GIS-based Flood Risk Analysis Across Large Metropolitan Areas

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Abstract

This paper examines the effects of urbanization on the flood hazard in semi-arid/arid southern California using traditional hydrograph, frequency-magnitude and statistical analysis augmented with GIS-based variable parameterizations and visualizations. It was found that the peak flood discharges were significantly increased in urban watersheds in conjunction with increasing mean baseflow in the streams. Urbanization resulted in a reduction in flood duration and the number of days of storm flows after the peak discharge. The rainfall-runoff relationship has also changed in urban watersheds and showed certain patterns across the watersheds over time. This research shows how GIS can serve as a platform for characterizing the cumulative impacts of neighborhood-specific land use changes and stream modifications on the flood hazards by estimating hydrologic parameters and integrating different types of spatial data sources. It concludes that floods behave differently in urbanized watersheds and non-urban watersheds.

Key words: Flood risk, urbanization, traditional methods, and GIS

1 Introduction

The relentless urban growth that characterizes many regions points to an increasing need to continuously assess the urban flood hazard from the urban planning, water resource and ecosystem management perspectives. Typically, urbanization leads to increasing imperviousness, which in turn causes increases in peak storm discharge and total runoff volume. These increased volumes travel more rapidly to surface waters, thus producing higher peak flows and velocities. As a result, communities and properties located in flood-prone areas are exposed to increased flood hazard, including inundation and erosion, as new development continues on the periphery of the existing urban landscape. In addition, this development poses significant threats to urban stream ecosystems through changes to both the regular flow and flood regimes. Improved spatio-temporal information about regular and flood flows and how they are affected by land use can help communities reduce their current and future vulnerability to floods and to find ways to promote or sustain healthy urban stream ecosystems.

The general impacts of urbanization on hydrologic processes and flood behavior - that decreases in the perviousness of the catchment lead to decreases in infiltration and increases in surface runoff - were first addressed by Dunne and Leopold (1978) and later validated in a series of intensive studies conducted in various physical settings by environmental agencies such as the USGS (e.g. Anderson 1968, Couch and Hamilton 2002, Konrad 2003) and individual researchers (e.g. Espey et al. 1965, Klein 1979, Bailey et al. 1989, Booth 1990, Konrad and Booth 2005). The adoption of GIS and remote sensing technology in this research has increased over time although the roles played by these tools are often limited to the preparation of spatial input datasets describing land use and land cover, soils, precipitation, and other watershed parameters (Weng 2001, Beighley and Moglen 2002, Bronstert et al. 2002, White and Greer 2006).

Overall, the association of urbanization and the change in flow and flood behavior is frequently approached by empirical regressions relating urbanization measures such as population density and impervious surface on the one hand and flow variables such as baseflow, storm flow, instantaneous peak discharge, maximum daily discharge on the other (White and Greer 2006). Statistical tests are often used to detect significant changes in flood characteristics across the landscape and/or through time. Meanwhile, hydrologic models are calibrated in some cases against a unit hydrograph from a particular event and then employed to predict hydrologic responses under different land use scenarios assuming the relationship between rainfall and runoff is known from historical hydrographs. The complexity of models varies from simple empirical models such as the curve number methods (SCS 1986) to complicated process models such as the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (USACE 2000).

The changes in land use associated with urban development affect flooding in many ways. For example, the runoff typically increases two fold as the percent catchment impervious surface cover (ISC) increases to 10-20%, threefold with an ISC of 35-40%; and more than fivefold with an ISC of 75-100% compared to a forested catchment (Arnold and Gibbons 1996). Similarly, lag time, the time elapsed from the center of the precipitation volume to the center of the runoff volume, is shortened in urban catchments, resulting in floods that peak more rapidly (Espey et al. 1965, Hirsch et al. 1990). Peak discharges are higher and of shorter duration (Seaburn 1969). And it has also been widely recognized that the impacts of urbanization on flood magnitudes are greater for floods with shorter recurrence intervals than those with long recurrence intervals (Hirsch et al. 1990). Hence, the 100-year flows nearly doubled when impervious surfaces covered more than 20% of the area and the number of smaller events (1- to 5-year recurrence intervals) increased several times in small (0.3 to 18 km^2) basins in western Washington (Hollis 1975, Booth 1988).

However, the aforementioned changes in flood behavior with increasing watershed urbanization will vary with basin characteristics, development patterns, and climatic setting. Most of the case studies reported in the literature were conducted in temperate areas, where response of watersheds to urbanization can be expected to differ from that in a arid or semi-arid area. The typical relationships between urbanization and flood characteristics may or may not apply in watersheds where the streams are characterized by large seasonal variability, very flashy flow regimes, and rapid response of runoff to rainfall, such as in our southern California study area. In addition, a variety of alterations to the hydrologic system in this region including water imports, ground water recharge, storage and extraction, construction of dams, debris basins, spreading grounds, and channel modifications may have obscured or even masked the effects urbanization of on flood behavior, and therefore dramatically increase the difficulty of flood hazard assessments that are associated with increasing imperviousness.

This paper examines the effects of urbanization on flood behavior in semi-arid/arid streams at a regional scale using traditional hydrological and statistical analysis techniques augmented with GIS-based variable parameterizations and visualizations. It aims to demonstrate that it is possible to characterize the cumulative impacts of neighborhood-specific land use change and hydrologic modifications on the regional flood hazard using GIS technology, and to show how this flood hazard has changed across the region over time spans ranging from decades to centuries. The methods that are to be used incorporate spatial information consisting of point-based hydrologic measurements, area-based land cover/land use maps and estimated hydrological parameters (e.g. catchment boundaries and rainfall amounts). These methods and data are used to generate multiple flood behavior parameters, which may be of greater use than single event simulations in depicting spatio-temporal trends and management needs.

