Urban Hydrology Restoration: a study in methods, models, and metrics in comparing filtration and infiltration approaches in stormwater control measures.

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Abstract

The deleterious effects of urbanization on the health of streams are typically addressed through a combination of regulations and stormwater structural control measures. Traditionally, filtration stormwater controls with underdrains connected to the storm drains are built to treat runoff from areas as part of the development process or as retrofits on public land if areas were developed before stormwater management regulations were in place. An additional method of stormwater control is one that implements smaller infiltration-focused stormwater controls on individual private and public parcels. To better understand the performance of both types of stormwater controls, a method was developed to compare between one infiltration scenario and two filtration scenarios. A numeric model was then run on the three scenarios to simulate hydrologic impacts on the receiving stream and two sets of metrics were evaluated to determine the effectiveness of the three scenarios. Results from this process indicated some ambiguity in comparisons between the scenarios, mostly due to the selected model's inability to simulate actual spatial distribution of stormwater controls. We recommend re-examination of metrics used for comparison, method of establishing equivalency of retrofit scenarios, and numeric model used to examine implementation scenarios.

Introduction

Urban development degrades the integrity of streams and impairs the delivery of the ecosystem services they provide (Konrad and Booth 2005; Walsh et al. 2005; Chadwick et al. 2006; Hawley and Bledsoe 2011; Somers et al. 2013). The modification of hydrologic patterns is arguably one of the critical drivers leading not only to stream function impairment, but also to the degradation of the ecological function of the entire watershed including upland areas (Grimm et al. 2008; Buyantuyev and Wu 2009). Beyond hydrology, urbanization impacts include the urban heat island phenomenon and its effects on human health and energy expenditures (Smargiassi et al. 2009).

The City of Austin has land development regulations aimed at mitigating the impact of urbanization on stream health. The Watershed Protection Department, as part of its water quality business plan, also prioritizes reduction of pollution to receiving waters (Objective 2) and improvement of baseflow in waterways (Objective 3). In conjunction with these goals, the City of Austin builds and incentivizes stormwater control measures (SCMs) as retrofits for areas where development occurred prior to the institution of any protective regulations. The conventional manner that water quality SCMs have been implemented includes treating drainage areas from multiple private and public parcels in a regional SCM and routing the treated runoff to drainage pipes and receiving streams. Although the design of these regional SCMs emphasizes pollutant removal, their implementation also provides some degree of erosion protection (HDR Engineering 2011). However, evidence of hydrologic benefits of regional SCMs is mixed (Burns et al. 2012; Bell et al. 2016). Furthermore, fully urbanized watersheds often have limited opportunities for these types of SCMs due to a lack of available land on which to construct the SCM.

The City of Austin conducted a modeling exercise examining the use of infiltration SCMs in the form of rain harvesting systems and raingardens in public and private spaces throughout a fully urbanized watershed. Different scenarios were modeled to determine the hydrologic impacts of implementing infiltration SCMs at different degrees of saturation. A maximum saturation scenario routed all runoff from most land uses to either a cistern or a raingarden, with the exception of transportation land uses. High saturation and low saturation scenarios were also modeled which reduced the amount of roof runoff to cisterns and pavement runoff to raingardens compared to the maximum saturation scenario. The exercise found that the hydrologic improvement in the watershed was proportional to the degree of saturation of infiltration SCMs (Glick et al. 2016). However, it is necessary to examine the results of the infiltrations scenarios, which retain runoff, in relation to the conventional service delivery model for retrofits mentioned above, which treat runoff via a filtration system. Both approaches need to be compared through a series of dimensions: drainage area treated, degree of pollutant removal, hydrologic performance, construction and maintenance costs, risk and impact of failure, associated environmental benefits and impacts, and social benefits and impacts.

In this study a potential framework in which comparisons of hydrologic benefits between the two techniques is presented (infiltration vs. filtration). First, a method of comparison was chosen to measure the impacts from two different, but relatively equivalent systems. Second, a model was selected to simulate the hydrology of the scenarios. Third, a comparison of their performance is done using two sets of metrics: hydrological and water balance. This framework of methods, models, and metrics is then reviewed to serve as a guide for future study.

Methods

Glick et al. (2016) produced a hydrologic model using the Soil and Water Assessment Tool (SWAT) within the study area that included existing SCMs as of September 2016. Three SCM implementation scenarios were modeled using this current condition model: Maximum, High, and Low. In the Maximum scenario, runoff from all directly connected impervious cover surfaces from most land uses was directed to either a cistern or a raingarden (Table 1), with the exception of transportation surfaces. The Maximum scenario was thought to be unrealistic in terms of implementation, so the High and Low scenarios were modeled which reduced the amount of runoff treated by cisterns and raingardens in the various land use categories within the study area.

Table 1: Percent impervious cover within each land use category treated by raingardens (RG) or cisterns (CS) in each of the three scenarios examined by Glick et al. (2016).

