Nat Hazards
DOI 10.1007/s11069-008-9241-7

ORIGINAL PAPER

Watershed urbanization and changing flood behavior across the Los Angeles metropolitan region

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Received: 18 June 2007 / Accepted: 18 April 2008

Abstract This article examines the effects of watershed urbanization on stream flood behavior in the Los Angeles metropolitan region. Stream gauge data, spatially distributed rainfall data, land use/land cover, and census population data were used to quantify change in flood behavior and urbanization in multiple watersheds. Increase in flood discharge started at the very early stage of the urbanization when the population density was relatively low but the rate of increase of flood discharge varied across watersheds depending on the distribution of the imperviousness surface and flood mitigation practices. This spatial variability in rainfall–runoff indices and the increasing flood risk across the metropolitan region has posed a challenge to the conventional flood emergency management, which usually responds to flood damages rather than being concerned with the broader issues of land use, land cover, and planning. This study pointed out that alternative land use planning and flood management practices could be mitigating the urban flood implemented hazard.

Keywords Urbanization · Flood behavior · Spatial and temporal variation · Geographic Information System

1 Introduction

It is widely recognized that urbanization can have serious implications for the long-term sustainability and health of human dominated stream systems causing problems, such as urban flooding, stream bank erosion, habitat degradation, and downstream pollutant loading when watershed development exceeds a certain impervious surface threshold (Pickett et al. 2001; Paul and Meyer 2001; White and Greer 2006; Randolph 2004; Konard and Booth 2005; Dougherty et al. 2006). Typically, urbanization refers to urban

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development and is defined as increasing land surface imperviousness which, in turn, leads to decreases in infiltration and increases in surface runoff. Stream flood hydrology changes along with the rainfall–runoff relationship in response to the expansion of the impervious surface in the watershed. Impervious surfaces increase the flood magnitude; shorten the lag time from the center of the rainfall volume to the center of the runoff volume; and increase the temporal and spatial variation in streamflow conditions (Espey et al. 1965; Seaburn 1969; Hirsch et al. 1990; Arnold and Gibbons 1996; Beighley and Moglen 2002; Konrad and Booth 2005; Randolph 2004; Dougherty et al. 2006).

The phenomena of increasing flood hazard in metropolitan areas and the associated physical processes have been widely addressed in various physical settings by environmental agencies such as the USGS (e.g., Anderson 1968; Laenen 1983; Couch and Hamilton 2002; Konrad 2003) and individual researchers (e.g. Espey et al. 1965; Dunne and Leopold 1978; Klein 1979; Bailey et al. 1989; Booth 1990; Konrad and Booth 2005). While most of these studies have focused on investigating temporal variations of streamflow conditions (Smith et al. 2002, 2005; Zhang and Smith 2003) in specific watersheds, a few studies have examined the spatial variation of changing flood hydrology in response to urbanization across watersheds. In addition, many of the empirical studies reported in the literature were conducted in temperate areas, where changes in stream hydrology and flood processes in response to urbanization and water resource redistribution are different than in arid or semi-arid areas.

This article examines the changing flood behavior in response to urbanization in multiple watersheds within semi-arid southern California over time spans ranging from decades to centuries. Geographical Information System (GIS)-based spatial analyses are used to augment the traditional methods—hydrographs, frequency-magnitude, and temporal statistical analysis. The article serves four goals: (1) presents a GIS-based method for quantifying spatially distributed rainfall and surface imperviousness data; (2) tests for trends in the average rainfall, annual storm total rainfall, and instantaneous annual peak discharge; (3) shows the response of flood frequency–magnitude and flood rainfall–runoff processes to urbanization over time; and (4) compares spatial variations of such responses in watersheds across the Los Angeles metropolitan region.

2 Methods

2.1 Study area

The extent of our study area was predefined by five 8-digit Hydrologic Unit Code (HUC) watersheds within the Los Angeles metropolitan region. The Calleguas Creek, Los Angeles River, San Gabriel River, Santa Clara River and Santa Monica Bay watersheds are shown in Fig. 1 along with the watersheds and streamflow and rainfall gauges selected for this study.

Until the 1880s, the Los Angeles area was small enough to escape the catastrophic consequences that follow from building a city on a floodplain. This gradually changed as the urban area expanded and the disaster brought by floods in 1914 served notice of the magnitude and extent of this hazard. The 1914 flood was exceptionally severe and partially attributed to the land use/land cover changes caused by railroads, pavement, and plows on the flood plains where willows and grasses used to grow (Orsi 2004). Flood-control systems were designed by engineers to accommodate floods and protect present and predicted future urban growth throughout the twentieth century. Indeed, no approaches were

