Estimating impervious cover from county tax records, and impacts of impervious cover on hydrology in the Walnut Creek watershed, Austin, Texas.

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Increasing impervious cover has been related to degradation of aquatic systems. Traditionally estimated impervious cover derived from aerial photography may be temporally intermittent based on availability of aerial imagery, and on a time scale inconsistent with assessing resulting changes to stream hydrology or aquatic ecosystem integrity. A method for estimating impervious cover on an annual time step in Austin, Texas, from county tax appraisal records is presented. Annual impervious cover estimates are correlated to changes in hydrologic metrics, which yield significant temporal trends in the absence of trends in rainfall. Walnut Creek as it undergoes urbanization may be transitioning to a more "flashy" hydrologic response with higher near-peak discharge, runoff depth and faster hydrograph recessions following storm events. There may be a threshold between 12.7% and 18% gross impervious cover in which Walnut Creek's hydrologic response was substantially altered beyond the landscapes natural capacity to restore sustainable function. There is no corresponding trend or significant breakpoint in annual rainfall. Impervious cover increases above the critical threshold may be responsible for a 54.9% increase in annual 95th percentile of discharge and a 31.3% increase in runoff depth.

Introduction

The impacts of watershed urbanization on aquatic systems including hydrologic and water quality degradation have been previously documented (Leopold 1968, Klein 1979, Scoggins 2000, Olivera and DeFee 2007). Impervious cover has been identified as an obtainable and useful indicator of urban land development (Scheuler 1994) and has been directly related to degradation of aquatic systems (DeGasperi et al 2009, May et al 2000, Jennings and Jarnigan 2002). The U.S. Environmental Protection Agency (EPA) has identified watershed impervious cover thresholds of less than 10% impervious cover as "sensitive", 10-25% impervious cover as "degraded" and greater than 25% impervious cover as a "non-supporting" watershed (EPA 2002). Research has corroborated an impervious cover threshold around 10% above which stream systems become unstable (Booth and Reinelt 1993, Olivera and DeFee 2007).

Impervious cover has historically been estimated by the City of Austin Watershed Protection Department geographic information system (GIS) staff and others (Jennings and Jarnagin 2002)

using aerial photography. In Austin, Texas, historical aerial photography spatial layers are available intermittently and in uneven time intervals.

In contrast, stream discharge data may be measured in sub-daily time scales (e.g., every 15-minutes), and water quality and biological (e.g., benthic macroinvertebrate) data are typically collected on a quarterly basis. The rate of change in hydrologic and ecological functions from either short-term climatic variations or long-term degradation with urban development may vary over time (Bronstert et al 2002), and biological communities may respond rapidly to environmental stressors (EPA 1989). Use of impervious cover estimates from intermittent land use or aerial photography records complicates correlative analyses with stream discharge and water quality data because of these time scale differences.

County tax appraisal district information may be a novel source of impervious cover information on an annual time step, and has previously been used to represent development over time in Austin (COA 2007) and in the Houston, Texas, area (Olivera and DeFee 2007). Building and exterior improvement footprints may be used as a surrogate for impervious cover, and impervious cover may be estimated over time as improvements are associated with a specific tax year reflecting the year of construction. However, as county appraisal records do not include information on public transportation infrastructure (e.g., roads and highways), sidewalks and driveways, impervious cover estimates from these records are likely to be lower than true values and need to be adjusted to yield accurate measurements. Parcel boundary information may be used to place the impervious cover in a spatial context.

Methods

One intensive effort to utilize aerial photography in a single watershed, Walnut Creek, in Austin, Texas, generated impervious cover estimates for seven years: 1964, 1970, 1980, 1988, 1997, 2003, 2006. The minimum time step between these impervious cover estimates was 3 years, and the maximum was 10 years with a grand mean of 7 years between estimates.

Walnut Creek is approximately 23 miles in length and has a drainage area of approximately 27,850 acres. The watershed is almost entirely (99.9%) within the boundaries of Travis County, and discharges directly to the Colorado River. The stream transitions from the Central Texas Plateau ecoregion in the northern headwaters to the Blacklands Prairie Ecoregion in the southern downstream portions of the watershed. The majority of development to date is clustered in the upper and midreach portions of the watershed, although future development along new transportation corridors is planned to occur in the lower midreach.

Travis County Appraisal District (TCAD) information was used to generate spatially-referenced annual impervious cover estimates. First-floor building footprints and any external improvements likely resulting in additional impervious cover (e.g., detached garages, tennis courts) were generated for each tax year and parcel id. There were 287 unique improvement detail class codes identified for use in estimating impervious cover. Each unique improvement is associated with both an area and year of construction estimate in the TCAD database, and may be spatially located using the property id code that exists in both the spatial parcel boundary layer and the TCAD appraisal database.

