-1.3%)	0.82 (-4.5%)	0.8 (-7.6%)
F_{Ld}	4.70	4.59 (-2.1%)	4.46 (-5%)	4.38 (-6.6%)
F_{Ln}	67.04	67.62 (0.8%)	67.38 (0.5%)	66.35 (-1%)
F_{Hd}	0.77	0.82 (6.7%)	0.96 (24.7%)	1.12 (45.2%)
F_{Hn}	65.73	66.46 (1.1%)	67.65 (2.9%)	66.73 (1.5%)
TQE	0.18	0.18 (3.2%)	0.19 (4.5%)	0.25 (40.8%)
F_{En}	18.77	16 (-14.7%)	10.81 (-42.4%)	6.88 (-63.3%)
F_{Ed}	1.26	1.18 (-6.4%)	1.17 (-7.3%)	1.22 (-3.2%)

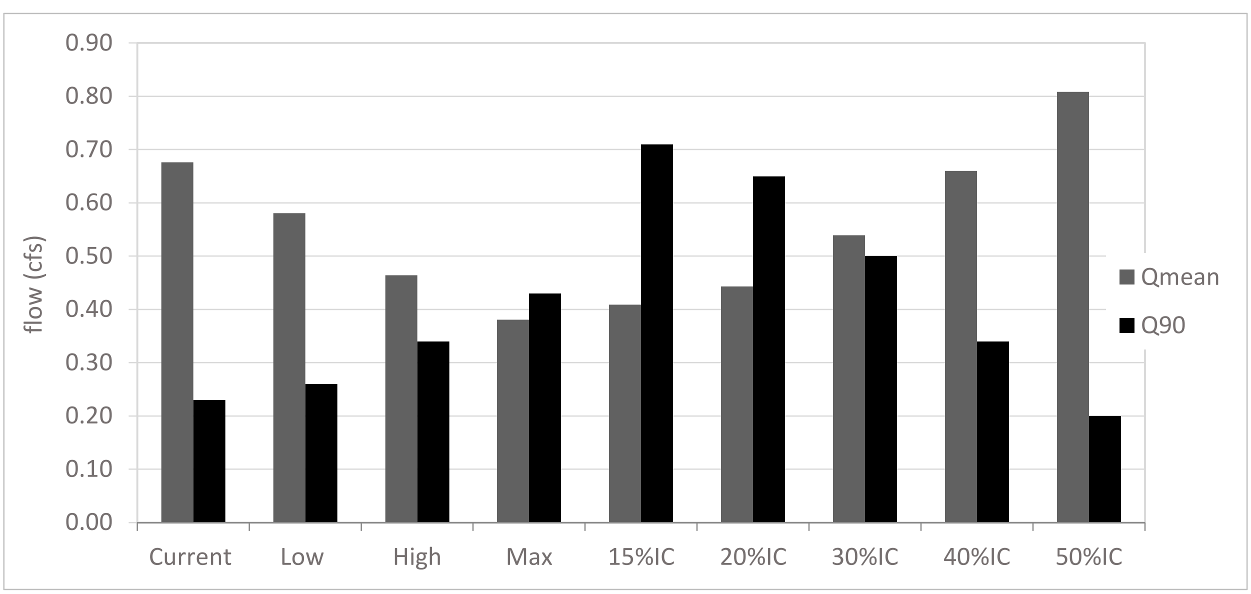

Figure 11: Average flow (Qmean) and the 90th percentile of flow (Q90) for the entirety of the modeling period (1989-2014) in comparison to various levels of effective percent impervious cover (IC)

Although Q_{peak} is an important metric to examine and results demonstrate a reduction of peak flows with the implementation of SCM (Figure 12), focusing only on peak flows is a narrow view of the full hydrograph. A more robust look at the flashiness of the system can be observed through statistics like the baseflow ratio (BFR) which increases with higher degree of SCM implementation (Fig 13). The High scenario has a BFR value (0.18) that is very close to the predicted BFR for 30% impervious cover (0.19). Another robust indicator of flow variability is overall standard deviation of flow values. Results showed decreasing standard deviation with increasing SCM implementation (Fig 14) reflecting the dampening effect of SCMs on the variability of the hydrograph.