Various hypotheses stated in the literature were tested to determine whether or not the typical relationships between urbanization and the flood hazard are present in our study. They were reformatted into four research questions as follows:

- How have the instantaneous annual peak discharges, maximum daily discharges, and mean annual daily discharges changed in urbanized/urbanizing watersheds? Has the relationship between rainfall, storm runoff and baseflow significantly changed in response to urbanization?
- Is there any spatial and temporal pattern to the rainfall-runoff relationship in our selected watersheds?
- How has the frequency, magnitude, and duration of individual flood events changed in the urbanized watersheds?

2 Methods

2.1 Study area

The extent of our study area was predefined by five 8-digit HUC (Hydrologic Unit Code) watersheds within the Los Angeles metropolitan area. The five watersheds of the

Calleguas Creek, Los Angeles River, San Gabriel River, Santa Clara River and Santa Monica Bay are shown in Figure 1 along with the geographic location and extent of the study region. In this semi-arid Mediterranean climatic region, winter storms bring heavy precipitation over periods of one or two days with most precipitation falling in a few major storm events between November and March. Heavy precipitation, short streams and steep watersheds emptying onto densely settled lowlands sometimes cause severe flood damage. The magnitude of these problems is occasionally compounded by the loss of vegetation in upland areas of watershed due to fire.

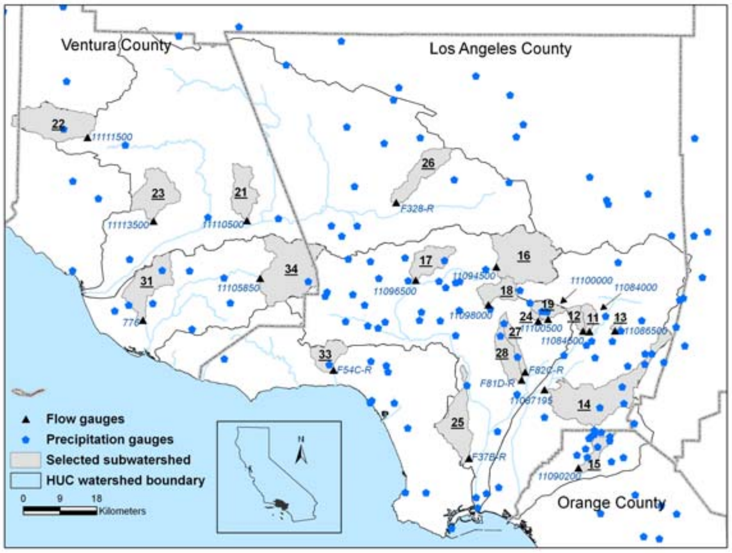

Figure 1 Streamflow gauge locations along with their watersheds and NCDC precipitation gauge locations within study area.

2.2 Stream gauge selection

The study area contains a total of 201 gauges, with 139 operated by the USGS, 40 by the Los Angeles County Department of Public Works (LADPW) and 22 by the Ventura County Watershed Protection District (VCWPD). Flow gauges were selected for the analysis based on the following criteria: (1) the entire watershed is contained within the study area; (2) the drainage area is less than 300 km^2; (3) there are more than 20 years of flow records; and (4) the gauges are not affected by hydraulic constraints (dams, reservoirs, etc) that were officially stated in the gauge report. Table 1 summarizes the twenty flow gauges selected for this study and Table 2 summarizes selected characteristics of the streams and watersheds above these gauges. These watersheds drain 1616 km^2 and range in size from 4.7 km^2 to (watershed #24) to 230 km^2 (watershed #14). Their locations range from the Los Angeles National Forest (1800 m above the mean sea level) to the coastal flat plain. The land use/land cover in these watersheds range from relatively pristine, shrublands to heavily developed watersheds such as is found in Compton Creek and Alhambra Wash.

Table 1 Summary of stream flow gauges used in study

Watershed #	Gauge no.	County ID	Agency	Discharge		Peak		Record (years)	No. events analyzed
				Begin	End	Begin	End		
11	11084000	37	USGS	3/10/1918	2/11/1962	3/10/1918	2/11/1962	46	8
12	11084500	37	USGS	3/10/1918	1/17/1979	3/10/1918	1/17/1979	64	11
13	11086500	37	USGS	10/1/1938	12/21/1970	10/1/1938	12/21/1970	34	6
14	11087195	37	USGS	3/10/1929	1/22/1964	3/10/1929	1/22/1964	36	6
15	11090200	59	USGS	1/12/1960	3/1/1981	1/12/1960	3/1/1981	23	4
16	11094500	37	USGS	2/5/1931	2/6/1950	2/5/1931	2/6/1950	21	3
17	11096500	37	USGS	10/1/1928	2/11/1973	10/1/1928	2/11/1973	46	6
18	11098000	37	USGS	2/20/1914	2/12/2003	2/20/1914	2/12/2003	95	10
19	11100000	37	USGS	12/24/1916	2/28/1970	12/24/1916	2/28/1970	55	9
21	11110500	111	USGS	12/31/1933	3/1/1983	12/31/1933	3/1/1983	51	10
22	11111500	111	USGS	3/10/1949	2/12/2003	3/10/1949	2/12/2003	54	9
23	11113500	111	USGS	1/19/1933	3/15/2003	1/19/1933	3/15/2003	77	12
24	11100500	37	USGS	12/24/1916	2/11/1962	12/24/1916	2/11/1962	49	7
25	F37B-R	37	LADPW	1/22/1928	to present	1/22/1928	to present	74	12
26	F328-R	111	LADPW	10/26/1956	to present	10/26/1956	to present	48	6
27	F82C-R	37	LADPW	10/1/1949	to present	10/1/1949	to present	56	7
28	F81D-R	37	LADPW	1/14/1930	to present	1/14/1930	to present	73	13
31	F776	111	VCWPD	10/1/1979	9/1/2003	NA	NA	24	0
33	F54C-R	37	LADPW	1/1/1930	to present	1/1/1930	to present	68	7
34	11105850	111	USGS	10/1/1933	10/1/1982	10/1/1933	10/1/1982	49	7