After the initial intersection of the parcel boundaries and the watershed boundary, there were approximately 3,700 acres of affected parcels outside the mainstem watershed boundaries. These intersected parcels with areas outside the watershed boundaries yield impervious cover equivalent to approximately 8% of the total estimated impervious area through 2009, and thus an adjustment

to correct for the intersected, extraneous areas was deemed necessary. A correction factor was developed to adjust for parcels that crossed the watershed boundary. It was assumed that the impervious cover associated with any parcel was evenly distributed across that parcel, and then the fraction of the total parcel area inside the watershed boundary (as a fraction of the original total parcel area) was used to adjust the cumulative impervious cover. For more accurate estimates, these parcels could be examined on a case-by-case basis to identify the location of the impervious area (inside or outside the watershed of interest), if there are sufficient staff time resources.

Mean daily discharge data was derived from the United States Geologic Survey (USGS) gauge on Walnut Creek at Webberville Road (USGS 08158600, waterdata.usgs.gov/tx/nwis/inventory/?site_no=08158600&). The Walnut Creek gauge is the longest continuously operated USGS stream discharge gauge in Austin, with discharge recording from May 1966 to present. Discharges were allocated into calendar year groupings (not water years) coincident with appraisal information. Total daily rainfall data was derived from the National Weather Service Austin gauge (http://www.srh.noaa.gov/ewx/?n=ausclidata.htm), using CF6 report data. Rainfall data are available for Austin from 1892 to present, although a period of record for the rainfall data coincident with the discharge data was used in this analysis.

Bulk data processing was completed in a personal Oracle 10g XE database, populated with data extracted from ARCMap 9.3.1 based on spatial queries. Statistical analyses were performed in SAS version 9.1. Linear regression results were verified by plotting residuals versus predicted values, and plots were examined for the absence of any marked trends to verify model fit and insure that no model assumptions were violated.

Multiple hydrologic metrics were used to describe Walnut Creek discharge characteristics (Table 1). The 90th percentile and number of low discharge durations (Richter et al 1989) was included based on correlation with biologic metrics from previous COA analyses (Glick et al 2009). Runoff depth and peak discharges were included based on importance in a Houston watershed (Olivera and DeFee 2007). Average fall and high pulse duration were included as descriptors of shape of the hydrograph (Richter et al 1989), reflecting change in the rate of response to runoff. Use of a digital filter to describe the relative fraction of discharge that is baseflow is an objective approach to discharge separation (Arnold et al 1995, Arnold and Allen 1999). Several additional metrics, including 95th percentile, mean, median and coefficient of variation were also assessed.

Table 1. Hydrologic metrics evaluated, calculated from mean daily discharge measurements.

Hydrologic Metric	Calculation Method
Peak discharge	Maximum discharge in time period
p90	90th percentile in time period
Mean	mean discharge in time period
COV	The standard deviation expressed as a fraction of the mean in the time period
Median	The median, or 50th percentile in time period
Runoff depth	The sum of discharge in time period divided by the drainage area
Average Fall	The absolute value of the mean of all negative differences between consecutive daily values in the time period (Richter et al, 1996)
High pulse duration	The mean duration of high pulses during the period with a high pulse defined as discharge greater than the 75th percentile. (Ritcher et al., 1989)
Low discharge duration	The number of durations the mean daily discharge was consecutively below 0.1 ft^3/s per time period. (Ritcher et al., 1989)
Baseflow Fraction 1	The fraction of discharge considered to be baseflow after one pass with a digital filter (Arnold et al 1995, Arnold and Allen 1999)

Results

Annual impervious cover estimates from TCAD based on assessed building footprints were generated for each year from 1967 to 2009. Watershed impervious cover estimates for 7 years were developed by City of Austin GIS staff using aerial photography for the mainstem of Walnut Creek (did not include the Little Walnut or Buttermilk tributaries), and represent the most accurate large-scale estimates available. Coincident years with aerially-estimated impervious cover and TCAD impervious cover (also only from the mainstem of Walnut Creek) were used to develop a calibration curve to account for the impervious cover lacking (e.g., transportation and civic infrastructure, sidewalks, driveways) in TCAD-derived estimates. An exponential curve yielded an R^2 value greater than 0.995, and was used to adjust the TCAD estimates to include impervious area not assessed by Travis County (Figure 1). The calibrated TCAD estimates yielded good agreement with the aerial photography estimates (Figure 2).