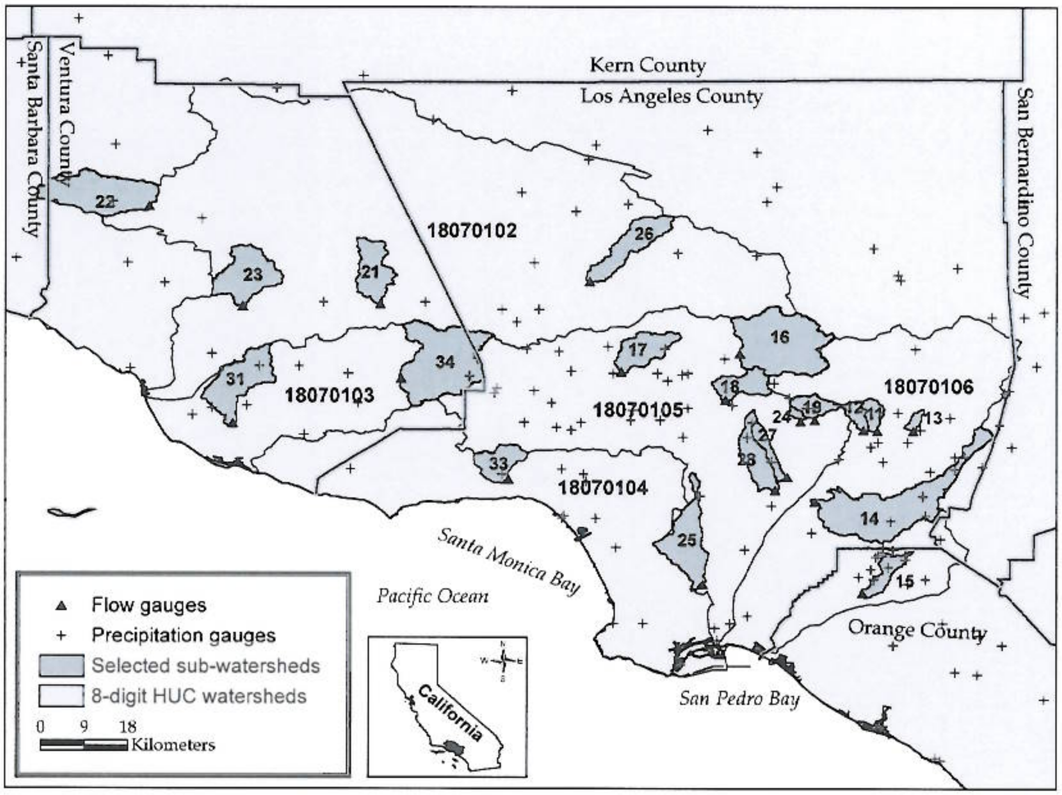

Fig. 1 Five 8-digit HUC watersheds plus NCDC precipitation gauge locations, subwatersheds, and stream flow gauges selected for current study

seriously considered to manage the floods and accommodate metropolitan growth other than engineered flood-control systems until the 1990s. During the past two decades, however, increasing numbers professionals, decision makers and citizens have taken the view that the increasing metropolis flood hazard cannot be reduced or mitigated solely by engineering works, especially in cases when people want to retain or restore hydrologic function and some of the riparian and other ecosystem functions that usually accompany river channels. New approaches (other than engineering approaches) are required to understand the flood processes that drive the increasing metropolis flood hazard and how this increasing flood risk currently varies across the region.

2.2 Watershed selection

The study area contains a total of 201 stream flow 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). Watersheds were selected for the study 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 were more than 20 years of flow gauge records; and (4) surface hydrologic systems are not affected by hydraulic constraints (dams, reservoirs, etc.) that were officially stated in the gauge report. Table 1 summarizes the 20 flow gauges selected for this study and Table 2 summarizes selected characteristics of the streams and watersheds above these gauges. The mean elevation of these watersheds ranges from 1,493 m above mean sea level in the Los Angeles National Forest to 47 m on the flat coastal plain. The land use/land cover in these watersheds varies

Table 1 Stream flow gauges used in study

Watershed #	Gauge no.	Agency	Flow records		Length of record (years)
			Start date	End date	
11	11084000	USGS	3/10/1918	2/11/1962	46
12	11084500	USGS	3/10/1918	1/17/1979	64
13	11086500	USGS	10/1/1938	12/21/1970	34
14	11087195	USGS	3/10/1929	1/22/1964	36
15	11090200	USGS	1/12/1960	3/1/1981	23
16	11094500	USGS	2/5/1931	2/6/1950	21
17	11096500	USGS	10/1/1928	2/11/1973	46
18	11098000	USGS	2/20/1914	2/12/2003	95
19	11100000	USGS	12/24/1916	2/28/1970	55
21	11110500	USGS	12/31/1933	3/1/1983	51
22	11111500	USGS	3/10/1949	2/12/2003	54
23	11113500	USGS	1/19/1933	3/15/2003	77
24	11100500	USGS	12/24/1916	2/11/1962	49
25	F37B-R	LADPW	1/22/1928	To present	74
26	F328-R	LADPW	10/26/1956	To present	48
27	F82C-R	LADPW	10/1/1949	To present	56
28	F81D-R	LADPW	1/14/1930	To present	73
31*	F776	VCWPD	10/1/1979	9/1/2003	24
33	F54C-R	LADPW	1/1/1930	To present	68
34	11105850	USGS	10/1/1933	10/1/1982	49

* No peak flood flows were recorded during the measurement period

from relatively pristine shrublands at high elevation to heavily developed urban watersheds. Sustained population growth has made this region one of the most rapidly growing areas in the country, and the resultant urban and suburban expansion has resulted in substantial changes in land use/land cover.

2.3 Rainfall surface interpolation

Spatially distributed rainfall surfaces were generated for each water year and storm event using the ANUSPLIN program and rain gauge observation data collected by National Climatic Data Center (NCDC). The 200 cooperative rainfall stations selected for surface simulation included stations within the study area and in a 0.50 degree buffer area to minimize edge effects. Limited by the processing capability of the program, storm events were sampled every five years rather than each year in the annual flood time series of each watershed. The sampling strategy not only reduced the number of simulations from many thousands to 87, but also ensured the representation of decadal variation in the storm rainfall amount, which corresponded to the temporal resolution at which urbanization was analyzed.