Table 2 Summary of the stream and watershed characteristics

Watershed #	Drainage area (km^2)	DEM derived drainage area (km^2)	Mean elevation (m)	Standard deviation elevation (m)	Mean stream gradient (%)	Strahler stream order	HUC	2001 population (#)	Impervious surface (%)
11	17.1	17.4	762.7	217.7	19.0	4	18070106	0	0
12	16.6	16.1	869.2	259.7	20.6	3	18070106	3	0
13	7.0	7.3	757.3	155.6	17.5	2	18070106	3	0
14	229.7	202.3	233.1	141.6	5.1	5	18070106	216,495	45.0
15	31.3	28.2	104.3	50.8	2.7	4	18070106	20,142	55.7
16	174.8	174.3	1401.9	240.6	13.8	5	18070105	118	4.5
17	54.7	54.8	740.7	252.4	12.3	5	18070105	3,466	2.4
18	41.4	42.1	1098.6	307.3	18.8	4	18070105	44	0
19	25.1	25.2	1085.6	247.9	20.4	4	18070105	0	0
21	62.2	61.0	759.8	280.7	14.7	3	18070102	13	0.1
22	129.5	129.0	1493.2	201.3	11.8	4	18070102	2	0
23	98.4	88.8	956.2	437.3	14.9	4	18070102	244	0.3
24	4.7	4.5	1062.6	176.3	24.1	3	18070105	0	0
25	58.5	90.4	47.3	25.1	0.3	1	18070105	300,802	66.7
26	69.7	70.6	845.3	225.8	7.2	4	18070102	1,406	1.0
27	28.2	20.9	208.3	78.3	1.5	1	18070105	37,929	61.6
28	39.4	52.3	198.2	89.8	1.7	2	18070105	132,341	60.6
31	119.1	93.8	109.9	104.8	4.6	4	18070103	10,431	6.6
33	46.6	44.1	419.0	94.5	8.2	4	18070104	3,010	3.0
34	182.9	179.9	473.5	163.5	6.3	5	18070103	58,892	15.3

2.3 Precipitation data

Precipitation data corresponding to the discharge events in each watershed were acquired and used to develop relationships between rainfall, runoff, storm runoff and baseflow. Data were obtained from the National Climatic Data Center (NCDC) for 200 cooperative precipitation stations that falling within Ventura and Los Angeles Counties and parts of the adjacent counties to minimize any edge effects in the precipitation simulations. The length of the time series varies among stations. Stations with gaps in the time series from 1921 – 2000 were kept in the simulation and effects of missing data on simulations were evaluated by the module in ANUSPLIN version 4.3 (Hutchinson 2004). A five step procedure was employed to develop the total precipitation volume within each watershed as follows. First, the watershed boundaries for selected flow gauges were delineated using the Arc Hydro tools in ArcGIS (CRWR 2002) with a 30m DEM downloaded from http://casil-mirror1.ceres.ca.gov/casil/gis.ca.gov/dem/. Second, precipitation events corresponding to the annual instantaneous peak events were selected every five water years in the time series (e.g. water year of 1930, 1935, 1940, etc.). Due to the fact that peak discharge did not occur simultaneously across watersheds, sometimes, multiple events were selected in the same water year depending on the occurrence of peak discharges in different watersheds. Third, the total precipitation and antecedent precipitation index (API) were calculated as depths in inches for the selected peak events. The total precipitation refers to the amount of precipitation during particular storm events whereas the API is the precipitation that accumulates from the date and time a precipitation event starts until the date and time at which instantaneous annual peak discharges is observed. In our study area, these two measures frequently equaled one another due to the short duration of storm events.

Continuous precipitation surfaces were generated for individual storm events and annual precipitation using ANUSPLIN version 4.3 (Hutchinson 2004) at the resolution of 450 by 450 m grid cell size in step four. The ANUSPLIN package has a program which fits an arbitrary number of (partial) thin plate smoothing spline functions incorporating one or more independent variables. The degree of data smoothing is normally determined by minimizing the generalized cross validation (GCV) of the fitted surface. We found that the module SPLINB worked best with our datasets (i.e. more than 200 climate station precipitation records and resampled 450 m DEMs). The SPLINB option allows missing data in the precipitation series and suits datasets with up to about 10, 000 data points. The package also provides comprehensive statistical analyses, data diagnostics and spatially distributed standard errors. The data errors or uncertainty that accompanied our reliance on this approach are evaluated later in the rainfall-runoff analysis. A comprehensive introduction to the technique of thin plate smoothing splines, with various extensions, is given in Wahba (1990). Additional discussion of the algorithms and associated statistical analyses, and comparisons with kriging, are given in Hutchinson (1993) and Hutchinson Gessler (1994).

The total precipitation and API falling within each delineated watershed were calculated by summarizing the products of precipitation depth and grid cell area (i.e. 450 by 450 m in this instance) in the fifth and final step.

2.4 Land use, percent impervious surface and population density estimates

The percent impervious surface was derived from 2001 land use data compiled by the Southern California Association of Governments (SCAG) and used to designate the level of urbanization in each watershed. The percent impervious surface relied on the conversion ratios between specific land uses and percent impervious surface obtained from the Los Angeles County Department of Public Works (LADPW) (LADPW 2006). If more than one type of development was present within a watershed, a composite value must be determined using an area-weighted average. The composite impervious value is calculated by multiplying each impervious value by the area it represents and dividing the sum of these products by the total area.

The 2001 population density in each watershed was approximated using the 2001 LandScan™ Global Population Database (Bhaduri et al. 2002, see http://www.ornl.gov/landscan/ for additional details) to examine the relationship between percent impervious surface and population density. This raster dataset contained cells that measure 1100 m on a side. The population density by watershed was calculated by dividing the population counts of each grid cell by the watershed area in km^2. The Los Angeles County Union census tract data series was acquired from Ethington et al. (2000) and aggregated into a watershed- based population densities to indicate the pace of urban development from 1940 to 2000 considering the correlation between percent impervious surface and population density. The watersheds that are outside Los Angeles County or situated in Los Angeles National Forest were excluded from the historical analysis because the census data from earlier censuses have not been mapped to 2000 census boundaries.