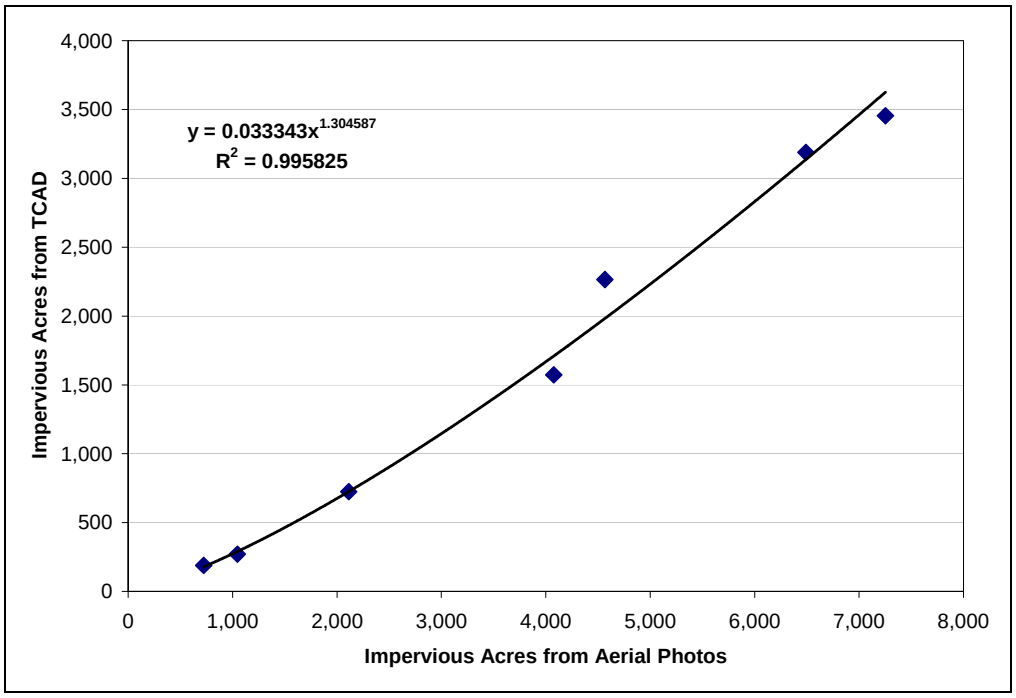

Figure 1. Calibration curve to adjust impervious acre estimates from TCAD based on impervious acres estimated from aerial photography (mainstem watershed area only).

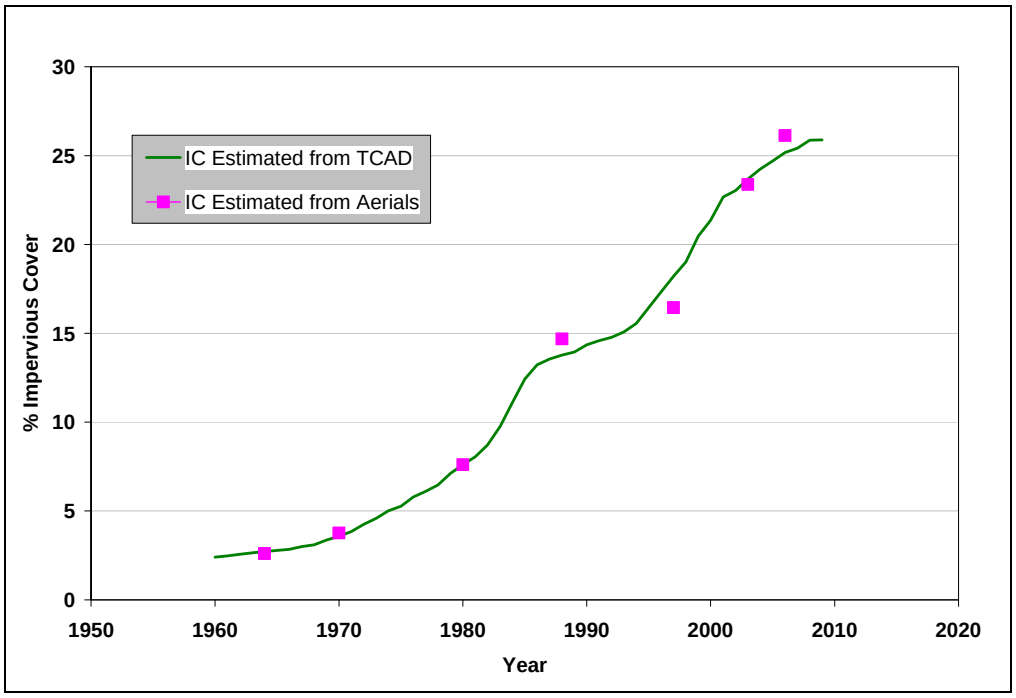

Figure 2. Comparison of adjusted (calibrated) TCAD impervious cover percentage and impervious cover percentage estimated from aerial photography (mainstem watershed area only).