A four-step procedure was employed to estimate the accumulated rainfall 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 30 m DEM downloaded from http://casil-mirror1.ceres.ca.gov/casil/gis.ca.gov/dem/. Second, the total

Table 2 Stream and watershed characteristics

Watershed #	Drainage area (km^2)	Mean elevation (m)	Standard deviation elevation (m)	Mean stream gradient (%)	Strahler stream order	Impervious surface (%)
11	17.1	762.7	217.7	19.0	4	0
12	16.6	869.2	259.7	20.6	3	0
13	7.0	757.3	155.6	17.5	2	0
14	229.7	233.1	141.6	5.1	5	45.0
15	31.3	104.3	50.8	2.7	4	55.7
16	174.8	1401.9	240.6	13.8	5	4.5
17	54.7	740.7	252.4	12.3	5	2.4
18	41.4	1098.6	307.3	18.8	4	0
19	25.1	1085.6	247.9	20.4	4	0
21	62.2	759.8	280.7	14.7	3	0.1
22	129.5	1493.2	201.3	11.8	4	0
23	98.4	956.2	437.3	14.9	4	0.3
24	4.7	1062.6	176.3	24.1	3	0
25	58.5	47.3	25.1	0.3	1	66.7
26	69.7	845.3	225.8	7.2	4	1.0
27	28.2	208.3	78.3	1.5	1	61.6
28	39.4	198.2	89.8	1.7	2	60.6
31	119.1	109.9	104.8	4.6	4	6.6
33	46.6	419.0	94.5	8.2	4	3.0
34	182.9	473.5	163.5	6.3	5	15.3

Bolded watershed #s indicate urban watersheds

rainfall depth and Antecedent Rainfall Index (ARI) were summed for each sampled storm event at all NCDC rain gauges. The total rainfall refers to the amount of rainfall collected from the beginning to the end of an event whereas the ARI sums the rainfall from the date and time a rainfall event starts until the date and time at which the instantaneous annual peak discharge is observed. Third, spatially distributed rainfall surfaces were interpolated for the sampled storm events using ANUSPLIN version 4.3 (Hutchinson 2004) and 450 by 450 m grid cells. ANUSPLIN fits an arbitrary number of (partial) thin plate smoothing spline functions incorporating one or more independent variables with the degree of data smoothing determined by minimizing the generalized cross validation (GCV) of the fitted surface (Hutchinson 1995). We found that the module SPLINB worked best with our datasets (i.e., 200 rainfall stations and resampled 450 m DEM). The SPLINB option allows missing data in the rainfall time series and suits datasets up to about 10,000 data points. A comprehensive introduction to the technique of thin plate smoothing splines, algorithms, and associated statistical analysis is given in Wahba (1990), Hutchinson (1993, 1995), and Hutchinson and Gessler (1994). The total rainfall and ARI volume received in each watershed during storm events was computed as the product of rainfall depth and watershed area in the final step.

2.4 Watershed urbanization characterization

The percent impervious surface for 2001 was used to designate the level of urbanization in each watershed based on land use/land cover data from the Southern California Association of Governments (SCAG). The SCAG land use map records development type and representative proportion impervious values have been assigned to each development type (class) by LADPW using field measurements, aerial photographs in sample areas and published reports (LADPW 2006). For undeveloped rural areas, 1% of the area is assumed impervious. If more than one type of development was present within a watershed, a composite value was determined using an area-weighted average.

The corresponding 2001 population density in each watershed was estimated using the LandScan™ Global Population Database (Bhaduri et al. 2002; see http://www.ornl.gov/landscan/ for additional details) in order to examine the relationship between percent impervious surface and population density. The grid based LandScan population density was generated by distributing best available census counts to 30″ by 30″ grid cells through a "smart" interpolation based on the relative likelihood of population occurrence in grid cells due to road proximity, slope, land cover, and nighttime lights (Bright 2002). The population density in each watershed was then calculated by summing the population counts of each grid cell and dividing these totals by the watershed area.

The strong correlation between imperviousness index and population density was suggested by this study and also other literature (Stankowski 1972; Graham et al. 1974; Hicks and Woods 2000). As a result, the historic population density data were used to represent progressive urbanization by decade during the period 1940–2000. Historical census tract population data were acquired from the Los Angeles County Union census tract population data series generated by Ethington et al. (2000). Decadal population data within each watershed were then estimated by remapping the census tract population data to the new watershed boundary. For the census tracts that were partially located within the watershed boundary, the population was split in proportion to their census tract areas. The watershed population density was derived by dividing the sum of all whole and partial census tract population falling in the watersheds by the watershed area. Watersheds that are located outside Los Angeles County or situated in Los Angeles National Forest were excluded from the historical analysis, because, the census data from earlier censuses were not mapped to 2000 census boundaries by Ethington et al. (2000).

2.5 Statistical tests

The Kendall non-parametric test was used to identify any significant trend in the flood measures including annual rainfall, annual storm rainfall amount, and the instantaneous peak discharge of the water year (PeakQ). The Kendall non-parametric statistical 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 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 (i.e., that there is no significant trend in the tested time series).

2.6 Quantification of changing flood behavior and associated rainfall–runoff processes

The flood frequency, magnitude, and duration of flood events were characterized for various watersheds to examine the changing flood behavior over time and across watersheds. Flood frequency and magnitude curves were plotted for two time periods, prior and post urban development, for each of the 20 selected watersheds. In order to estimate the frequency of peak flood flows, the recurrence intervals of the peak discharges (T) during the period were determined using the Weibull plotting position formula (Gordon et al. 1992):

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

where n is the number of ranked discharge values and m is the rank of each discharge value. The breakdown of the 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 at a cutoff year in the 1960s. Flood discharges were plotted against corresponding recurrence intervals for each of the two periods on a logarithmically transformed scale.