2.5 Statistical tests

The Kendall non-parametric test was used to identify any significant trend in the annual rainfall, instantaneous annual peak discharge (PeakQ), maximum daily discharge (MaxQ), and mean annual daily discharge series (MeanQ). This particular test is designed to detect a monotonically increasing or decreasing trend in the data rather than an episodic or abrupt event (McCuen 2003). The null hypothesis, which assumed that the tested variables are a sample of n independent and identically distributed random variables, was rejected if the calculated test statistic (Kendall's τ) corresponded to a probability value (p value) greater than some critical level of significance, taken here as 5%. The smaller the p value, the more convincing is the rejection of the null hypothesis (e.g. that there is no significant trend in the tested time series). In an urbanized or urbanizing watershed, PeakQ and MaxQ are expected to increase with increasing urbanization. But the literature does not indicate what happens to MeanQ, presumably because of its weak connection with flood behavior and the likelihood that it is influenced by factors other than land use/land cover.

2.6 Flood behavior analysis

It is less obvious how urbanization changes the fraction of precipitation that leaves the watershed as direct surface runoff and/or recharge groundwater and subsequent baseflow (Paul and Meyer 2001). This relationship is difficult to estimate due to the complex spatio-temporal variability of the infiltration, overland flow, and subsurface flow generation processes. The long term focus and large spatial extent of the current study compounded these problems due to the paucity of spatial data and uncertainties that accompanied the watershed parameterization and flow characterization.

We nevertheless calculated three variables in hopes of shredding light on this fraction as follows:

- The runoff index, which is the ratio of observed runoff to total precipitation. This index typically varies with the different land use/land cover and hydrologic soil groups in the watershed. This index is sometimes used as a measure of the freshwater availability.
- The ratio of direct storm runoff to total runoff. Increases in storm runoff result in a reduction in baseflow discharge in urban watersheds.
- The ratio of PeakQ to API, which measures how much runoff is generated per unit of precipitation.

All of the abovementioned variables get to know how the water's residence time in the watershed is modified as the watershed is urbanized and the impervious cover increases.

The traditional hydrograph method, a powerful conceptual tool for describing rainfall-runoff relationships, was used to examine changes in flood duration and number of days after the peak discharge after urbanization. For each peak events selected, the Web-based Hydrograph Analysis Tool (WHAT) (see http://pasture.ecn.purdue.edu/~whaT/) was employed to separate the storm runoff and baseflow from the observed total runoff using the one parameter digital filter method (Lyne and Hollick 1979, Nathan and McMahon 1990, Arnold and Allen 1999). Flood durations were estimated by counting the time period between the starting point and the ending point of each individual event. The determination of the starting and ending points of events is tricky in the case of double peak events, in which hydrographic shape was modified into two peaks instead of one peak with one rising and one receding limb. This problem was avoided by picking alternative flood events in the same water year, e.g. the second largest, or third largest event and so on. Figure 2 shows an example of the determination of the starting and ending points as well as the result of baseflow separation using the WHAT tool in one of the watershed #23.

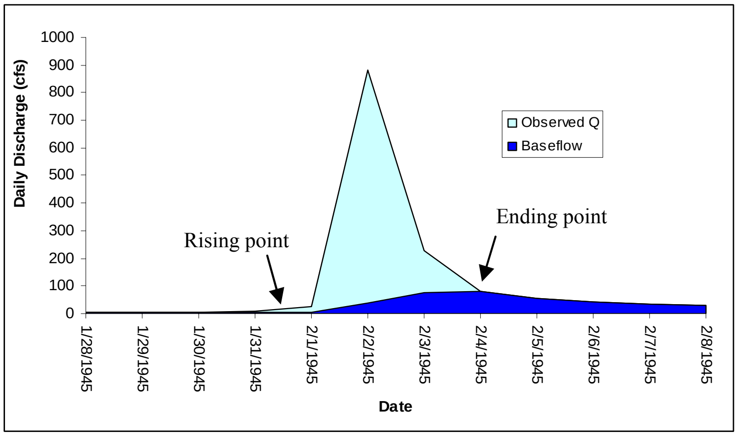

Figure 2 An example of baseflow separation using the WHAT tool and the determination of starting and ending points of a flood event. Storm events lasted 4 days and 2 days after the peak discharge in this particular event at gauging station no. 11113500.

Flood duration and number of days of storm flows after peak discharge were estimated at five year intervals from 1920 to 2000 using the hydrograph method for four urban and four non-urban (mountainous) watersheds, which have the most storm events selected. The effects of drainage area size on number of days of stormflow following the peak discharge were taken into account by normalizing the observed number of days after peaks using theoretical values estimated using the following equation:

$$N = A^{0.2} \qquad (1)$$

where N is the number of days after peak and A is the drainage area of gauged watershed in square miles by Clement (1984).

Hydrographs were plotted in two urbanized and two non-urban watersheds for four storm events that occurred in the 1932, 1945, 1965 and 1990 water years. Visually, these graphs highlighted the different hydrologic responses to the same regional wide flood events among watersheds, and demonstrated how different levels of urbanization modified the rainfall-runoff relationship.

Finally, flood frequency and magnitude curves were plotted for two consecutive time periods, prior and post development, for each of 20 selected watersheds. To estimate the frequency of peak flood flows, the recurrence intervals of the peak discharges (T) during the period were determined using a Weibull plotting position formula (Gordon et al. 1992):

$$T = (n+1) / m \qquad (2)$$

where *n* is the number of discharge values ranked and *m* is the rank of each discharge value. The breakdown of time series into two stages varied among watersheds to ensure that at least 20 years of records were included within each time period. Most of the time series were divided into prior and post development sets using a year in the 1960s. Discharge values and recurrence intervals were plotted separately for each of the two periods on logarithmic scales, and flood magnitudes were estimated from linear regression lines calculated with the logarithmically transformed data.