Impervious cover in the greater Walnut Creek watershed is increasing over time, changing from 4% in 1967 to 28.5% in 2008 (Figure 3, Figure 4). Walnut Creek impervious cover exceeded 10%, the EPA "sensitive" threshold, in the year 1979, and exceeded 25% impervious cover, the EPA "non-supporting" threshold, in the year 2000.

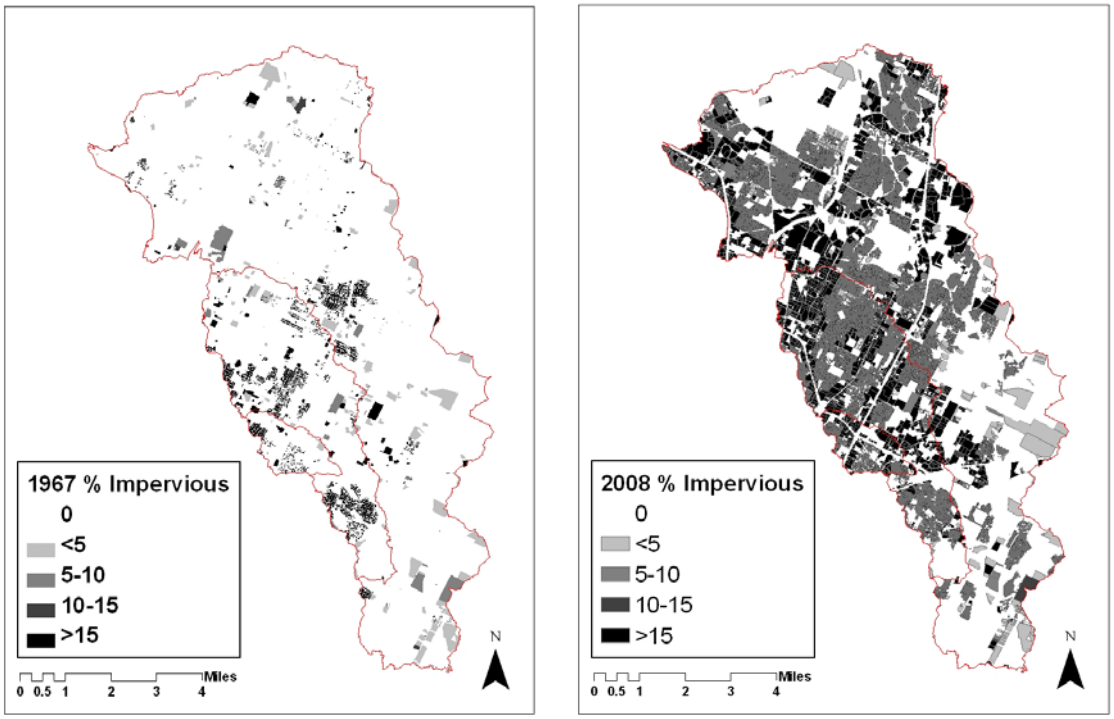

Figure 3. Percent impervious cover by parcel (not including roads) in 1967 (left) and in 2008 (right) for the Walnut Creek watershed.