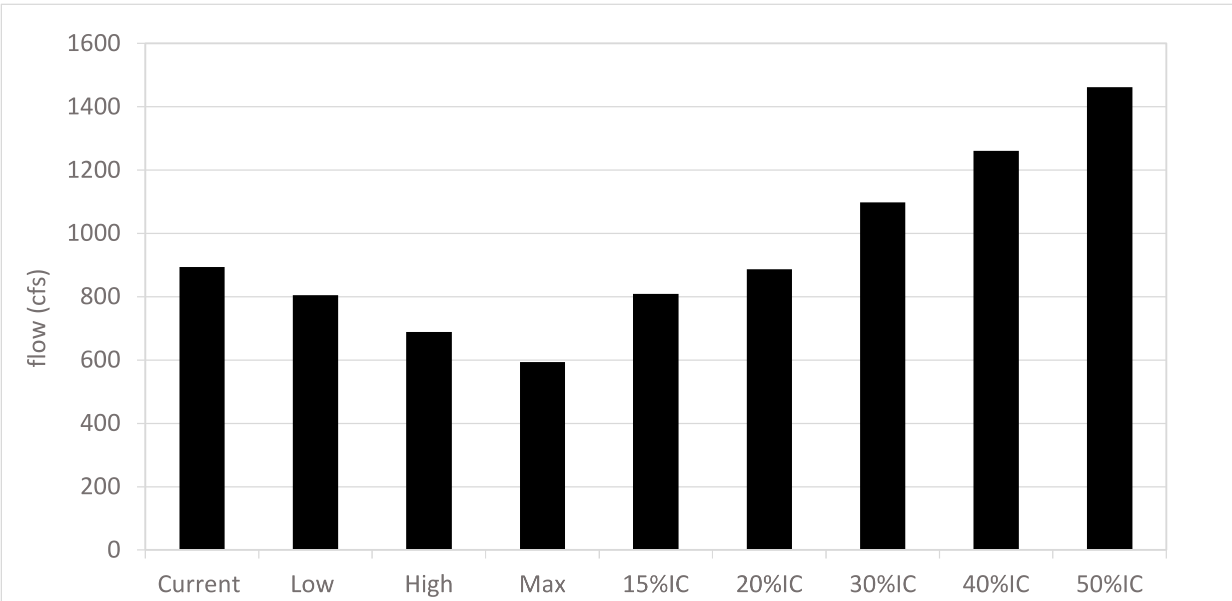

Figure 12: Qpeak: peak flow for the entirety of the modelling period (1989-2014)