Flood duration and number of days of storm flows after peak discharge were estimated for the "simple" annual storm events sampled at five year intervals from 1921 to 2000 for three urban and three non-urban (i.e., forested) watersheds. Flood durations were estimated by counting the time period between the starting and ending point of each individual storm event. The "simple" annual storm event hydrographs were characterized by a single discharge peak produced by a short period of rainfall. The effects of drainage area size on flood duration and post flood duration were counted by normalizing the observed post flood duration using the theoretical duration (N) calculated as follows:

$$N = A^{0.2} \qquad (2)$$

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

Three ratios—the rainfall–runoff ratio, storm ratio, and PeakQ to ARI ratio—were used to quantify the changes in rainfall–runoff processes in response to watershed urbanization during the largest storm of the water year. The rainfall–runoff ratio, the ratio of observed runoff to total rainfall, measures rainfall characteristics, antecedent soil moisture and the variation of land surface processes. The storm ratio refers to the ratio of direct storm runoff to total runoff, which measures the influence of urbanization on watershed water balance. The ratio of PeakQ to ARI quantifies the changing magnitude of flood peaks given the same short-term soil moisture content. The direct storm runoff component for each sampled storm event was separated from the observed total runoff by running the WHAT tool that uses the digital filter method to separate the baseflow (Web-based Hydrograph Analysis Tool, see http://pasture.ecn.purdue.edu/~what/ for additional details) (Lyne and Hollick 1979; Nathan and McMahon 1990; Arnold and Allen 1999).

3 Results

3.1 Spatial and temporal patterns in average annual rainfall and annual storms

The spatial pattern of annual average rainfall is shown in Fig. 2. From coast to mountain, average rainfall varies from <300 mm along the coast to >700 mm in the mountains. Excluding the high mountain watersheds, average rainfall across the watersheds is highly variable and terrain-dependent. Watersheds in the foothills such as #11, #12, #13, #16, #18, #19, and #24 receive annual rainfall greater than 500 mm on average. Watersheds located near the coast (#15) and in mountain valleys (#21, #23, and #26) receive less than 400 mm average annual rainfall.

Major storms approach the region from the west or northwest primarily in the form of winter orographic rainfall associated with extratropical cyclones of North Pacific origin.

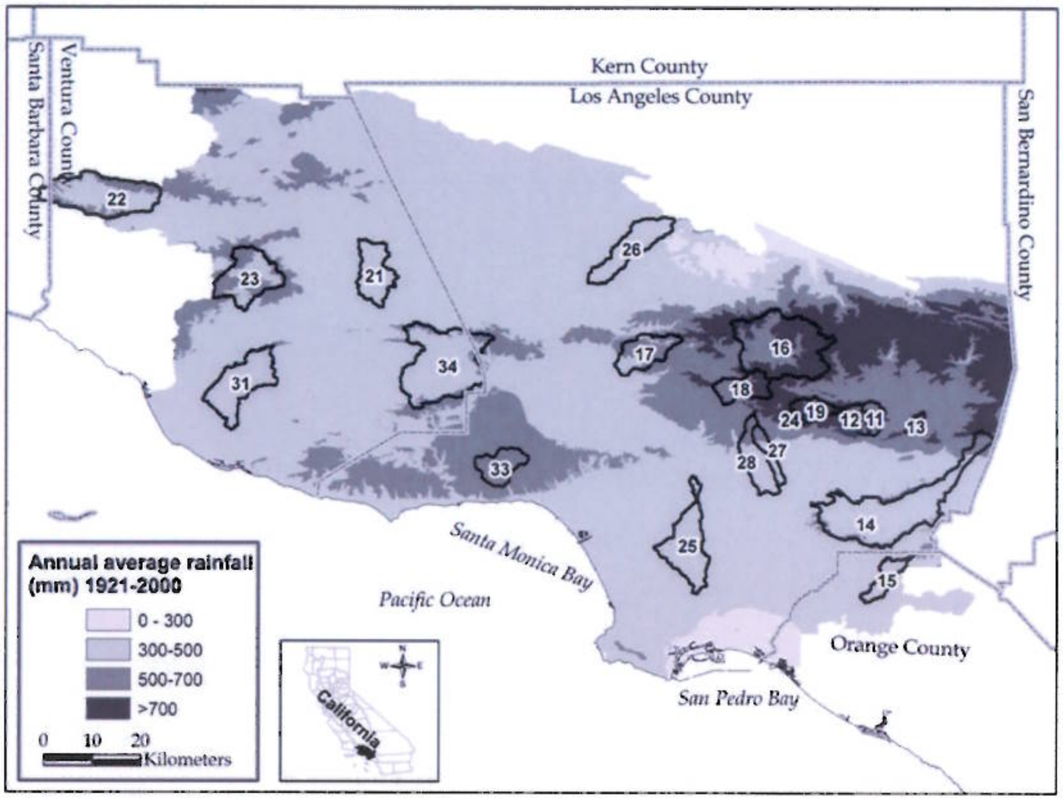

Fig. 2 Annual average rainfall in 1921–2000 using ANUSPLIN

Air masses and frontal systems associated with major storms produce rainfall simultaneously throughout the study area. The mountain ranges lie directly across the path of the inflow of warm, moist air, and orographic effects greatly intensify precipitation. Heavy precipitation, steep hillslopes, and relatively short streams emptying onto densely settled lowlands sometimes cause severe flood damage (State of California Resources Agency 2001). During the 17 February 1990 winter storm, the average rainfall was 61.9 mm. However, the foothill watersheds #18 and #19 received >100 mm of rainfall and the coastal watershed #31 received approximately 30 mm in this storm. This particular storm produced annual flood peaks in watersheds #18, #23, #25, and #28 but not watersheds #22 and #27. The annual peak flood was not recorded for the remainder of the watersheds due to missing flood peak data in the time series.

Over a longer term, the 80-year change in annual average rainfall is practically nil given that the Kendall nonparametric tests showed stationary signals in 20 watersheds (Table 3). No significant trend was found in annual storm total rainfall time series over the 80-year term period except in watershed #22 (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 be invoked to explain or account for whatever changes have occurred.