3 Results

3.1 Land use patterns and population changes in last 60 years

A single composite impervious surface value (%) was calculated for each watershed based on the 2001 SCAG land use data. The degree of urbanization, indicated by percent impervious surface, varies from 0% to 66.7% among the 20 watersheds examined in this paper. Thirteen of the 20 watersheds listed in Table 2 are relatively pristine as evidenced by percent impervious surface values of less than 5%. Three watersheds (#14, #34, and #31) have experienced moderate development (e.g. urbanizing watersheds) given imperviousness values of 45.0%, 15.3 %, and 6.6% respectively (Table 2). The four remaining watersheds (#15, #25, #27, and #28) are dominated by residential, commercial, and transportation land uses and percent impervious surface values are greater than 50%.

The watersheds with high imperviousness values in Los Angeles County also recorded the highest population densities in 2001. Regressing percent imperviousness against the overall population density generated a coefficient of determination R^2 of 0.95 indicating that population density is a good surrogate measure for percent impervious surface when land use data are not available.

3.2 Annual rainfall, PeakQ, MaxQ and MeanQ time series statistics

The annual rainfall falling within each watershed was stationary over time in 15 of 20 watersheds with a decreasing trend detected in the other five watersheds (Table 3). Based on this, it is reasonable to assume that any increase in flow in the streams is not due to a wetter weather regime. Factors other than climate should contribute to whatever changes have occurred. Kendall tests on instantaneous annual peak discharge (PeakQ) for all watersheds detected significant increases in the four "urban" watersheds and one urbanizing watershed (#34) starting from 1930s to 2000 at the 0.05 significance level (*p* value < 0.05; Table 3). The increasing dry and wet weather flows at these stations indicate why increasing stream bank erosion and more frequent urban flooding have been ascribed to the increasing urban development (e.g. CH2M HILL, 2005, Alhambra Creek Watershed Planning Group 2001, Los Angeles and San Gabriel Rivers Watershed Council 2005).

Table 3 Level of significance (*p* value) for calculated statistics τ for Kendall nonparametric tests on PeakQ, MaxQ and MeanQ. Bold numbers indicate significant trend at 0.05 level significance and (-) indicates decreasing trend.

Watershed #	Annual Rainfall	PeakQ	MaxQ	MeanQ
11	0.397	0.495	0.348	0.237
12	0.450	0.497	0.952	0.892
13	0.496	0.635	0.858	0.721
14	0.771	0.663	0.576	0.371
15	0.122	**0.000**	**0.000**	**0.000**
16	**0.050**	0.601	0.834	0.600
17	0.273	0.942	0.722	0.906
18	0.160	0.849	0.897	0.309
19	0.248	0.465	0.736	0.493
21	**0.031(-)**	0.774	0.516	0.586
22	**0.001(-)**	0.088	**0.020**	**0.010**
23	**0.034(-)**	0.950	0.513	0.139
24	0.415	0.649	0.551	0.940
25	0.054	**0.000**	0.094	0.103

26	**0.012(-)**	0.132	0.144	NA
27	0.654	**0.002**	0.217	**0.025**
28	0.759	**0.000**	**0.028**	**0.001**
31	0.216	0.276	0.535	0.131
33	0.490	0.700	**0.026**	0.948
34	0.797	**0.000**	**0.001**	**0.000**

MaxQ and PeakQ statistically increased respectively in five watersheds during the time period of record. However, the increases in MaxQ and PeakQ did not necessarily take place simultaneously in the same watersheds. The increasing trend was also shown in non-urban watersheds. For example, two urban watersheds (#15 and #28) experienced increases in both PeakQ and MaxQ in contrast to the other two, watershed #25 and #27, which recorded increases in PeakQ but not MaxQ. Statistically significant increases were reported for MaxQ and PeakQ in one rapidly urbanizing watershed (#34) highlighted in Table 3 such that the increasing trend in both PeakQ and MaxQ started emerging from 1930 to 1982.

Statistically significant increases in MeanQ were detected in five watersheds, three of which are in urban watersheds, one in a rapidly urbanizing watershed, and one Sespe Creek located in headwaters of an American Wild and Scenic River. In conjunction with the increasing trend in MeanQ, many of the streams have also changed from ephemeral to perennial streams, defined by whether or not streams carry flowing water continuously throughout the year. For example, Arroyo Simi at USGS no. 11105850 (#34) shows how this system, which used to be dry in dry seasons (e.g. June, July, Aug, Sep and Oct), started to capture flows during the period 1960-1969 (Table 4) and that the magnitude of these flows kept increasing over the next 12 or so years. But the timing of this switch from ephemeral to perennial characteristics in each gauged stream was watershed specific and varied from the 1940s to early 1980s.

Table 4 Monthly mean daily discharge (cfs) by decades at gauge no. 11105850 (Arroyo Simi near Simi Valley, CA)

Water year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1930-1939	0.0	0.0	5.9	7.4	41.7	140.5	1.1	0.1	0.0	0.0	0.0	0.0
1940-1949	0.0	13.5	12.1	38.5	377.7	348.4	171.8	0.0	0.0	0.0	0.0	0.0
1950-1959	0.0	3.7	6.1	11.0	271.8	14.1	55.7	0.0	0.0	0.0	0.0	0.6
1960-1969	25.5	31.6	66.6	220.0	67.7	97.0	29.8	40.8	29.5	25.2	46.4	45.1
1970-1979	33.7	587.2	480.3	887.9	1295.7	956.4	78.7	34.3	31.3	37.7	38.1	35.5
1980-1982	61.6	275.7	314.6	726.2	710.2	1829.5	187.8	61.2	49.6	44.3	48.5	109.2