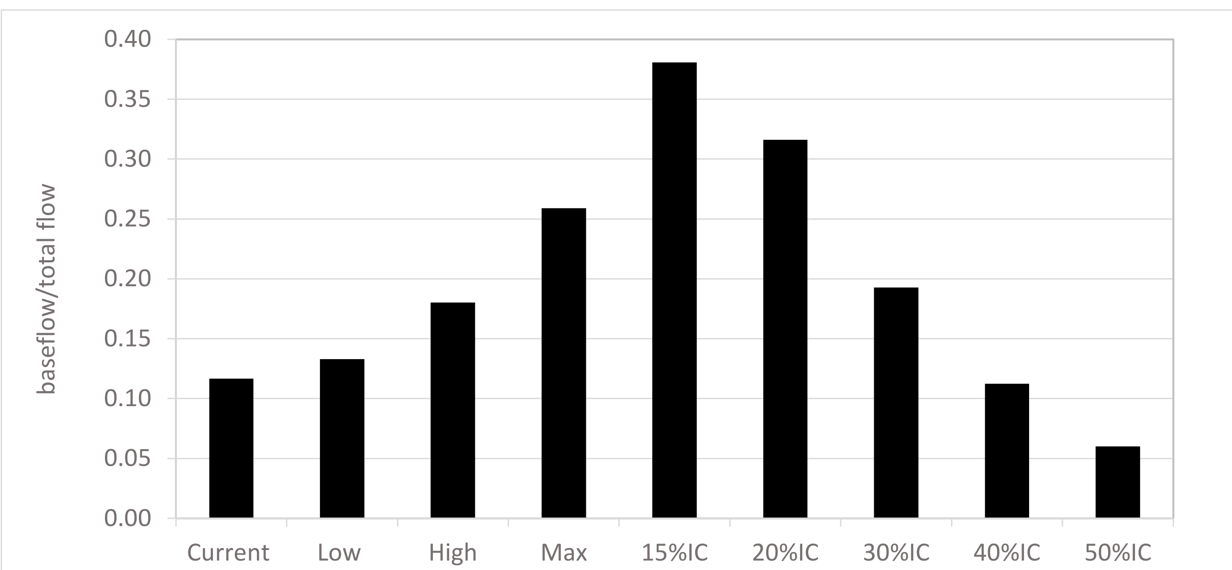

Figure 13: Ratio between base flow and total flow (BFR) for the entirety of the modeling period (1989-2014)

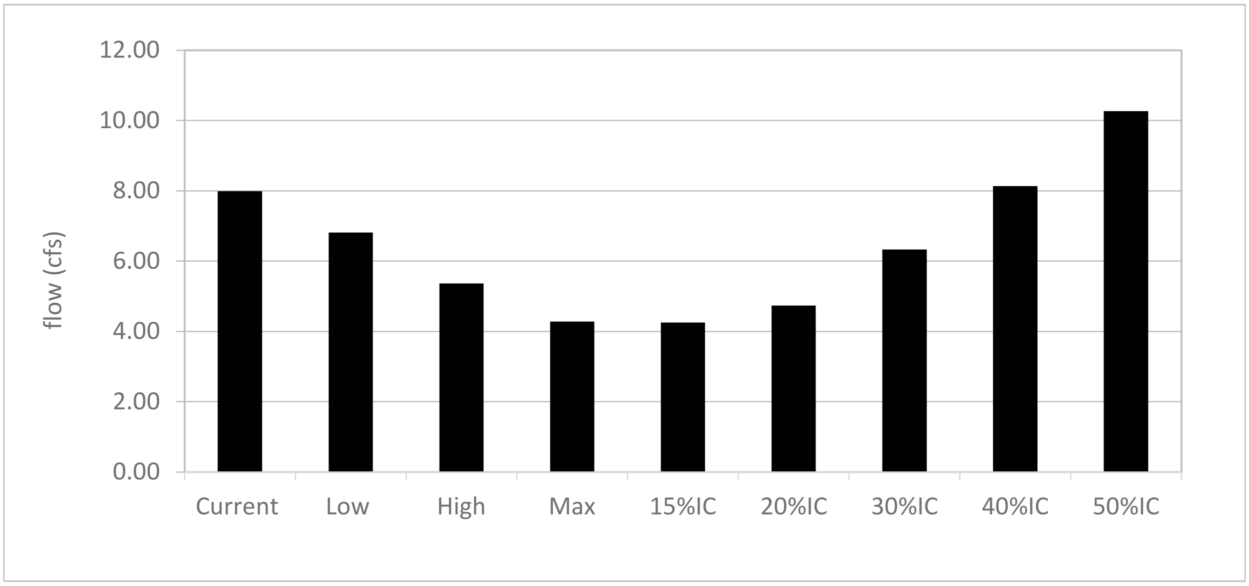

Figure 14: Flow standard deviation for the entirety of the modeling period in the current and 3 modeled SCM scenarios (1989-2014)

Changes in the flashiness of the system are also illustrated by changes in the rising and falling limbs of the hydrograph (Figure 15). Larger values for these two metrics represent a rapid runoff from impervious surfaces and a lack of return flow from the shallow groundwater. Compared to current conditions, there is a decrease in the magnitude of both metrics with increased implementation of SCM.