3.2 Response of annual flood PeakQ to watershed urbanization

The degree of urbanization, indicated by percent impervious surface, varies from 0 to 66.7% among the 20 selected watersheds. Fourteen of the 20 watersheds listed in Table 2 are relatively pristine as evidenced by impervious surface values of <10%. One watershed

Table 3 Level of significance (p value) for τ as calculated with Kendall nonparametric tests on annual rainfall, annual storm total rainfall, and PeakQ

Watershed #	Annual average rainfall	Annual storm total rainfall	PeakQ
11	0.397	0.792 (−)	0.495
12	0.450	0.910 (−)	0.497
13	0.496	0.753 (−)	0.635
14	0.771	0.927	0.663
15	0.122	0.310	0.000**
16	0.050	0.962	0.601
17	0.273	0.944	0.942
18	0.160	0.840 (−)	0.849
19	0.248	0.857 (−)	0.465
21	0.031 (−)	0.324	0.774
22	0.001 (−)	0.034**	0.088
23	0.034 (−)	0.176	0.950
24	0.415	0.944 (−)	0.649
25	0.054	0.196	0.000**
26	0.012 (−)	0.722	0.132
27	0.654	0.681 (−)	0.002**
28	0.759	0.919 (−)	0.000**
31	0.216	0.119	0.276
33	0.490	0.303	0.700
34	0.797	0.457	0.000**

** Correlation is significant at the .05 level (2-tailed) and (−) signs indicate decreasing trends

(#34) has experienced moderate development given the imperviousness value of 15.3%. The five remaining watersheds (#14, #15, #25, #27, and #28) are urbanized watersheds and dominated by residential, commercial, and transportation land uses, with impervious surfaces greater than 45%. A coefficient of determination R^2 of 0.95 ($n = 20$) was generated when the overall watershed percent imperviousness was regressed against population density, indicating that population density is a good surrogate measure for percent impervious surface when historical land use data are not available.

Kendall tests on PeakQ detected significant increases in four of the five urban watersheds and also in the moderately developed (i.e., urbanizing) watershed from 1921 to 2000 at the 0.05 significance level (p value <0.05, Table 3). No trend was detected in PeakQ time series in watershed #14 because of the unavailability of PeakQ data after the 1960s. Not surprisingly given the literature, increasing stream bank erosion and more frequent urban flooding have been observed in some of the urban stream channels (e.g., Alhambra Creek Watershed Planning Group 2001; CH2M Hill 2005; Los Angeles and San Gabriel Rivers Watershed Council 2005). The Average PeakQ data by decade are plotted in Fig. 3 against the corresponding population density for each urban watershed with the exception of watersheds #14 and #15 due to missing PeakQ data. Increasing PeakQ is associated with increasing watershed population density although the rate of increase varied from twofold in the urban watersheds to sevenfold in the urbanizing watershed. This result shows that the most dramatic changes occurred when the population density was relatively low (e.g. #25 and #28). The differences in hydrologic response among watersheds at similar levels of urbanization may be attributed to the distribution of the impervious surfaces in the watersheds, and the nonlinear nature of the relationship between urbanization and hydrologic response.

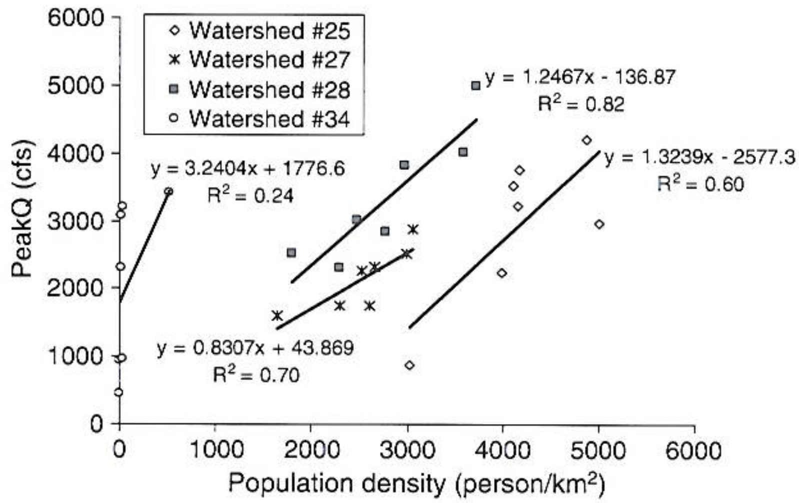

Fig. 3 The correlation between PeakQ and population density by decade (from the 1940s to 1990s) in four urban watersheds

Table 4 Average flood duration and number of days of storm flow after peaks based on individual events in six watersheds

	Watershed #	Flood duration (days)	Number of days after the peak flow		Observed value normalized by theoretical value
			Observed	Theoretical	
Urbanized watersheds	#25	2.9	1.6	1.9	0.88
	#27	3.2	1.4	1.6	0.88
	#28	3.6	1.8	1.7	1.04
	Mean	3.2	1.6	1.7	0.93
Non-urban watersheds	#18	4.3	2.7	1.7	1.53
	#23	4.3	2.3	2.1	1.13
	#33	3.9	2.1	1.8	1.20
	Mean	4.2	2.4	1.9	1.29

3.3 Response of flood duration, frequency and magnitude to urbanization

Flood durations and the number of days of storm flow after peak discharge are summarized for selected single peak storm events in Table 4. These data show that the duration of urban floods is one day less than that experienced in non-urban watersheds (Table 4). The average length of storm flow after the peak flow was 1.6 and 2.4 days in urban and non-urban watersheds, respectively. After the post peak flow flood durations were normalized by the theoretical post peak flow flood length, the mean duration of 0.93 computed for urban watersheds is substantially shorter than the 1.29 value calculated in non-urban watersheds.