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

The current study used the "High" scenario from Glick et al. (2016) as the reference infiltration SCM scenario and generated an additional two filtration SCM scenarios for comparison. The three scenarios we examined in this study can be described as:

1) Infiltration: small-scale SCMs (rain gardens and rain harvesting cisterns) receiving runoff from 75% of all roof surfaces in all land uses and runoff from 50% of all paved surfaces in all land uses except those in single family residential and transportation;

2) Filtration SCM for Equivalent IC: sedimentation/filtration SCMs were designed to treat runoff from a drainage area that contributes equivalent amount of impervious cover as the infiltration SCMs in the entire study area; and

3) Filtration SCM for Equivalent Vol: sedimentation/filtration SCMs were designed to treat runoff from a drainage area that contributes approximately equivalent water quality volume as those treated by infiltration SCMs in the entire study area.

Study Area

The area of study is the headwater reach of the Waller Creek watershed located in the urban core of Austin, TX, encompassing approximately 2.79 km^2 (1.08 mi^2) bound to the south by Koenig Lane where USGS gage 08156910 is located (Figures 1, 2). Glick et al. (2016) described the study area in more detail including slopes, soil types, and historical land use. As of 2015, the study area was approximately 47% impervious cover with a mixture of single family, duplex, multifamily, commercial, office, and industrial land uses. The drainage area was split into four areas called sub-basins so that within each sub-basin the slopes, soil types, and land use are similar.

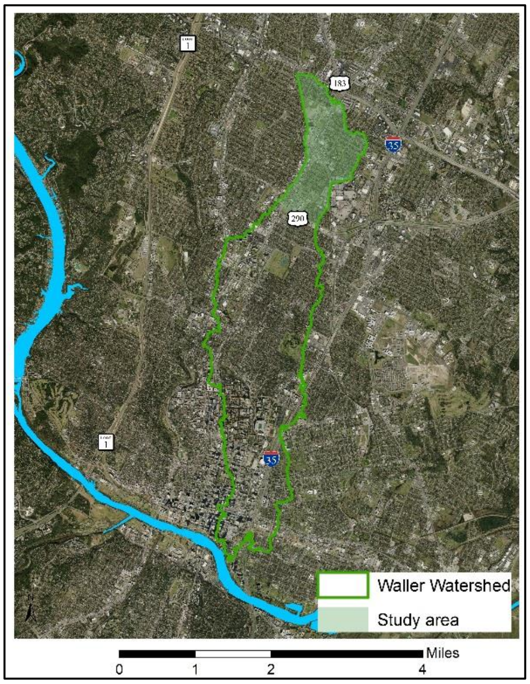

Figure 1: Waller Creek Watershed and study area

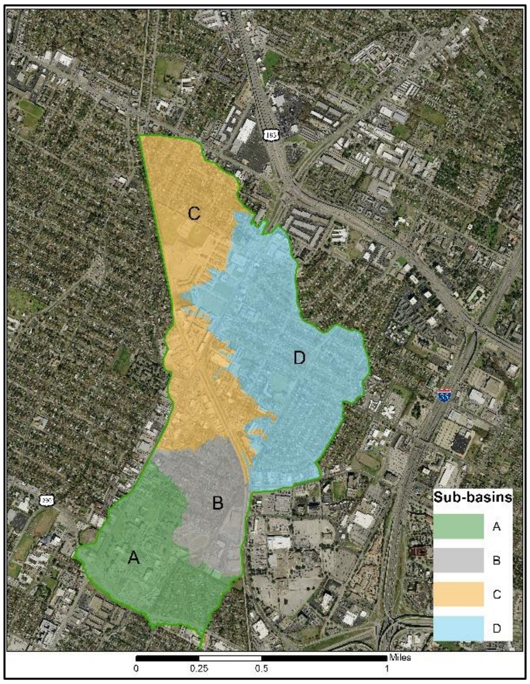

Figure 2: Study area and model sub-basins

Treatment Equivalency

SWAT is a lumped parameter hydrologic model that aggregates information from a sub-basin to produce a hydrologic response. When incorporated into ArcGIS, SWAT takes spatial information from each sub-basin and transforms it to lumped parameters. As the number of sub-basins increases, then, the accuracy of the hydrologic response increases. However, to truly perform as a spatial model, overland routing would need to be incorporated, which is lacking in SWAT. As implemented with the four sub-basins, it is more of a semi-spatial model which lumps drainage areas together into each sub-basin. The model is thus incapable of modeling the distribution of controls in the infiltration scenario described above. Water will not be captured at each cistern or raingarden, it will instead be captured at the outlet of the sub-basin in one large infiltration depression. Thus, the model comparison in this study is more of a comparison of an infiltration facility scenario at each sub-basin outlet against two filtration facility scenarios at each sub-basin outlet.

Determination of Filtration SCM for Equivalent IC Scenario

To arrive at a hypothetical sub-basin to be treated by a filtration SCM for impervious cover equivalent to that of the infiltrationSCM scenario, the following equation was used:

$$Filtration\ EqIC = \sum\left[\frac{Infiltration\ IC_i}{IC_i}\cdot Area_i\right] \tag{1}$$

The term *Infiltration IC* is the amount of area that is treated by infiltration stormwater controls. The terms *IC* and *Area* are the amounts of area that are impervious cover and the total drainage area for each sub-basin, respectively. Thus, the term within the summation symbol takes the ratio of treated impervious cover to total impervious cover for each sub-basin and multiplies that ratio by $Area_i$, the area of that sub-basin. This term results in an equivalent amount of area that is treated by a filtration SCM for each sub-basin if the entire sub-basin is impervious cover. The *i* terms are then added to arrive at the total amount of area that is treated by SCMs in the study area.