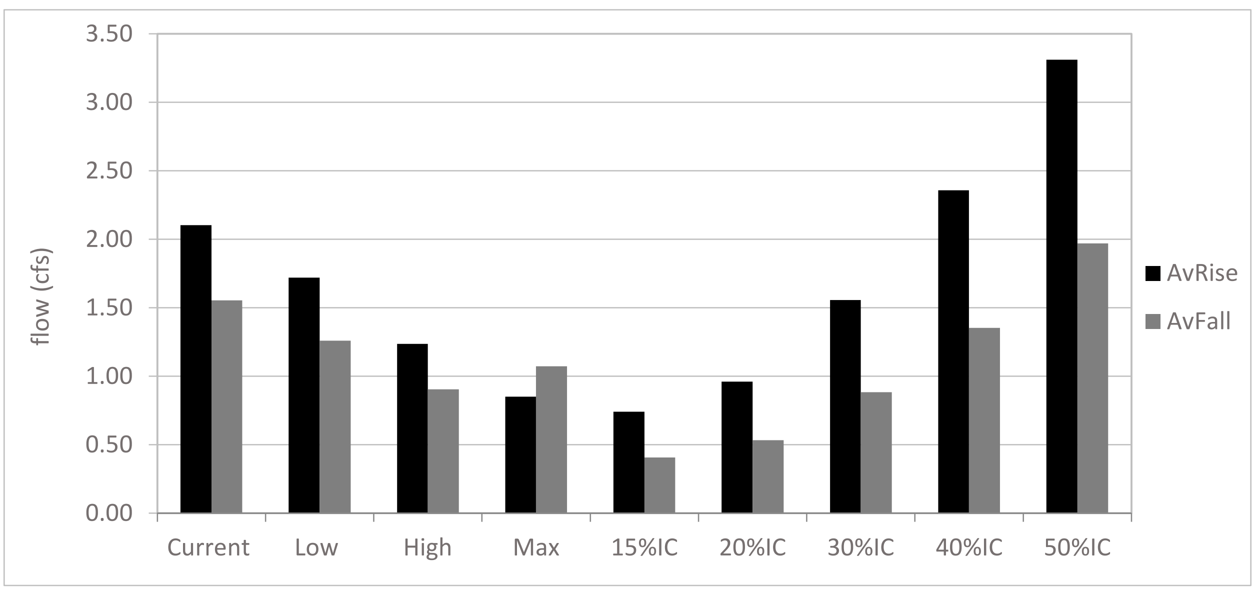

Figure 15: Average daily rise in flow for the entirety of the modeling period (1989-2014)

Although the three SCM implementation scenarios did not substantially change the duration of low flow events, or the duration of erosive flows (>50 cfs), it increased the duration of high flow events (sustained flow > 0.1 cfs) (Figure 16, 17).