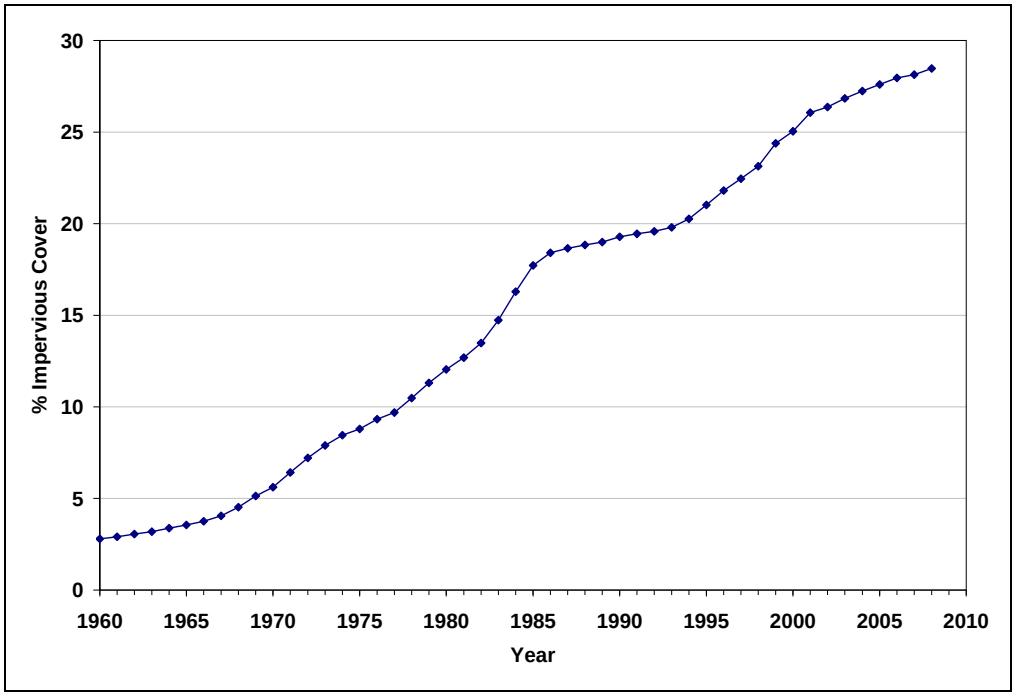

Figure 4. Walnut Creek (entire watershed) calibrated impervious cover over time (1960-2009).

Walnut Creek hydrologic metrics are changing over time as assessed on an annual scale by linear regression and correlation analyses from 1967 to 2009 (Table 2). Adjusted R^2 values are low due

to the high degree of variability between years. Significant ($\alpha<0.05$) or near-significant ($\alpha<0.06$) relationships are observed for average fall, high pulse duration, baseflow fraction, runoff depth, 90th percentile, 95th percentile and annual mean discharge. Average fall, runoff depth, 90th percentile, 95th percentile and annual mean discharge are increasing over time. High pulse duration and baseflow fraction are decreasing over time. All annual hydrologic metrics exhibiting a statistically significant or near-significant temporal regression relationship also yield a significant ($\alpha<0.05$) relationship with annual percent impervious cover. The maximum R^2 value from linear regression of hydrologic metrics with percent impervious cover was 0.21, generated for the 95th percentile of annual discharge. While statistically significant, the low R^2 value suggests other factors influence the observed variability in hydrologic metrics. Annual time steps are convenient but arbitrary and may not reflect climatically significant periods like droughts that span parts of consecutive years.

Table 2. Linear regression and Kendall's tau-β correlation analyses of Walnut Creek hydrologic metrics over time (1967-2009, n=42). Significant results are highlighted in green (<0.05) and near significant in yellow (<0.06).

			Regression			Correlation	
Metric	**adj. R^2**	**Type**	**Estimate**	**StdErr**	**Pr>|t|**	**tau-B**	**Pr>|r|**
		intercept	-584.5452	302.7100	0.0604		
Average Fall	0.07	year	0.3058	0.1523	0.0513	0.2381	0.0244
		intercept	84.6273	34.3188	0.0179		
High Pulse Duration	0.10	year	-0.0404	0.0173	0.0242	-0.1519	0.1516
		intercept	4.5732	1.6880	0.0098		
Bflow1	0.11	year	-0.0021	0.0008	0.0184	-0.2675	0.0129
		intercept	-15.5216	8.0389	0.0604		
Runoff Depth	0.07	year	0.0081	0.0040	0.0513	0.2027	0.0555
		intercept	-25.3782	37.1096	0.4979		
p10	-0.01	year	0.0136	0.0187	0.4694	0.0604	0.5715
		intercept	-459.4273	289.4555	0.1201		
p75	0.04	year	0.2417	0.1456	0.1045	0.1433	0.1798
		intercept	-1677.4947	665.7362	0.0157		
p90	0.12	year	0.8683	0.3349	0.0131	0.2149	0.0433
		intercept	-4530.8964	1450.5842	0.0033		
p95	0.18	year	2.3297	0.7297	0.0027	0.3017	0.0044
		intercept	-20438.9937	26403.4851	0.4433		
Annual Peak	-0.01	year	11.0835	13.2812	0.4088	0.0965	0.3625
		intercept	-19.8499	66.5165	0.7669		
Low flow frequency	-0.02	year	0.0107	0.0335	0.7503	0.0687	0.5609
		intercept	-775.1290	401.2937	0.0603		
Mean	0.07	year	0.4054	0.2019	0.0512	0.2027	0.0555
		intercept	-1564.5148	1736.2149	0.3728		
Stdev	0.00	year	0.8437	0.8733	0.3396	0.1340	0.2054
		intercept	-200.5115	140.5654	0.1613		
Median	0.03	year	0.1056	0.0707	0.1431	0.1361	0.2013
		intercept	43.6838	30.0007	0.1530		
COV	0.02	year	-0.0201	0.0151	0.1902	-0.1584	0.1345
		intercept	-30.8323	215.1889	0.8868		
Annual Rainfall	-0.02	year	0.0325	0.1082	0.7657	0.0255	0.8098

The trends in mean discharge and baseflow fraction could be a function of the observed change in near-peak (reflected in 90th and 95th percentile of stream discharge). There is no significant change over time in annual rainfall totals assessed by linear regression or correlation for the same time period (Figure 5). The lack of a corresponding trend in rainfall suggests that it is not the likely cause of the significant hydrological changes over time.