Table 2 below shows the steps required to develop this amount. The columns *InfiltrationIC*, *IC*, and *Area* are all taken from GIS layers for each sub-basin. The column, *Infiltration IC/IC*, depicts the ratio, and the column *(InfiltrationIC/IC)*Area* provides the watershed area draining to a filtration stormwater control that would produce an equivalent amount of impervious cover treated by infiltrationstormwater controls using this method.

Table 2: Method to calculate the equivalent amount of impervious cover for a Filtration watershed.

Sub-basin	InfiltrationIC (acres)	Impervious Cover (acres)	Area (acres)	(InfiltrationIC/ IC)	(InfiltIC/IC)*Area
1	17.75	55.01	136.88	0.3226	44.15
2	12.94	32.84	87.92	0.3940	34.64
3	38.79	97.23	210.00	0.3989	83.77
4	40.63	113.65	254.75	0.3575	91.07
Total	**110.10**	**298.74**	**689.54**		**253.63**

From this table, one can see that the 110.10 acres of area treated from infiltration SCMs is generated from the 689.54 acres of the watershed area. Mathematically, this method is equivalent to dividing the *Infiltration IC* by the percent impervious cover of the sub-basin. For every acre of the total drainage area treated, the amount of impervious cover treated will increase by the percent impervious cover of the sub-basin. Thus, the total drainage area routed to the filtrationSCM to treat the *InfiltrationIC* area can be found by dividing the amount of *InfiltrationIC* by the percent impervious cover of the sub-basin. The total drainage area treated under this filtration SCM scenario was found to be 253.63 acres to treat 110.10 acres of impervious cover. This equivalence is input into the model (see next section) by having the ponds for each sub-basin in the FiltrationIC Scenario only treating 253.63 acres of the watershed when combined. The remaining area is bypassed around the ponds and into the receiving stream.

Determination of Filtration SCM for Equivalent Volume Scenario

For urban areas, the SWAT model input would include the drainage area to the filtrationSCM and the impervious cover present in that drainage area. Thus, in this scenario the volume treated by the infiltration scenario was used to back calculate the drainage area treated. The following approach was used.

1. The area and percent of impervious cover (as calculated above) was noted for each sub-basin.
2. This area was multiplied by a water quality depth captured to arrive at a volume, denoted *Total Volume Treated* in Table 3. The depth calculated for cisterns and rain gardens are:
    a. For areas assumed to contain rain gardens, the depth of water quality captured equals the first one-half inch of runoff plus an additional one tenth inch for each ten percent increase in impervious cover over twenty percent. This is per Environmental Criteria Manual requirements for conventional SCMs.

   b. For areas assumed to contain cisterns, the depth of water quality captured was assumed to be 0.15 ft (1.8 inches).

3. The Equivalent Area Treated by infiltration SCMs is then calculated by:

$$Equivalent\ Area = Total\ Volume\ Treated\ /(0.5 + (\%IC - 0.2)) \qquad (2)$$

4. This Equivalent Area is then converted to Equivalent IC for filtrationSCMs:

$$Equivalent\ IC\ Treated = Equivalent\ Area * \%IC \qquad (3)$$

The output of this process is given in Table 3. This shows that 219.8 acres draining to filtrationSCMs designed per ECM criteria would provide equivalent volume to that of the infiltration scenario. The amount of volume to be treated by filtration ponds in each sub-basin is also depicted.

Table 3: Calculated values for the equivalent amount of treated volume for a Filtration watershed.

Sub-basin	**Total Volume Treated (ft^3)**	**%IC**	**Equivalent Treatment Area (ac)**	**Equivalent IC Treated (ac)**	**Equivalent Vol Treated (ft^3)**
1	87,324	0.402	34.3	13.78	87,391
2	71,277	0.374	29.2	10.90	71,391
3	202,903	0.463	73.3	33.92	203,018
4	225,043	0.446	83.1	37.06	225,070
Total	**586,546**		**219.8**	**95.65**	**586,870**

By design, infiltration SCMs receive runoff directly from impervious surfaces (e.g., roofs to cisterns, paved areas to raingardens) while filtration SCMs receive runoff from both pervious and impervious surfaces (yards, driveways, sidewalks, parks, streets, and roofs) within the treated drainage area (Table 2). Therefore, the total drainage area treated differs among scenarios when treating the same amount of impervious cover or having equivalent capture volumes (Table 4). To treat the equivalent amount of impervious cover a building footprint of approximately 4.2 acres is required for the Sedimentation/Filtration pond, which is about one-third of the total area. In addition, to treat about the equivalent volume of water quality as the infiltration SCMs, approximately 3.7 acres would be needed to build the ponds. Note that the water quality volume captured by this scenario is not exactly equal to the water quality volume captured by the infiltration SCM, due to the use of both rain gardens and cisterns, which capture different amounts of water quality volume.

Table 4: Model scenarios: Infiltration, Filtration Equivalent Impervious Cover (Eq IC), and Filtration Equivalent Volume (Eg Vol). Note that both filtration scenarios treat both pervious and impervious surfaces in the drainage area.