The magnitude of flood peak discharge at 2-, 10- and 50-year intervals increased from the 1960s onwards in the four urban watersheds (#25, #27, #28, and #34). The flood frequency and magnitude relationship fitted a logarithmic function very well, such that the fitted curves appeared to be linear when peak discharges were plotted against the

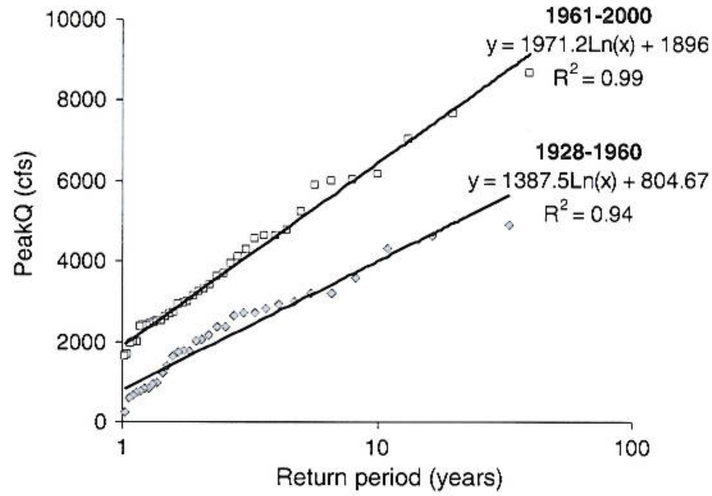

Fig. 4 Flood frequency-magnitude curves during two time periods in watershed #25. The fitted logarithmic regressions are statistically significant ($p < 0.001$)

Table 5 Increase in peak flood discharge prior to and post-1960 given flood frequencies of 2-, 10-, and 50-years in each selected watershed

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

recurrence interval on a transformed logarithmic scale (Fig. 4). The curve for the period 1961–2000 shifted towards higher peak values for both high-frequency low magnitude (e.g., 2-year) events and low-frequency high magnitude (e.g., 50-year) events. The increase in flood peak discharge prior to and post-1960 for different recurrence interval floods in these same four watersheds is shown in Table 5. The results show that the relative increase for the 50-year floods was greater than for 2-year floods in two of the four watersheds (#27, #34), less in another (#25) and similar in the fourth watershed (#28).

3.4 Spatial and temporal patterns in rainfall–runoff processes

The runoff coefficient was highly variable across watersheds over time. The average runoff coefficients of selected watersheds ranged from 0.04 to 0.73. No linear correlation was found between runoff coefficients and corresponding percent watershed impervious area (IA). Therefore, watersheds were regrouped into three categories representing urban, non-urban (i.e., mostly forested), and mountainous watersheds (i.e., steep bare rock cover) to examine the differences in watershed responses to storm events (Fig. 5). The low coefficients were frequently associated with non-urban watersheds while the high coefficients occurred in both urban and mountainous watersheds. Overall, the mean coefficient for the urban group of 0.38 is three times larger than the mean value of 0.11 for the non-urban group. The mean coefficient for the mountainous watersheds of 0.26 more closely resembles the coefficients reported in urban watersheds. These mountainous watersheds are covered by bare rock surfaces, steep slopes, and thin soils, which results in land surface characteristics similar to those of urban paved watersheds. These land surfaces produce surface runoff quickly and result in a large percentage of the total rainfall being coverted to flood waters.

Within particular watersheds, the runoff coefficients varied from 0 to 1 during individual storm events. Increasing runoff coefficients over time were identified for three urban watersheds using the Kendall tests at the 0.01 significance level. In these watersheds, the increase in average runoff coefficients by decade was positively correlated with population density (Fig. 6). Interestingly, watershed #25 with the highest population density experienced the smallest increases in runoff coefficients compared to watersheds #27 and #28 with their relatively lower but rapidly increasing population densities (confirming the earlier observation that the hydrologic response changes quickly in the initial stages of the development process).

On average, the majority (i.e., 70–90%) of the rainfall is contributed to the storm runoff component regardless of the watershed imperviousness index. The partition of the rainfall between storm runoff and base flow varies by a factor of two across various storm events. The urban watersheds overall recorded the largest mean storm ratio of 0.89 compared to values of 0.81 and 0.80 in forested and mountainous watersheds, respectively (Fig. 5). Given the same amount of runoff, the urban watersheds will generate larger discharges while the non-urban forested watersheds retain more surface runoff and sustain higher base flows following the peak flood discharge.

Surprisingly, the average storm to total runoff ratios by decade decrease as population density increases over time (Fig. 6). This may be due to the baseflow separation method used in the WHAT tool, which may have consistently overestimated the baseflow in