3.3 Change in rainfall-runoff flood behavior

The runoff coefficient was highly variable across watersheds over time. The coefficient averaged by watershed varied from 0.01 to 0.99 (Table 5). The low values were frequently associated with non-urban watersheds while the high values were occurred in both urban and non-urban watersheds. But the correlation between the mean runoff coefficients and corresponding percent impervious surface values were not significant based on the existing storm event data. Nevertheless, some temporal patterns are shown in Figure 3 in three of four urban watersheds, where an increasing pattern was observed after 1955. The runoff coefficients in urban watershed #15 were dropped because of large residues in precipitation surfaces caused by missing data in the time series. Table 5 summarizes mean, low and high values of the runoff coefficients. It shows that three urban watersheds and mountainous watersheds #11, #12, #18, #19, and #23 have relatively higher mean values than the remaining watersheds. These results support the notion that urban paved land surfaces tend to generate more runoff from the individual rainfall events than non-urban (e.g. forested) land surfaces. The high values reported for these mountainous watersheds occurred in landscape with bare rock surfaces (Jennings 1977), steep slopes (Table 2) and thin soils. These characteristics are similar to those of urban paved land surfaces and both types of land surface produce rapid response of surface runoff with a large percentage of the total rainfall coverted to flood waters.

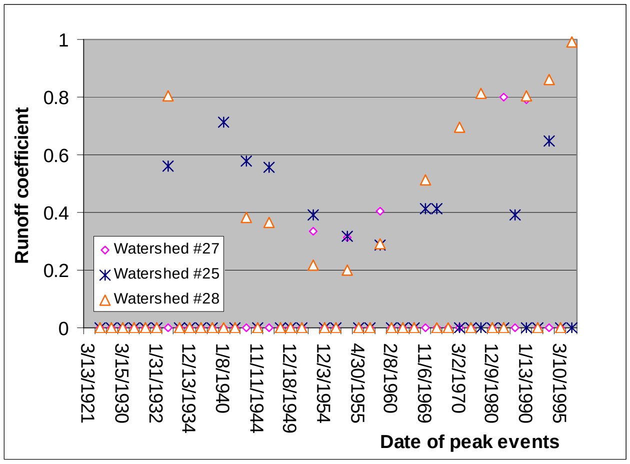

Figure 4 Runoff coefficients in three urban watersheds for selected storm events

Table 5 Summary of the three ratios that measure flood behavior. (ND: No Data)

Watershed ID	No. events	Impervious surface (IA) (%)	Total runoff / Total precipitation			Storm runoff / Total Runoff			PeakQ/API		
			Mean	Low	High	Mean	Low	High	Mean	Low	High
11	8	0	0.42	0.10	0.94	0.92	0.87	0.94	4.6	0.2	18.9
12	11	0	0.47	0.11	0.99	0.89	0.81	0.93	3.1	0	12.3
13	6	0	0.17	0.02	0.46	0.89	0.74	0.98	1.4	0.1	3.4
18	10	0	0.39	0.02	0.99	0.73	0.54	0.86	2.9	0.3	10.3
19	9	0	0.35	0.09	0.73	0.70	0.47	0.78	2	0.6	6.2
22	9	0	0.18	0.06	0.43	0.71	0.42	0.82	11.6	0.1	57.3
24	7	0	0.25	0.02	0.59	0.80	0.72	0.89	1.7	0.2	4.6
21	10	0.1	0.31	0.09	0.68	0.87	0.75	0.95	9.9	1	24.9
23	12	0.3	0.47	0.18	0.97	0.76	0.34	0.88	11.8	0.6	27.9
26	6	1	0.05	0.01	0.12	0.87	0.74	0.93	0.4	0.2	0.8
17	6	2.4	0.22	0.01	0.68	0.95	0.93	0.98	3.5	0	22.7
33	7	3	0.30	0.11	0.45	0.86	0.81	0.90	33.9	2.1	113.6
16	3	4.5	0.50	0.27	0.84	0.74	0.73	0.75	3.7	2	5.7
34	7	15.3	0.06	0.01	0.11	0.92	0.88	0.96	1.3	0.1	6.9
14	6	45	0.35	0.10	0.68	0.91	0.83	0.96	5.1	0.6	11.9
Mean (IA < 50%)			0.30	0.08	0.64	0.84	0.69	0.91	6.5	0.5	21.8
15	4	55.7	ND	ND	ND	0.84	0.68	0.91	ND	ND	ND
28	13	60.6	0.59	0.20	1.08	0.89	0.71	0.95	11.8	3.9	27.7
27	7	61.6	0.46	0.31	0.79	0.91	0.81	0.96	20.6	5.3	38.8
25	12	66.7	0.51	0.29	0.90	0.88	0.68	0.96	7.9	3.7	24.3
Mean (IA > 50%)			0.52	0.27	0.92	0.88	0.73	0.98	13.4	4.3	30.3

The average storm runoff ratio by watershed ranged from 70% to 95% (Table 5). A large fraction of the rainfall is contributed to the storm runoff component and very small fraction to the baseflow component in this region. The ratios in the watersheds with high percent of impervious surface exceeded 85% with a wider range of ratios evident in non-urban watersheds. The ratios did not fluctuate very much over the time, although the variability was a little greater in non urban compared to urban watersheds. In this semi-arid climatic regime, the storm water versus baseflow component in runoff generation is largely dominated by the weather such that other factors seem to contribute little to this flood metric.

The highest PeakQ to API ratios occurred in both urban and non-urban watersheds (Table 5). But the average ratio of the urban watersheds was still higher than that of the non-urban watershed group even with the extreme high values in some mountainous watersheds. Peak discharge responded very quickly to rainfall events in these urban watersheds with an average 13.4 cfs per inch of precipitation versus 6.5 cfs per inch in the other group. These results confirm that impervious surfaces in both the natural and built environments produce large and erratic flood discharges. The increase in this ratio was significant at the 0.05 level of significance in just one watershed (#27), signifying a changing response to rainfall events due to land surface changes in this watershed from 1949 to the present.