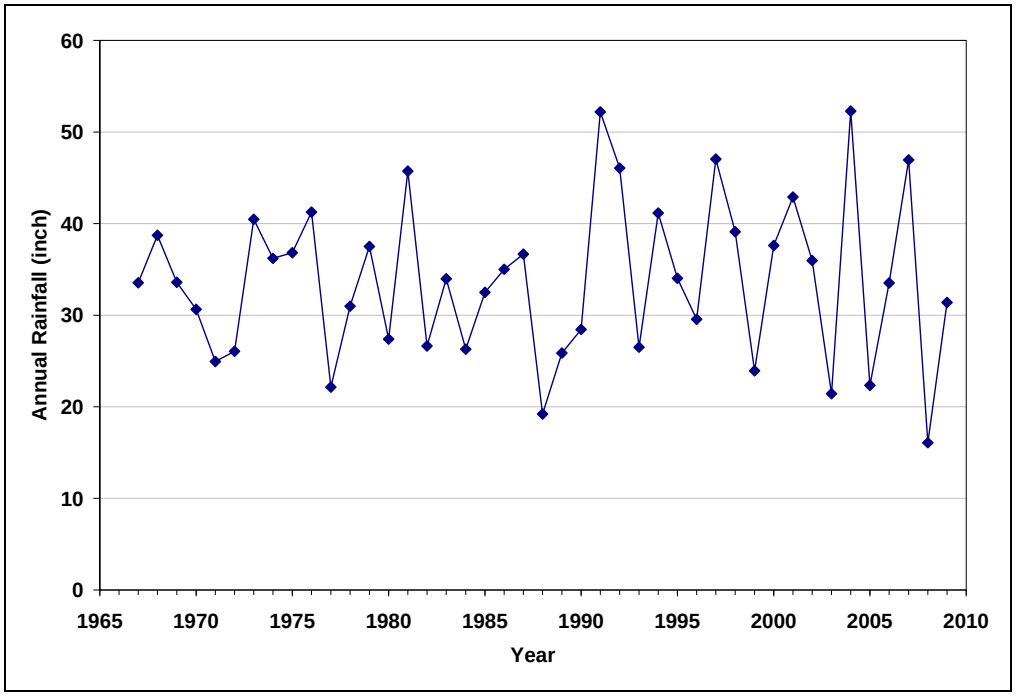

Figure 5. Austin annual rainfall totals from 1966 – 2009.

Changes in observed stream discharge trends were assessed using cumulative annual statistics. Changes in the slope of cumulative values plotted over time reflect a change in trend. Multiple linear regression analysis was used to identify breakpoints in cumulative statistics. A categorical variable was used to divide the period of record into two groups, and was entered first into a regression equation of the form:

Cumulative Stream Discharge Metric = Group Variable + Year

The regression was run 40 times for each hydrologic metric exhibiting a statistically significant trend over time and annual rainfall total, incrementing the categorical variable by one year each time. For example, the first group value would be "0" for years 1967 and 1968, and "1" for 1969 to 2009. The second regression would have the group value set to "0" for years 1967, 1968 and 1969 and "1" for 1970 to 2009. For each model, the sum of squares of the error was recorded and plotted by year group. The breakpoint yielding the minimum error was deemed to reflect the most likely year in which the change in hydrologic metric trend occurred. Because a minimum sum of squares value will always be generated for each metric, the significance of the breakpoint was evaluated by the non-parametric Wilcoxon rank-sum test on the annual (not cumulative) hydrologic metric between the resulting groups of years (before versus after the predicted break).

Statistically significant (probability greater than $\chi 2 < 0.05$ from Wilcoxon rank sum test of breakpoint) changes in trend were determined for 3 hydrologic metrics, and near-significant (probability greater than $\chi 2 < 0.06$) were determined for 2 hydrologic metrics (Table 3). There

was no statistically significant breakpoint determined for the cumulative annual rainfall records. The impervious cover values corresponding to the breakpoints for the hydrologic metrics range from 12.7% to 18.4% impervious cover, were exceeded in the watershed boundaries sometime between 1981 and 1986, and fall within the range of impervious cover described by EPA (2002) as "degraded."

The predicted breakpoints may represent the impervious cover levels when Walnut Creek's hydrologic response was significantly altered by development beyond the landscapes natural capacity to restore sustainable function, but do not imply that development with lower impervious cover did not incrementally degrade Walnut Creek hydrology. Again, the lack of an observed significant or coincident breakpoint in rainfall suggests that changes in Walnut Creek hydrology were not explained by climatic variation. The change in the hydrologic metrics suggest that Walnut Creek is transitioning to a more "flashy" discharge regime with more surface runoff resulting in higher near-peak discharges with faster hydrograph recession and less shallow aquifer communication.