	Infiltration	Filtration Eq IC	Filtration Eq Vol
Total area treated (acres)	110.1	253.6	219.8
Impervious area treated (acres)	110.1	110.1	95.65
Capture Volume (ft^3)	586,547	675,851	586,870

Modeling the Scenarios

The 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 (12/4/2014), 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 available COA flow data at Waller Creek at 23rd Street further down in the watershed (period of record 1992-present) as well as at the USGS Gage at Koenig. The model incorporated existing SCMs.

Landscape management (irrigation, fertilization and mowing) was also incorporated for residential and commercial lawn areas, with the exception of high slopes, and the plant cover was assumed to be Bermuda grass. All scenarios assumed that pervious surfaces within the sub-basins had Bermuda grass lawns as the dominant vegetation in all land uses. A minimal amount of annual irrigation was applied equally to all scenarios as 9.84 inches of water (250 mm) based on plant growth in heat-units, in 10 uniform applications of 0.984 inches each from June through August or September. Timing differed in each year based on plant growth, but total water applied was the same. Areas with a slope greater than 15%, generally associated with creek banks, were not irrigated in the model.

The results of the above methods to determine the equivalent areal extent of treated water quality were applied to the headwaters of Waller Creek and input into SWAT, using the model described above (Glick et al. 2016). The filtration SCM scenarios were modeled as implementing full sedimentation/filtration water quality ponds compliant with the City of Austin Environmental Criteria Manual and designed to fully capture within the sedimentation chamber the first one-half inch of runoff plus an additional one-tenth inch for each ten percent increase of impervious cover over twenty percent within the drainage area to the control (City of Austin). To simulate the filtration SCMs' water quality capture, the "reservoir" feature in SWAT was used. Each sub-basin consists of a reservoir feature, where a fraction of the sub-basin is routed to the reservoir. The fractional area from each sub-basin summed to the total area treated in Table 4 for each scenario. Water volume is removed from the reservoir through evaporation, seepage, and discharge. The discharge rate was set to mimic capturing the water quality volume and releasing any excess proportional to the depth of the water in the reservoir.

In contrast, the infiltration SCM scenario was modeled using the “depression” feature in SWAT. Each sub-basin contains a depression where a portion of the flow was routed to this single feature rather than individual infiltration features and the total amount from the portions equaled the total area treated in Table 4. Water is lost from this feature through evaporation, seepage, and discharge, where the discharge calculations are set to zero for incoming water below the water quality capture volume and then releasing anything in excess.

Metrics

The resulting hydrographs for each of the three scenarios generated by SWAT were evaluated by computing two sets of metrics. The first set of calculated metrics, denoted *hydrologic metrics*, that have been shown to correlate with a multi-metric Aquatic Life Score used by the City of Austin (Glick et al. 2010) as well as additional metrics related to the potential for creek erosion (Glick et al. 2016) (Table 5). Most hydrologic 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 it explained a higher proportion of variation.

Table 5: Description of hydrologic metrics utilized to compare model scenario outputs

Hydrologic metric	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; Booth et al. 2004)
T_{dry}	--	Fraction of time during the period that the flow was less than 0.1 cfs (Richter et al. 1996)
F_{Ld}	days	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}	days	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}	days	Average number of erosive flow events per year, where flow was above the 50 cfs erosion threshold, lasting at least 15 minutes
F_{Ed}	hours	The average duration of erosive flow periods above 50 cfs

A second set of metrics was examined to determine the effect of each scenario on the upland areas. These *water balance metrics* were taken directly from SWAT output (Table 6) for the three model scenarios. The SWAT output for each scenario consists of monthly totals of the metrics below. These water balance metrics were then calculated as the average annual volume for the period of record used in the simulations.

Table 6: Definition of water balance metrics utilized. Although SWAT (Neitsch et al. 2011) outputs for these metrics are generated as mm, we calculated the overall volumes by multiplying the output with the study area extent and report values in English units

Metric	Units	Description
Runoff volume	ft^3	Average annual volume of flow contribution to stream flow from surface runoff.
Lateral flow volume	ft^3	Average annual volume of flow contribution to stream flow from lateral subsurface movement of water
ET	ft^3	Average annual volume of evapotranspiration (loss of water soil, water bodies, and vegetation in the form of water vapor) from the watershed.
number of water stress day	days	Average annual number of days in which the soil water content is below what is required for plant growth. That is, when the plant water uptake in a day is lower than the maximum plant evapotranspiration on a given day and thus plants have a water deficit.

An analysis was conducted using WinXSPro to evaluate potential changes to erosive flows, defined in this study as those larger than 50 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.

Results and Discussion

Metric Results

The degree of changes to the hydrology of the system as measured by the hydrologic metrics in response to the SCM scenarios varies among metrics (Table 7). The peak flow (Q_{peak}) and flow variation (COV) decrease for each SCM scenario when compared to the current state of the watershed, which should be expected as stormwater runoff is retained/detained during storm events. The lowest peak flow was noted in the infiltration scenario; however, the smallest flow variation was noted in the Filtration Eq IC scenario. This provides some evidence that the infiltration scenario may act as the best buffer against the very largest of flow values while the Filtration Eq IC scenario will buffer the hydrology in the higher frequency moderate to high volume storms.