3.4 Comparison of flood durations in urbanized and undeveloped watersheds

Flood durations and the number of days of storm flow after peak discharge were compiled for eight watersheds (Table 6). The number of events analyzed ranged from a minimum of 7 events and maximum of 16 events per gauge depending on the length of station record. Storm events (annual peak events) in four urban watersheds lasted 3.22 days on average, which was about 0.9 days shorter than that experienced in non-urban watersheds (Table 6). The average length of storm flows after the peak flow was recorded 1.7 days in urban watersheds compared to 2.3 days in non-urban watersheds (Table 6).

Table 6 Averaged flood durations and number of days of storm flows after peaks based on individual events in eight watersheds

		Flood duration (days)	Number of days after the peak (days)		Observed value normalized by the theoretical value
			Observed	Theoretical	
Urbanized watersheds	11090200	3.2	1.9	1.7	1.16
	F37B-R	2.9	1.6	1.9	0.88
	F81D-R	3.6	1.8	1.7	1.04
	F82C-R	3.2	1.4	1.6	0.88
	Mean	3.2	1.7	1.7	0.99
Non-urban watersheds	11086500	4.0	1.9	1.2	1.52
	11098000	4.3	2.7	1.7	1.53
	11113500	4.3	2.3	2.1	1.13
	F54C-R	3.9	2.1	1.8	1.20
	Mean	4.1	2.3	1.7	1.35

The theoretical number of days of storm flow after the peak discharge was recorded varied from 1.6 to 2.3 days in urban watersheds and 1.2 to 2.0 days in non-urban watersheds (Table 6). These values are a function of the watershed area size and the key result here is that normalized number of days after peaks was shorter in urban watersheds than those in non-urban watersheds. This result confirmed the fact that urban development resulted in a reduction in flood duration.

Four peak storm events in 1932, 1945, 1960 and 1990 were selected to compare the shift of hydrograph shapes between urban and non-urban watersheds. These events were selected because their corresponding rainfall events were relatively uniform across the entire region and the corresponding hydrographs were characteristic of single peak storms with one rising and one receding limb. The daily discharges in cfs were divided by API in inches to accommodate the possible effects of drainage size and topography on flood processes or hydrographic shapes. Three variables including baseflow, duration, and volume of peaks, which can be measured from hydrographs, behaved differently in urban and non-urban watersheds:

- In urban watersheds, baseflow returned to pre-storm levels 1 or 2 days after the peak discharge arrived. In comparison, baseflow persisted at a higher level in the non-urban watersheds (Figure 4). More water per unit of precipitation was recharged to baseflow in the non-urban watersheds.
- During the storm events of 1965 and 1990, peaks flows per unit of precipitation in the two urban watersheds exceeded those in the two non-urban watersheds. However, the opposite characterized the events of 1932 and 1945, so that higher peak flows per unit of precipitation were generated in the non-urban watersheds.
- The receding limbs of the urban hydrographs were steeper than those calculated for the non-urban watersheds in 1965 and 1990.

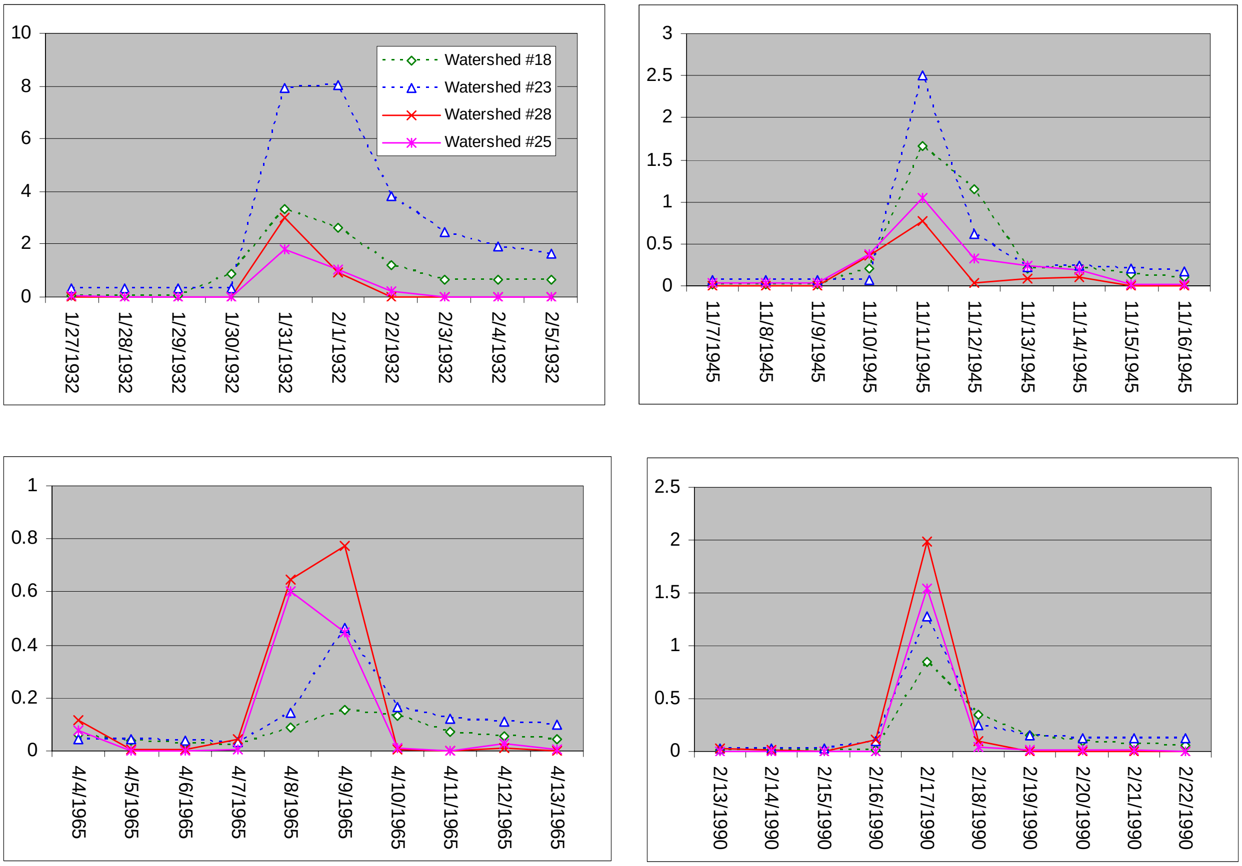

Figure 4 Comparison of flood hydrographs for four storm events in four selected watersheds. The percentage impervious surface in watershed #18, #23, #28, and #25 were 0%, 0.3 %, 60.6%, and 66.7% respectively. The Y axis values show the observed daily flow in cfs normalized by API in inches.