Table 3. Significant temporal breakpoints for changes in hydrologic metric trends.

Metric	Breakpoint in Cumulative	Watershed Impervious Cover	Mean before Break	Mean After Break	$\chi 2$	Pr>$\chi 2$
Avg fall	1983	14.7	19.000	26.091	4.3538	0.0369
High Pulse Duration	1981	12.7	5.118	3.863	4.6923	0.0303
Mean	1985	17.7	24.847	35.508	3.8278	0.0504
Runoff Depth	1985	17.7	0.498	0.711	3.8278	0.0504
p95	1986	18.4	74.550	123.000	4.4371	0.0352
Annual Rainfall	1988	18.8	32.556	34.968	0.5313	0.4661

The change in hydrologic response is illustrated in a plot of the annual 95th percentile of stream discharge with impervious cover over time (Figure 6). The predicted threshold impervious cover was 18.4% in 1986. Variability in the annual 95th percentile of stream discharge increases dramatically after 1986, reflecting a 65% increase in average annual 95th percentile after 1986.

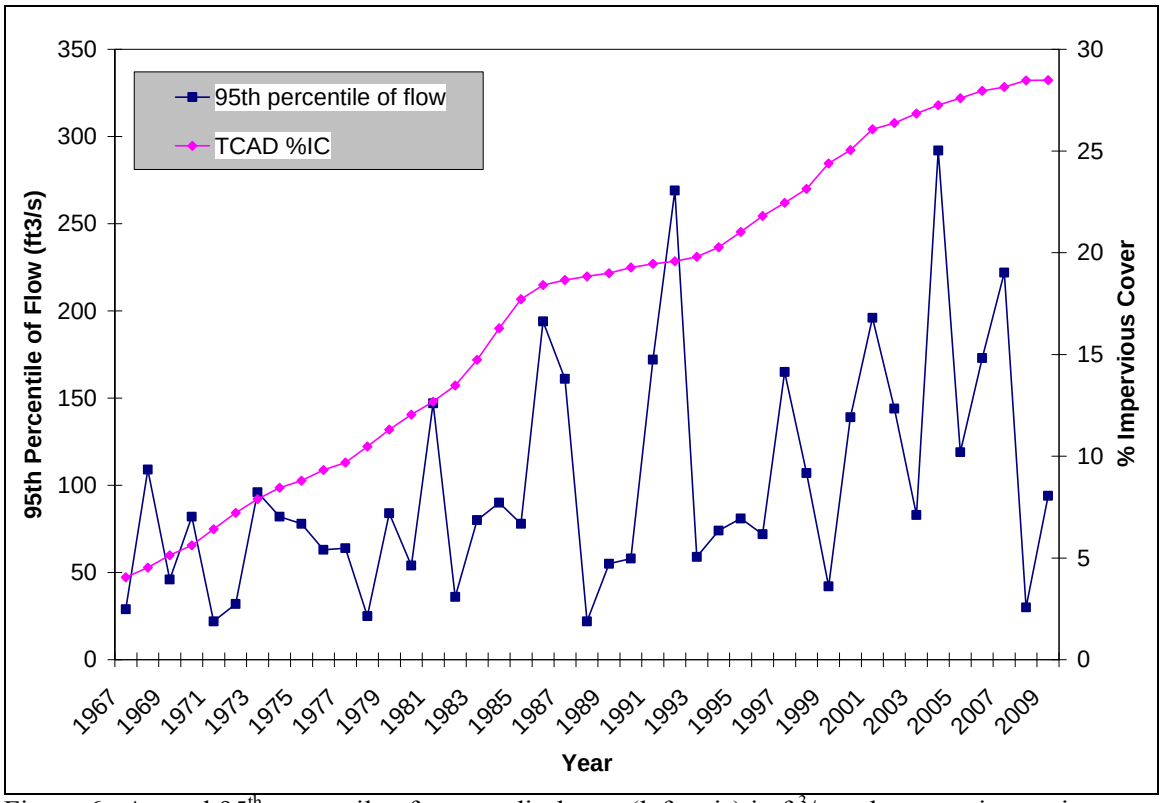

Figure 6. Annual 95th percentile of stream discharge (left axis) in ft^3/s and percent impervious cover (right axis) for Walnut Creek over time (1967-2009).

Regression models were developed for the hydrologic metrics yielding significant breakpoints (presented in Table 3) based only on annual rainfall totals for the time period before the identified breakpoint year (Table 4).