The decrease in the mean flow (Q_{mean}) is possibly due to the decrease in peak flows with each SCM scenario as the 90th percentile (Q_{90}) flow increased. SCMs change the flow regime from the current conditions by redistributing the flow into baseflow; thus, increasing the flow rate for 90% of the flows. This can also be noted by examining the baseflow ratio (BFR) which indicates that a higher amount of the stream flow occurs under baseflow conditions for all three SCM scenarios. The mean flow decreased the most in the infiltration scenario which coincides with the largest decrease in peak flow. The 90th percentile flow and baseflow ratio increased the most in the Filtration Eq IC scenario which indicates that more flow is being distributed into baseflow in the Filtration Eq IC scenario then for any of the other scenarios.

Changes in flashiness of the system are also illustrated by the rising and falling limbs of a hydrograph which are described by the average rise rate (+mean) and average fall rate (-mean) metrics. The average rise rate will increase as stormwater rapidly flows over impervious cover during storm events and quickly causes the stream flow to increase. Each SCM scenario lowers the average rise rate by intercepting some of the storm volume; however, the average rise rate is lowest in the Filtration Eq IC scenario. Coupled with the peak flow and COV metrics, this provides further evidence Filtration Eq IC scenario buffers the hydrology in moderate to high volume storm events.

The average fall rate will decrease if water is detained and slowly released after a storm event as would be done in the Filtration Eq IC scenario. This not only lowers the largest fall rates by lowering peak flows but the slower release of stormwater from the SCM will buffer the fall rate due to the velocity restrictions of the SCMs. When water is retained and infiltrated or lost to ET , the average fall rate will probably not decrease as much as in the Filtration Eq IC scenario. The lowering of the peak flow should lower the largest fall rate similar to the Filtration Eq IC scenario; however, the water is not continuously released back into the stream directly after the storm. Only when the retained water has moved laterally through the shallow groundwater and returned to the stream will the scenario add water to baseflow. According to first principles, this movement will take an extended and, as of yet unknown time-period, which would not be accounted for in these metrics.

The fraction of time during the period that the flow was less than 0.1 cfs (T_{dry}) might indicate that not much of the water retained in the infiltration scenario travels laterally through the shallow groundwater and into the stream as the metric is only slightly lower than the current conditions metric. The fraction of time the flow was less than 0.1 cfs in the Filtration Eq IC scenario is lower when compared to the infiltration and current conditions scenario because the SCMs extend the falling limb of the storm event as described above. The duration of low flow events (F_{Ld}) is lower in the Filtration Eq IC which supports the idea that filtration SCMs support longer periods of flow in the creek; however, the higher number of low flow events (F_{Ln}) in the Filtration Eq IC scenario might indicate that the flow in the stream is below 0.1 cfs in baseflow but increases to above 0.1 cfs during small storm events. The same metrics in the infiltration scenario again provide some evidence that water is retained or infiltrated and does not contribute to changes in stream flow for small storms.

These metric results have been tabulated below with the more favorable result for each metric highlighted in yellow. An inspection of this tabulations shows that 10 of 14 metrics support the idea that filtration systems provide more favorable hydrology for benthic macroinvertebrate communities. An ideal magnitude of the mean flow and the 90th percentile have not been established for the benthic communities and are not included in the above counts. Looking at metrics that incorporate baseflow, only the following 4 of the 16 metrics should be examined:

BFR, T_{dry}, F_{Ln}, and F_{Ld}. Of these 4, 3 metrics favor filtration scenarios (BFR, T_{dry}, F_{Ld}). However, T_{dry} is a combination of F_{Ln} (which favors infiltration scenarios) and F_{Ld} (which favors filtration scenarios). This confounding of metrics within another metric makes any comparison difficult and emphasizes the need for an uncertainty analysis of the model.

Hydrologic metrics associated with erosion (the last three in Table 7) show that the average duration of the erosive flows, F_{Ed}, decreases the most relative to current conditions in the Filtration Eq IC scenario. The average annual number of erosive events, F_{En}, and the average duration of the erosive events, TQE, both decreased the most in the Infiltration scenario. For benthic macroinvertebrates, mobilization of habitat bed particles constitute important disturbance events. A substantial reduction in the frequency of these is a desirable outcome to improve stream function. However, this study does not examine how much of a departure in the frequency of these disturbance event is associated with substantial improvement in macroinvertebrate scores.

Table 7: Hydrologic metrics for the Infiltration and Filtration SCM scenarios for the entirety of the modeling period (1989-2014). Percent departure from current conditions shown in parenthesis.