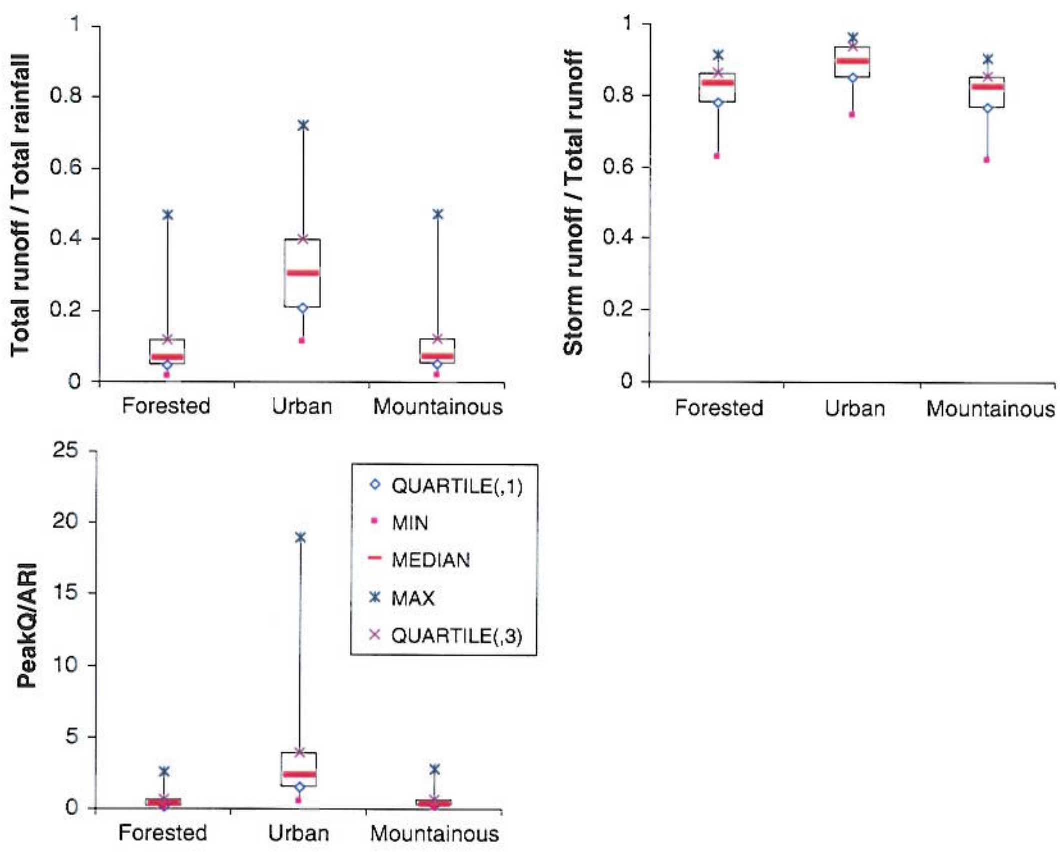

Fig. 5 Three ratios that measure changing rainfall–runoff relationship

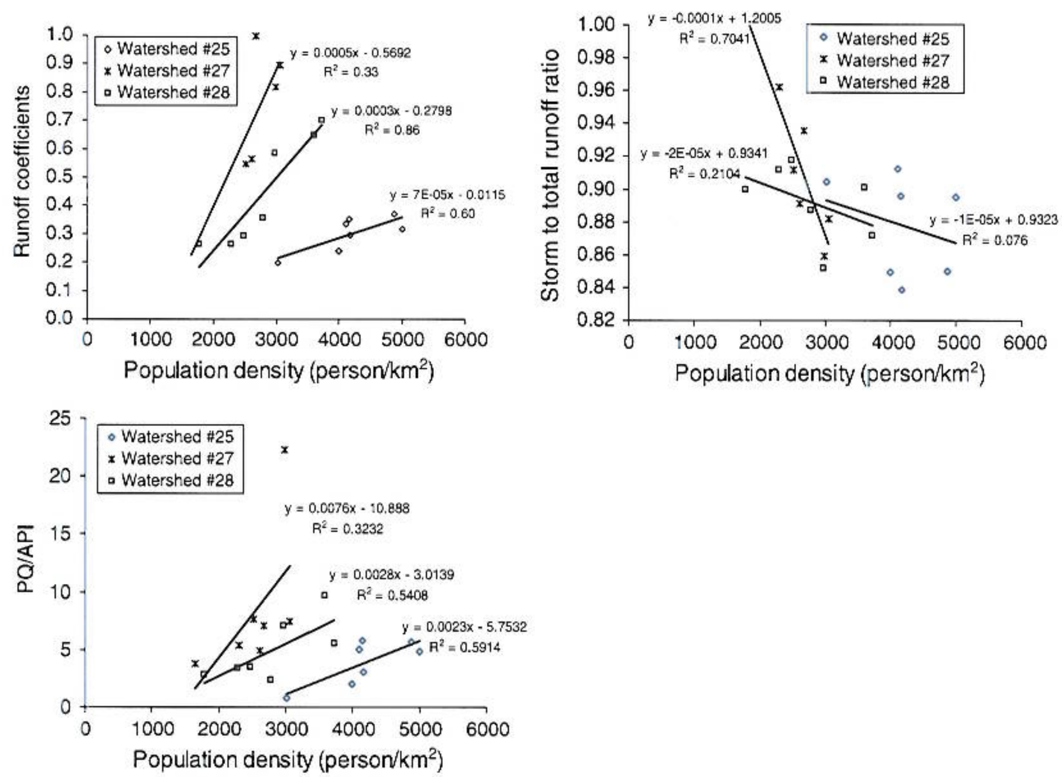

Fig. 6 The correlation between runoff coefficients, PQ/API, storm to total runoff ratio, and population density in three urban watersheds by decade

urban watersheds. The digital filter method utilized by the WHAT tool assumes that the direct runoff can be associated with high frequency waves and the base flow can be associated with low frequency waves. This method has no physical meaning and the results rely on user input. The impervious surface in these watersheds and modified stream channels (many channel reaches have been straightened and converted to concrete box channels for flood control in the Los Angeles Metropolitan Area) might diminish the rising baseflow after storm events that normally occur in natural systems. Consequently, the negative correlation between the average ratio of direct runoff to total runoff and population density shown in Fig. 6 is a reflection of the hypothetical rising baseflow given the increasing total runoff during the storm rather than the actual processes operating in the urban watersheds.