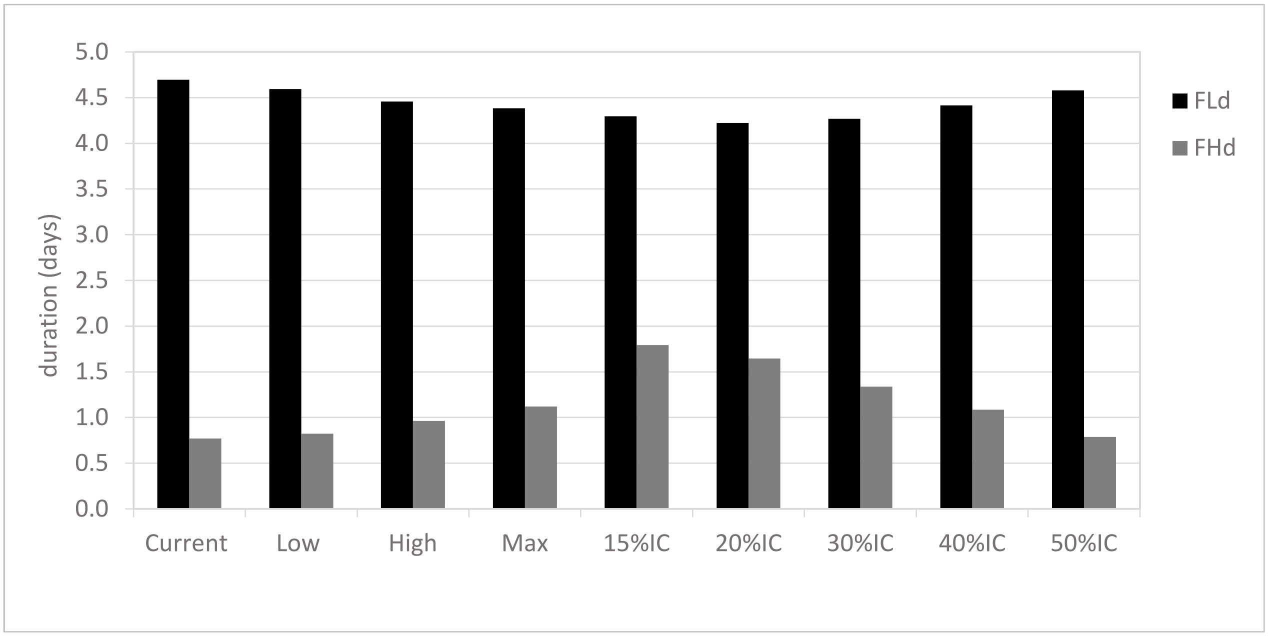

Figure 16: FLd: Average duration (days) of low flow (<0.1 cfs) events and FHd, average duration of high flow (sustained flow > 0.1 cfs) events over the entirety of the modeling period (1989-2014)

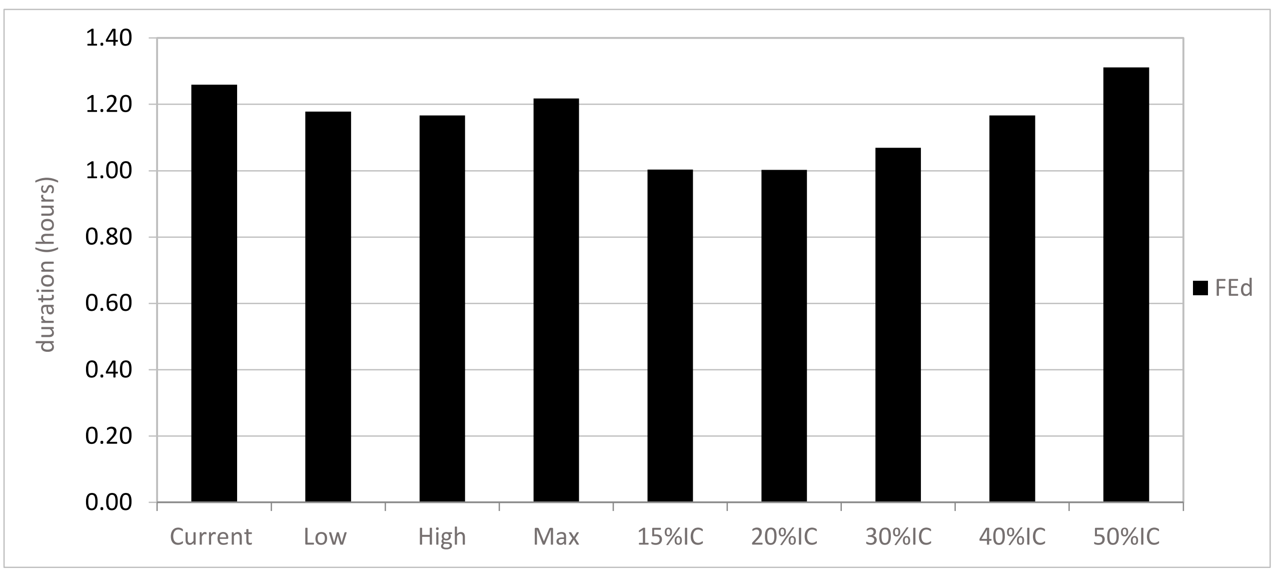

Figure 17: FEd, average duration (hours) of erosive flows (>50 cfs) over the entirety of the modeling period (1989-2014)

The number of low and high flow events did not change the pattern observed in current conditions. However, the number of erosive flow events decreased from current conditions in all three SCM scenarios (Figure 17), again demonstrating a hydrologic buffering effect on this flashy stream. The reduction in the number of erosive events in the High implementation scenario coincides with the metric results for impervious cover levels between 20 and 30%.