Hydrologic metric	current	Infiltration (%Δ)	Filtration Eq IC (%Δ)	Filtration Eq Vol (%Δ)
Q_{mean}, cfs	0.68	0.46 (-31.9%)	0.56 (-17.2%)	0.57 (-15.9%)
Q_{peak}, cfs	893	688.64 (-22.9%)	791 (-11.4%)	798 (-10.6%)
Q_{90}, cfs	0.23	0.34 (47.8%)	0.47 (104.3%)	0.43 (88.7%)
COV	11.80	11.54 (-2.2%)	10.51 (-11%)	10.73 (-9.1%)
BFR	0.12	0.18 (50%)	0.23 (91.7%)	0.21 (75%)
+mean	2.10	1.24 (-41%)	0.81 (-61.3%)	0.87 (-58.5%)
-mean	1.55	0.91 (-41.6%)	0.63 (-59.5%)	0.68 (-56.4%)
T_{Qmean}	0.06	0.08 (35%)	0.09 (42.7%)	0.08 (35.4%)
T_{dry}	0.86	0.82 (-4.3%)	0.66 (-23%)	0.7 (-18.4%)
F_{Ld}, days	4.70	4.46 (-5.1%)	2.66 (-43.4%)	2.92 (-37.9%)
F_{Ln}	67.04	67.38 (0.5%)	90.65 (35.2%)	87.81 (31%)
F_{Hd}, days	0.77	0.96 (24.7%)	1.41 (83.1%)	1.28 (66.2%)
F_{Hn}	65.73	67.65 (2.9%)	87.31 (32.8%)	85.12 (29.5%)
TQE	0.0026	0.0014 (-46.2%)	0.0017 (-34.8%)	0.0016 (-39.6%)
F_{Ed}, hours	1.26	1.18 (-6.3%)	1.09 (-13.5%)	1.11 (-11.9%)
F_{En}	18.77	10.81 (-42.4%)	12.65 (-32.6%)	13.54 (-27.9%)

The water balance metrics (Table 8) generally agree with the results from the hydrologic metrics (Table 7). Less water runs off the surface in the infiltration scenario as seen by the runoff volume when compared to the filtration scenarios (-38% vs. 0%). More water was potentially retained and either infiltrated where it returns to the creek via lateral groundwater movement (lateral flow volume) or is lost to evapotranspiration. Most of the water appears to be lost to ET since the addition of baseflow seems limited under the infiltration scenario which was also noted in the hydrologic metrics. This would also explain why the number of water stress days on plants in the upland decreased in the infiltration scenario.

In the filtration SCM scenarios, no additional water is retained, infiltrated, or lost to ET when compared to current conditions (Table 8). Treated water in these scenarios is found in the runoff volume. From a modeling perspecive, the filtration SCMs do not decrease the volume of water that runs off, instead the water is detained and released into the stream under controlled conditions. The controls redistribute the stormwater back into the flow of the stream which is reflected in the hydrologic metrics (Table 7). It is unclear why the number of stress days decreased slightly in the two filtration SCM scenarios (-12 and -10%) since there is no apparent mechanism that would provide this water to the upland areas where stress response would be assessed.

Table 8: Water balance metrics for the Infiltration, Filtration Equivalent Impervious Cover (Eq IC), and Filtration Equivalent Volume (Eq Vol) SCM scenarios. Percent departure from current conditions shown in parenthesis.

Metric	Current	Infiltration (%Δ)	Filtration Eq IC (%Δ)	Filtration Eq Vol (%Δ)
Runoff volume (ft^3)	23,538,322	14,533,855 (-38%)	23,564,925 (0%)	23,626,997 (0%)
Lateral flow volume (ft^3)	242,379	297,554 (23 %)	242,379 (0%)	240,408 (-1%)
Evapotranspiration (ft^3)	66,516,205	74,152,120 (12%)	66,663,997 (0%)	66,683,703 (0%)
number of water stress day	76.5	56 (-27%)	68 (-12%)	69 (-10%)

Equivalence Suitability

Using the framework described above provided a foundation in which to examine the impacts of two modes of providing hydrologic benefits to the streams in Austin, Texas. This exercise was also effective in informing how to approach future comparison studies. However, it highlighted the complications and limits in moving forward with this approach. Results from applying this framework suggested that a deeper discussion is warranted.

First, the method of developing equivalence between scenarios utilizing infiltration SCMs and filtration SCMs needs further examination. Equations 1 and 2 may not be the most optimal method of determining equivalence. Using the Filtration Eq IC scenario (Equation 1), the same amount of impervious cover is treated when compared to the infiltration scenario; however, the filtration scenario captures runoff from roadways. This could lead to a large number of homes and commercial sites not being treated under the current equivalency methodology because less of the watershed drainage area would actually be routed to the filtration SCM. Even less impervious cover is treated in the Filtration Eq Volume scenario (Equation 2) and the problem of less of the watershed drainage area being treated that is noted above will be further exacerbated using the equivalent volume methodology.

An additional way to think about equivalency could be to consider the result of implementing alternative approaches on the hydrology of the creek itself as well as the overall water balance of the watershed. Rather than comparing the downstream hydrology under different scenarios, it might be more useful to compare different scenarios that offer the same benefit to hydrology. This would allow for a comparison of cost, maintenance, failure rate, etc. of the different scenarios without the confounding factor of how each scenario impacts the hydrology of the system. Furthermore, each metric will have different scenario outcomes. For example, one metric might show 2 filtration ponds are equivalent to 5 infiltration raingardens; whereas another metric might show that 3 filtration ponds are equivalent to 10 infiltration raingardens. From this, the range and potential benefits of scenario outcomes can be compared in a quantitative and statistical manner.