The overall response of peak discharge to storm rainfall in urban watersheds was much larger than that recorded for the other two watershed types as evidenced by the mean PeakQ/ARI values (Fig. 5). The average ratio of 3.97 in the urban watersheds was ten times larger than the mean ratio of 0.40 in the non-urban watersheds for example. Steep, bare rock covered mountainous watersheds generate higher storm peaks than the non-urban forested watersheds, but their peaks are much smaller than the peaks generated in the urban watersheds given the same storm size. Figure 7 shows a quicker, steeper, and higher response of PeakQ to the storm rainfall in two urban watersheds (#25 and #28) compared to the forested (#18) and mountainous watersheds (#23). It also shows that the variation in PeakQ/API across watersheds is much greater than the variation in runoff coefficients since the runoff coefficients are to some degree normalized by storm size. Such variations in runoff coefficients and PeakQ/API tend to be smaller across urban watersheds than

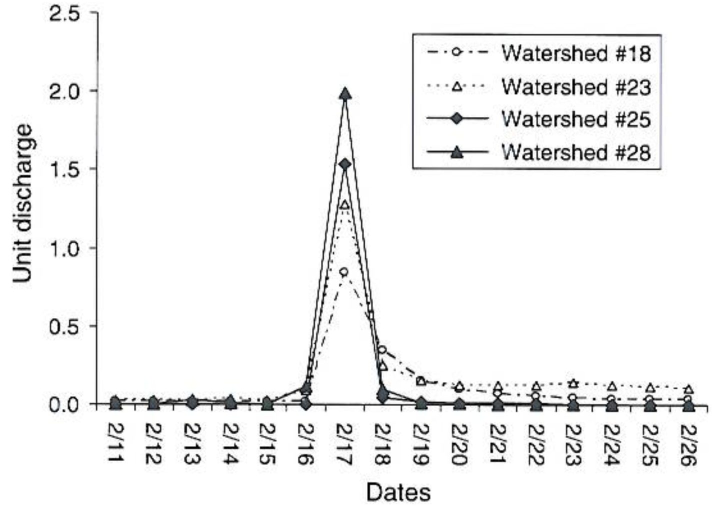

Fig. 7 Flood hydrographs for the February 17 1990 storm in two urban (#25 and #28), one forested (#18), and one mountainous watershed (#23). The *Y* axis is unit discharge, which is observed daily flow in cfs normalized by ARI in inches

non-urban watersheds. It suggests that surface runoff generated from impervious surfaces is less sensitive to storm size than in the case for other surfaces.

Over time, Fig. 6 shows how PQ/API increased with population density in three urban watersheds at three different rates. The watersheds #27 and #28 are similar in terms of population growth, landform, land use/land cover, and hydrologic characteristics, but the slope of the regression line for watershed #28 is much gentler than that for watershed #27. This result gives some insights as to how that impacts of urbanization on flood hydrology might be potentially reduced through appropriate watershed management.

4 Discussion and conclusions

Results presented in this study have shown the potential increase in flood risk for various watersheds as a result of growing population in the Los Angeles metropolitan region. The 20-gauged watersheds situated in various parts of the region provide an excellent opportunity to observe the spatial variations in long-term impact of changing impervious surface on watershed flood behavior. Generally, over the entire region, a large fraction of the rainfall falling on the land surface is carried away by storm runoff. Urban watersheds, on average, lose 90% of the storm rainfall to runoff, whereas the non-urban forested watersheds retain 25% of the rainfall. Statistically significant increases in peak discharge and reductions in flood duration were detected in the urban watersheds.

The change in flood discharge starts with the initial development (i.e., urbanization) phase when the population density is relatively low. The rate of flood discharge increase with population density depends on the distribution of the impervious surface and character of the storm water conveyance system. Within particular urban watersheds, the change in flood behavior can be predicted by establishing the empirical correlation between rainfall–runoff indices and progressive urbanization using historical census population data and stream flow and rainfall measurement data (as shown in Fig. 6).

In our study, both the frequent and rare floods were sensitive to urbanization and resulted in increased magnitudes for floods with various recurrence intervals. This finding does not agree well with the literature which reports that flood magnitudes of rare events are less sensitive to increases in watershed impervious surface cover than those with shorter recurrence intervals (Hollis 1975; Booth 1988; Hirsch et al. 1990; Konrad 2003). The variations in runoff coefficients and PeakQ/API are smaller across urban watersheds compared to non-urban watersheds, suggesting that surface runoff generation from impervious surfaces is less sensitive to storm size than that from other surface types.

Future work is needed to explain the spatial variation in rainfall–runoff processes in response to watershed population growth and impervious surface cover. Figure 6 showed how urban watersheds with the same population density might result in various runoff coefficients, PQ/API indices, and storm to total runoff ratios. This variability is presumably caused by variations in the distribution of impervious elements in the watersheds. Population density is a good overall indicator of urbanization; however, it does not characterize percentage of the impervious surface, drainage distance to outlet, and the hydrologic connectivity of impervious elements to the watershed outlet. The response of flood behavior to urban watersheds of the same population density could vary from watershed to watershed due to variations in the character of the impervious surface and its connectivity with the storm water conveyance system and stream network. More work is needed to develop cost-effective methods for: (1) characterizing the land surface characteristics at finer resolution; (2) depicting the storm water conveyance systems over large areas; and (3) linking (1) and (2) to the stream network. The development of several modeling systems inside GIS frameworks and the increasing availability of high resolution remotely sensed datasets point to new opportunities so long as we can find ways to compile input data in relatively quick and affordable ways.

These types of advances are needed now. Given the same population growth trajectory, the impacts of population growth on flood behavior vary across different watersheds. Some effective flood risk mitigation practices can be learned by comparing the different responses of flood behavior to watershed urbanization. New policies and practices are needed to keep the direct runoff under control and hence mitigate flood hazard during high intensity storms as various groups look to conserve and/or restore hydrologic functions in urban areas. Conventionally, flood management has responded to flood damage while ignoring the broader issues of land cover/land use, planning, and their management. It is time to change this culture, so that alternative and site specific practices to simultaneously promote healthy streams and provide an acceptable level of flood control can be explored, proposed, and implemented.

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