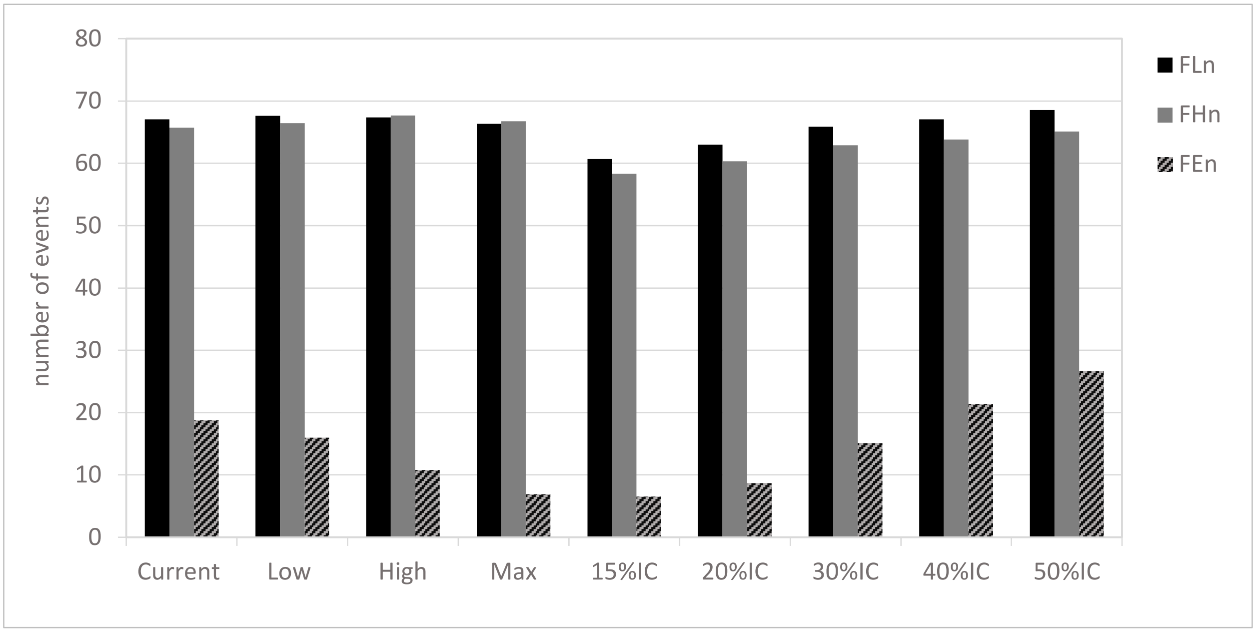

Figure 17: FLn: Average number of low flow (<0.1 cfs) events, FHn, average number of high flow (sustained flow > 0.1 cfs) events and FEn, average number of erosive flows (>50fcfs) over the entirety of the modeling period (1989-2014)

Discussion

The results from the simulations show substantial changes in a range of hydrologic metrics which are generally proportional to the density of SCMs in the three modeled scenarios (Table 7). The biological stream response in WLR3 would vary between the SCM scenarios evaluated based on the predicted hydrologic metric values. The increase in baseflow as measured by the ratio of baseflow to total flow (BFR) showed the largest percent increases among all the selected hydrologic metrics. BFR is predicted to increase from 0.07 in the current condition to 0.11 in the low SCM scenario. The potential changes in ecological integrity of WLR3 resulting from even the Low SCM implementation would likely be magnified to a much larger effect, resulting in more wetland communities, better microbial soil and sediment health, improved riparian buffers and lower stream temperatures (Booth et al. 2004, Walsh et al. 2015).