Scenarios to model should include the watershed area under no impervious cover conditions and the watershed realistically treated using a full sedimentation/filtration facility following criteria in the ECM. The former scenario will produce results that can be targeted in treatment scenarios. The latter will produce results which ERM currently uses as a minimum treatment standard; however, construction of a full sedimentation/filtration facility may not be feasible in some urban areas while alternative infiltration or hybrid approaches may require less land acquisition and therefore be less costly to implement. Modeling results of proposed scenarios could be used to discern the difference in hydrology and watershed function from either of these targets. This study did use full sedimentation/filtration facilities following criteria in the ECM as part of the filtration scenarios but that was for comparing scenario amongst themselves, rather than against a targeted treatment or minimum treatment standard. Thus, it is debatable if either of these scenarios reflect realistic designs that ERM would follow if implementing water quality treatment of this area.

Metric Suitability

Hydrologic metrics were selected based on their previously found relation to aquatic macroinvertebrate communities in Austin, Texas (Glick et al. 2010; Richter 2011a). However, the following metrics used in this report were noted as being highly correlated in previous analyses: Q_{mean} was positively related with Q_{90}; Q_{peak}, +mean, and -mean were all positively related to each other; and T_{dry} was positively related with F_{Ln} (Richter 2011b). A rise in either the Q_{mean} or Q_{90} led to an increase in the benthic macroinvertebrate community overall aquatic health. It should be noted that the reason the benthic community health increased with inreasing Q_{mean} was because sites with a higher mean were less intermittent than sites with lower Q_{mean} and no ideal magnitude of Q_{mean} could be established for overall aquatic health. Similarly, decreases in the Q_{peak}, +mean, -mean, T_{dry}, or F_{Ln} led to an increase in aquatic health. Results in this study show conflicting trends for the Q_{mean} with the Q_{90}; Q_{peak} with both +mean and -mean; and T_{dry} with F_{Ln}. Thus, it would be difficult to determine which of these scenarios would improve aquatic health based on these metrics alone.

Using a single hydrologic metric to determine if a scenario has improved hydrology in the downstream segment of the stream is not recommended since individual metrics only characterize a small part of the hydrograph. In fact, authors of these hydrologic metrics tend to group them into categories to describe certain aspects of the flow regime. Richter et al. (1996) used the following groups: magnitude, magnitude and duration of annual extreme conditions, timing of annual extreme conditions, frequency and duration of high and low pulses, and rate and frequency of change in conditions. The metrics used in this study could be classified according to these groups (Table 9). Notice that the study uses no measure of timing but contains an over-abundance of high and low flow pulse descriptors. Rather than examine this set of hydrologic metrics which have offered no clear direction as to which scenario above would provide more ecological lift to the macroinvertebrate community, it may be more beneficial to re-examine the initial list of hydrologic metrics provided by Richter et al. (1996) in the Indicators of Hydrologic Alteration (IHA) methodology and additional metrics named Environmental Flow Components added to the IHA methodology (Mathews and Richter 2007a). In addition, the ERM Division should develop an approved list of hydrologic measures used to evaluate scenarios so that a consistent evaluation can be done going into the future.

Table 9: Metrics used in this study grouped according to methods developed by Richter et al. (1996).

Statistics group	Hydrologic metric
Group 1: Magnitude	Q_{mean}
	Q_{90}
Group 2: Magnitude and duration of annual extreme conditions	Q_{peak}
	COV
	BFR
Group 3: Timing of annual extreme conditions	
Group 4: Frequency and duration of high and low pulses	F_{Ld}
	F_{Ln}
	F_{Hd}
	F_{Hn}
	TQE
	F_{Ed}
	F_{En}
	TQ_{mean}
	T_{dry}
Group 5: Rate and frequency of water condition changes	-mean
	+mean

Analysis of the metrics calculated in this study suggested that each scenario would decrease the Q_{peak} during modeled time frame and redistribute stormwater to baseflow. Filtration scenarios were thought to accomplish this by detaining water and extending the storm through the slow release of the water quality volume. The infiltration scenario was thought to accomplish this by retaining water, infiltrating water, and adding to baseflow as water moved laterally through the shallow groundwater. Additional tools are needed to confirm these suggestions including but not limited to modeled hydrographs and flow duration curves.

Finally, the uncertainty in both sets of the metrics was not quantified, and thus, could not be used in making more direct statistical assessments between the scenarios. Future models should run for multiple years, where annual values of the metrics are calculated so that variation of each metric can be estimated. This would allow for a statistical comparison between each scenario which would allow for a more complete comparison of the scenarios.

Model Suitability

There are several concerns about the validity of using SWAT in this modeling exercise. The SWAT model was calibrated to the downstream USGS gage under current conditions, but no calibration of the model has been done to assess the validity of flow and infiltration through the SCM facilities. It should be determined how sensitive the model is to changes in the ET to assess how much infiltration or runoff might change. Lastly, one of the calibration parameters in the model is related to how much water flows to the deep groundwater instead of the shallow groundwater. This is an empirical value and the sensitivity of this parameter was not assessed in this exercise so it is unknown how much changing that value would change the lateral flow in the upland and addition of water to the baseflow in the infiltration scenario. These concerns can be alleviated by collecting field data using an experimental design or study on a suite of SCMs.