Cumulative Stream Discharge Metric = Annual Rainfall Total [for years < breakpoint]

Predicted values were then generated for years after the breakpoint as if there was no additional impervious cover added to the watershed beyond the breakpoint year. The mean of the predicted values for the remaining period of record (breakpoint thru 2009) were then compared to the mean of the actual observed values. The models account for variation in rainfall, but change in observed versus predicted values are only indirectly related to change in impervious cover as the hydrologic metrics and impervious cover are both increasing over time. There was not a significant relationship between annual rainfall and high pulse duration. For average fall, mean discharge and runoff depth metrics the predicted R^2 values are reasonable and suggest that impervious cover increase after the breakpoint may have resulted in 71%, 31% and 31%, respective, change in mean hydrologic metric values. The mean annual 95th percentile of discharge may have increased 54% due to increasing impervious cover after the breakpoint, although the model R^2 value is relatively low (0.28).

Table 4. Regression results based on period of record before breakpoint, and comparison of mean versus predicted values after the temporal breakpoint.

Metric	Prior to breakpoint		After breakpoint		
	Pr>|t|	R^2	Observed Mean	Predicted Mean	% Change
Avg Fall	0.0047	0.42	34.0	19.9	71.2
High Pulse	0.9053	.	.	.	.
Mean	0.0008	0.49	35.5	27.0	31.3
Runoff Depth	0.0008	0.49	0.711	0.542	31.3
p95	0.0155	0.28	123.0	79.4	54.9

Conclusion

County tax appraisal records provide a source for estimating impervious cover in a spatial context. Impervious cover in the Walnut Creek watershed is increasing over time, changing from 4% in 1967 to 28.5% in 2008.

Walnut Creek hydrologic metrics are changing over time in the absence of a corresponding change in annual rainfall. Stream discharge response to runoff appears to be degrading, becoming more "flashy" with increased runoff depth, increased near-peak discharge, faster recession following storm events and decreasing baseflow.

There appears to be a development threshold value of impervious cover between 12.7% and 18.4% at which Walnut Creek's hydrologic response to runoff was substantially altered. Increasing impervious cover over these thresholds up to 18.4% may be responsible for a 54.9% increase in the annual 95th percentile of discharge, a 31.3% increase in runoff depth, and a 71.2% increase in the average fall.

Discussion

There is a clear need in regulatory planning to identify critical development thresholds above which a watershed may no longer function sustainably. These thresholds should be treated as maximum limits, as urbanization below these thresholds may still yield degradation in water quality. Design criteria for best management practices on a site basis should focus on reducing urban development footprints to levels at or below these thresholds to maintain cumulative aggregations of impervious cover on a watershed scale below the critical limit.

Impervious cover is a useful surrogate for urban development, and may be determined based on relevant county tax appraisal records on a time step more consistent with stream discharge or environmental quality data. The impervious cover estimated here is the total, or gross, impervious area. The effective, or directly connected, impervious area may provide more accurate assessments of development impacts on hydrologic alteration (Sutherland 1995), although a previous City of Austin analysis in small watersheds found no improvement on correlations with stormwater runoff event mean concentrations with directly-connected impervious cover estimation over gross impervious area (COA 2009).

Because regulatory thresholds and the accompanying economic costs must be justified based on demonstrated impacts to aquatic systems, the connection between quantitative impervious cover level and demonstrable impacts to either hydrology or aquatic communities is of critical importance to meaningful environmental protection. Hydrology is most likely the most important

variable affecting the biological assemblages of intermittent Central Texas streams, and the relation of hydrologic metrics to biological effects continues to be a high priority.

The impervious cover estimation method explored here should be evaluated in other watersheds with long periods of stream discharge records and varying development patterns. Barton or Onion creeks, because these creeks recharge the Edwards Aquifer and supply water to the habitat of the endangered Barton Springs salamander, would be excellent candidates if Hays County tax appraisal records can be obtained. Multiple estimates of impervious cover, like those derived from aerial imagery, would be needed to adjust appraisal records for non-assessed impervious area. Entities with access to impervious cover estimates from less than 3 time periods would most likely be unable to employ this method.

The impacts of impervious cover on Walnut Creek hydrology may have already been partially mitigated by the construction of structural flood control and water quality BMPs. Once the treatment areas of these stormwater control devices are delineated, they could be incorporated into modeling analyses as an additional explanatory variable. The inclusion of flood and water quality controls on hydrologic alteration analysis could be used to not only to better identify potential impervious cover thresholds, but also to provide insight into the cumulative effectiveness of structural BMPs.

A Soil and Water Assessment Tool (SWAT) model is being calibrated for Walnut Creek by the City of Austin. It may be possible to further evaluate the conclusions of this analysis by experimentally altering the input land use patterns to reflect a specific point in time (e.g., prior to observed breakpoints) and then modeling stream discharge to the present day using real historic climate inputs.

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