The modeled SCM scenarios in this study represent levels of stormwater treatment that disconnect up to 71% of the total impervious cover in the Max scenario, 43% in the High and 14% in the Low scenario. These values are relatively optimistic when compared to adoption and/or treatment levels in similar programs and studies around the country (Roy et al. 2008, Thurston et al. 2010, Pennino et al. 2016) where current maximum implementation levels result in impervious cover disconnection in the 10-15% range. The resulting hydrologic changes predicted by the High model scenario correspond well with total catchment impervious cover values of between 20 and 30%. Although this is not representative of a pre-development or undeveloped condition, this range has been shown to be protective of a range of aquatic life indicators (King et al. 2016). These predicted changes in hydrology are significant from an ecological perspective, even with relatively modest reductions/treatments of effective impervious cover. Aquatic life use EII scores in Austin creeks, based on benthic macroinvertebrate and diatom communities, can be predicted using hydrologic metrics (Richter 2011). Based on the hydrologic metric outputs of the Low and High scenarios, there could be a 20-40 point increase, respectively, in aquatic life use EII scores in this urban creek, potentially raising it 3 narrative EII categories (12.5 points per category).

Overall, the predicted response of the system showed changes in hydrologic metrics expected to be beneficial to aquatic life and to restoring a system to a less flashy regime with, higher ecological integrity. The percent change in metrics (from <1% to over 287%) is probably not a direct indicator of the ecological response that is expected, but does help understand potential scale and magnitude of this master suite of variables (Poff et al. 1997, 2006, Hawley and Vietz 2016). Relating the changes in hydrologic metrics back to the desired results in terms of actual costs, ecosystem services, desired aquatic life use values, and of course better quantitative accounting of the benefits to erosion and flooding risk are longer term goals that will be incorporated and evaluated as this project evolves.

Recommendations

- Measuring actual implementation over time along with the corresponding change in measured hydrology is necessary to validate model results and quantify the potential practicality of this strategy for watershed scale restoration. This validation would provide valuable insights into the usefulness of the model for predicting hard to quantify hydrological and ecological results, particularly when they may be cumulative over an extended period of time. However, in a second iteration of this modeling exercise but prior to further validation, a sensitivity analysis will be run which will identify parameters in the model which can greatly alter results. If the COA does not have a strong grasp on the range of these sensitive parameters then further investigations will be undertaken to strengthen our knowledge of them.
- Additional evaluation of the modeling effort should be undertaken to assess some discrepancies seen between the uniform impervious cover simulations and the calibration runs. The effects of the distribution of impervious cover and assumed management practices were both identified as possible sources of the discrepancies, and determining the effect of each on flow results would be valuable in anticipating response of the system to implemented controls. Further analysis of results will also provide valuable insight into the water balance, and if unexpected results are obtained when SCMs are built, may provide information on identifying the divergence of reality from simulation. For example, a possible problem identified was the redirection of shallow groundwater through preferential pathways that may be introduced with utility line installation.
- A careful evaluation of hydrologic metrics and their suitability for setting goals or for projecting improvements in aquatic life or stream health should be conducted from the perspective of measureable effects within a watershed. Initial studies for hydrologic metrics correlated with aquatic life indicators were based on a smaller dataset than is now available, most monitoring sites had very large drainage areas, and consideration of other classification variables may not have been comprehensive. Another consideration if used in conjunction with modeling exercises is how well the models used will represent the selected metrics. The scale of the time-step is also a factor and some metrics may need to be calculated on a different time step than others. The "reference value" that some

metrics are compared to needs to be carefully considered. For example, should the high flow criteria be the 75th or 90th percentile for the current condition, within each simulation, or is there a critical number such as the 50 cfs used for a scour threshold at WLR3?

- Other interactions such as the retention of water in the rain gardens possibly increasing evapotranspiration need to be examined, both through the rain gardens themselves and also probably through re-uptake by plants from the soils and shallow groundwater as the seepage from the raingardens moves towards the creeks. Development of a water balance in the model will give further information on the mechanisms by which the hydrologic changes take place with the incorporation of SCMs.

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