Policy Direction

In conclusion, the findings of this study document a connection between both infiltration and filtration SCMs and positive hydrologic and water balance outcomes when compared to the current condition of the system. Objectives for the Watershed Protection Department (WPD) include restoring and/or preserving baseflow quantity and quality to the maximum extent possible in urban creeks as well as achieving stable stream systems. Past policies and practices have emphasized filtration SCMs to meet these objectives and the results of this study support the argument that implementing regional and on-site filtration SCMs enhances baseflow quantity and stability in an urban creek.

Results also showed that infiltration SCMs restored baseflow quantity and stability in this urban creek. Note that the extent of the baseflow improvement under both cases is uncertain due to the issues discussed above. First principles indicate that some water will be infiltrated and routed back to the creek as baseflow using infiltration SCMs. Additional modeling will allow staff to estimate with more certainty the volumes and timing of baseflow return to the creek. A heuristic from Hermance (1998) and de Marsily (1986) shows that the lag time between rain events and the return of infiltrated water as baseflow in the creek is longer and the volume of water is moderated when compared to stormwater that flows through a filtration system. However, that moderation results in large differences in the water available for other processes, such as evapotranspiration and additional water quality treatment. In order to continually improve WPD services to the public, there is a need to better understand the strengths and weaknesses of both filtration and infiltration methods to maximize the benefits they provide to urban stream health and watershed function.

Recommendations

1. Comparing between service delivery models requires appropriate methods, models, and metrics. The method of comparison used to develop equivalent scenarios should be re-examined.
    - For a true comparison of equivalency of treating the same amount of impervious cover, the transportation land use needs to be compensated for by either modeling a hybrid infiltration

- scenario where the transportation land use is captured or removing the transportation land use from either scenario;
- The hydrology of the receiving stream could be considered as a point of equivalency. Different treatment scenarios that produce similar hydrology could then be examined for provision of co-benefits, cost, maintenance, failure, etc.;
- Another potential method of comparison is looking at the scaling characteristics of each SCM. For example, analyzing infiltration SCMs at various quantities per acre throughout the watershed might produce some insight into their overall effectiveness; whereas scaling filtration SCMs might produce more ecological benefit at a different amount per acre. For example, modeling four infiltration SCMs per acre across a watershed might be comparable to one filtration SCM per ten acres.

2. Staff in ERM should examine an alternative metric list that:
   - Represents the entire hydrograph;
   - Represents the physical processes governing hydrology and ecology;
   - Includes the original Indicators of Hydrologic Alteration (IHA) metrics and Environmental Flow Components added to the IHA methodology as hydrologic metrics shown to be related to biological communities (Mathews and Richter 2007b).

3. Metrics should be examined through a statistical analysis using multiple year-long hydrographs to quantify the uncertainty in the scenarios for comparisons.

4. Staff in ERM should examine and approve a list of tools such as hydrographs and flow duration curves to supplement analysis of above metrics.

5. A study should be done to assess infiltration and ET dynamics in current code SCMs since our modeling efforts are sensitive to these assumed values and our code and criteria are increasingly moving towards soil and plant solutions to stormwater management.

6. A spatially-explicit model to better simulate overland and subsurface flow is necessary to more accurately evaluate the characteristics of infiltration SCMs. As discussed above, SWAT aggregates flow at the outlet of each sub-basin. Conducting the model in this manner for infiltration SCMs (even if they're treating equivalent volumes or areas) does not represent spatially linked processes. A more applicable model should both look at overland and subsurface flow from first principles. A potential candidate is the Gridded Surface/SubSurface Hydrologic Analysis (GSSHA) model (Richter et al. 2019).

7. Future comparison dimensions:
   Beyond the comparison presented in these results, there are additional outputs from the two approaches that may be substantially different and are worth examining in future research (Table 10). Some elements can be compared quantitatively (e.g., installation cost, maintenance, potable water savings) while others are more qualitative in nature (e.g., alignment with Imagine Austin Comprehensive Plan priorities, potential increase in tree survival, climate change resiliency, promotion of resource stewardship).

Table 10: Performance dimensions for infiltration and filtration service delivery models

Criteria	Type	Description
Pollutant load removal	quantitative	Data-based results and empirical documentation of effluent concentrations
System installation cost	quantitative	Data-based design and construction costs as well as potential land purchasing and acquisition costs
System O&M life cycle cost	quantitative	Data-based operation and maintenance costs through the full life cycle
Potable water savings	quantitative	Data-based reduction in potable water cost for end users as well as overall potential potable water demand reductions within the study area
Cost distribution	quantitative	Stakeholder potential contributions (COA departments, end users, non-profits) to the installation and/or maintenance costs
Failure rate	quantitative	Data-based rate of non-compliance for infiltration and filtration systems
Impact of failure	quantitative	Proportion of serviced area affected by failing infrastructure and cost for rehabilitating functionality to failing infrastructure.
Heat island mitigation	quantitative	Modeling of projected cooling effects from evapotranspiration and potential energy savings from indoor air conditioning
Consistency with Imagine Austin	qualitative	Potential alignment with priority programs identified in the Imagine Austin comprehensive plan
Impact on property tax revenue	quantitative	Data-based tax revenue to municipality of utilized space for implementation of SCMs
Tree establishment and survival	quantitative	Modeling of planted tree survival, natural tree recruitment, and mature tree survival during period of record

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