3.5 Change in flood frequency and magnitude prior to and post 1960

Flood frequency and magnitude curves were plotted for the two time periods prior to 1960 and post 1960 in three urbanized and one of the rapidly urbanizing watersheds. Figure 5 shows two curves in one of the watershed (#25). The other three watersheds (#27, #28 and #34) had similar curve patterns and were summarized in Table 7 using the fitted logarithmic regression equations. Urban Watershed (#15) was dropped from the analysis because the length of record and number of peak records in each time period were too short. The curves have all shifted towards higher peaks for both the high-frequency low magnitude events (e.g. 2-year) and low-frequency rare events (e.g. 50-year) as well. The magnitude of flood peak discharge at 2-, 10- and 50-year interval increased by more than 23% comparing prior to and post 1960 in four selected watersheds (Table 7). The percent of increases in flood discharge of different recurrent intervals depends on the specific watershed and also the relatively infrequent large events were as sensitive as the frequent, small events. This result does not agree well with what has been reported in the literature (e.g. Hirsch et al. 1990, Konrad 2003, White and Greer 2006). Given the flood peak magnitude (e.g. bankfull discharge) the recurrence interval decreased after urbanization. High magnitude floods became even more frequently than relatively smaller magnitude events.

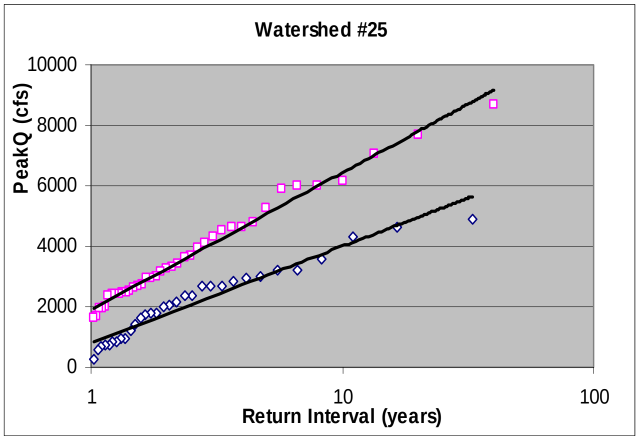

Figure 5 Flood frequencies during two time intervals in watershed # 25. The lines represent values predicted by the linear regression equations of the respective data. All regressions are statistically significant ($p<0.001$). Frequency curves in red indicate the time period from 1961 to 2000 and the curves in dark blue indicate the time period from 1921 to 1960.

Table 7 Increase in peak flood discharge attributed to urban development in four watersheds. The percent impervious surface of the watershed is listed in the parenthesis under the watershed id #.

Flood frequency	Chance that peak flood discharge will be exceeded in any year (%)	Increase in flood peak discharge (%)				
		# 25 (66.7%)	# 27 (61.6%)	# 28 (60.6%)	# 34 (15.3%)	Mean
2-year	50	46	23	35	54	39
10-year	10	38	31	35	61	41
50-year	2	35	34	35	62	41

4 Discussion and Conclusions

This research shows that GIS provides a platform for conducting changing flood behavior analyses by estimating hydrologic parameters and integrating different types of spatial data sources. The GIS-based spatio-temporal framework can be used to adjust and augment the traditional engineering approach based on historic peak flood characteristics to consider the unique response of watersheds to urbanization at the regional scale. This research also offers insights into how rapid urbanization and the accompanying flood management interventions have altered the vulnerability of the region to the flood hazard. From the time series data, all of the watersheds that were defined as urbanized have experienced increasing flood peaks. The same is true for a rapid urbanizing watershed located in the city of Simi Valley. The time series data also showed, surprisingly, that the urbanized watersheds have witnessed increasing baseflows as well and the character of these streams have changed from ephemeral to perennial at times in the past four or five decades. The results of this research also showed that urbanization has resulted in a reduction in storm duration, the number of days of storm flows after peak discharge, and baseflow recharge.

However, it was much more complex to analyze the flood behavior using measures at the watershed scale. Three measures adopted in the analysis did not show statistically significant correlations with percent impervious surface except some occasional cases based on the existing storm event data. Urban watersheds and some rocky mountainous natural watersheds tend to have higher values of the runoff coefficients and flashier responses to storm events than the others. Runoff coefficients within urban watersheds showed an increasing pattern over time only after the 1950s, but this trend was not statistically significant. The relationship between runoff generated and rainfall received needs to be examined at a finer temporal scale with enough sample storms to control for the effects of antecedent soil moisture and magnitude of rainfall events on rainfall-runoff processes. The impacts of urban development on flood events with different intervals in this region did not agree with what has been reported in the literature.

To conclude, our primary goal is to measure how the flood hazard has changed and whether or not the present-day hazard varies substantially across the Los Angeles Metropolitan Region. The work is exceedingly difficult given the large number and variety of flood interventions that operate at different scales and the spatio-temporal variability and complexity of the hydrologic regime itself. But our current results do show how urbanization and water imports have modified the hydrologic regime in selected parts of the study area. Ongoing work will endeavor to clarify how the flood hazard has changed notwithstanding the large number and variety of interventions or whether or not some parts of the metropolitan area have a higher probability of flood events than others.

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