The Effects of Watershed Urbanization on the Stream Hydrology and Riparian Vegetation of Los Penasquitos Creek, California

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The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Peñasquitos Creek, California

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Abstract

We investigated the effects of watershed urbanization on streamflow characteristics and the riparian vegetation community of Los Peñasquitos Creek, in coastal Southern California. We used stream gage records to assess streamflow changes and historic aerial photographs to measure land use and riparian vegetation changes in the watershed. During the period 1966–2000, urban land uses increased from 9% to 37% of the watershed. Over the same time period, median and minimum daily discharges, dry-season runoff, and flood magnitudes in Los Peñasquitos Creek increased significantly. Altered channel geomorphology and a doubling of the area of riparian vegetation accompanied changes in streamflow characteristics. The increased area of impervious surfaces and imported municipal water supplies associated with urbanization in the watershed have driven changes in the historic riparian vegetation community by altering streamflow characteristics and channel geomorphology. Thus, watershed urbanization in coastal Southern California can significantly modify the character and integrity of stream and riparian ecosystems, which has significant implications for their conservation in the light of rapid pace of urbanization in the region.

Keywords: Urbanization; Impervious surface; Stream; Watershed; Riparian vegetation; Hydrology; Runoff; California

1. Introduction

There has been considerable research concerning the consequences of altering riverine hydrology (see review in Poff et al., 1997), and there is increased interest in urbanization as a source of hydrological alterations (Paul and Meyer, 2001). Given the close coupling of stream hydrologic characteristics and riparian plant species ecology (Stromberg, 1993, 1998; Scott et al., 1996; Poff et al., 1997; Mahoney and Rood, 1998; Shafroth et al., 1998), we examined the effects of watershed urbanization on riparian vegetation communities via alterations in the hydrologic regime of a coastal Southern California stream system.

Urbanization within a watershed increases the area of impervious surfaces (Paul and Meyer, 2001), which

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decreases infiltration of precipitation and increases runoff (Dunne and Leopold, 1978; Gordon et al., 1992; Leopold, 1994). Runoff increases in proportion to the cover of impervious surface in a watershed (Arnold and Gibbons, 1996), and the increased storm runoff increases peak discharges and flood magnitudes (Dunne and Leopold, 1978). Increases in flood magnitudes are greater for floods of shorter recurrence intervals than those with long recurrence intervals (Hirsch et al., 1990). Reduced infiltration of precipitation to groundwater aquifers may reduce groundwater recharge and stream base flow (Paul and Meyer, 2001). However, importing water into an urban watershed for landscape irrigation may increase stream base flow (Hirsch et al., 1990; Paul and Meyer, 2001; Greer and Stow, 2003).

Recent research has demonstrated the intimate relationship of riverine hydrology and fluvial processes and riparian plant species recruitment and survival (Scott et al., 1996, 1997; Shafroth et al., 1998; Stromberg, 1993, 1998). Riparian plant species establish in locations where there are suitable conditions for seed germination and sufficient water for seedling survival, and where the species can tolerate physical disturbance from floods (Stromberg and Patten, 1992; Hupp and Osterkamp, 1996; Scott et al., 1996; Mahoney and Rood, 1998). Thus, the structure of riparian vegetation communities is often a mosaic of species and age class composition produced by spatial and temporal variations in stream discharge patterns (Stromberg et al., 1997; Auble and Scott, 1998; Shafroth et al., 1998).

Poff et al. (1997) discuss the concept of “natural flow regime” of riverine systems, which they characterized as the magnitude, frequency, duration, timing, and rate of change of discharge. The natural flow regime determines the species composition and spatial patterns of riverine biological communities; thus, modifications to the natural flow regime, as a result of river regulation and impoundments, have well-documented effects on riparian vegetation communities (Harms et al., 1980; Conner et al., 1981; Hunter et al., 1987; Stromberg and Patten, 1992; Stromberg, 1993; Stevens et al., 1995; Poff et al., 1997). However, there has been little research published on the influence of urbanization-induced hydrologic changes on riparian vegetation communities (Poff et al., 1997; Paul and Meyer, 2001). Because urbanization of watersheds can modify the natural flow regime of stream systems, it is expected that riparian vegetation communities ultimately would be affected by urbanization as well.

We evaluated the potential effects of watershed urbanization on a coastal stream and associated riparian vegetation community. Our research objectives were to (1) quantify the urbanization of a coastal Southern California watershed; (2) evaluate potential urbanization-induced changes in streamflow characteristics in this watershed; (3) quantify temporal changes in the distribution of the riparian vegetation community in this watershed; (4) evaluate whether these distribution patterns are consistent with observed hydrologic changes.

Streams and associated riparian vegetation are important natural resources in the urbanizing areas of Southern California and are a focus of conservation and land management activities. Many local governments in Southern California are conducting land use planning efforts that attempt to balance urban development needs with natural resources protection. These planning efforts often target streams and riparian communities for preservation, but generally do not consider the indirect effects of watershed urbanization on hydrologic processes. As these indirect effects can change the character and quality of stream and riparian habitats, land use plans must consider how watershed-scale processes, such as hydrologic regimes, control the characteristics of riverine resources and how they are affected by land use changes. For conservation of riverine resources to be successful, we must develop a better understanding of the dynamics of these habitats, in the face of urbanization, to inform land planning and management.

2. Methods

2.1. Area description

Our study was conducted in the Los Peñasquitos Creek watershed, San Diego County, California (Fig. 1A). The Los Peñasquitos Creek watershed encompasses approximately 15,759 ha, spanning the area from Iron Mountain (elevation 822 m above mean sea level) on the east to Los Peñasquitos Lagoon at the coast. Coastal sage scrub and chaparral characterize

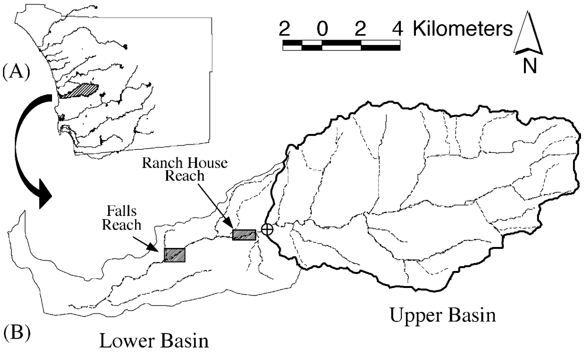

Fig. 1. (A) Location of the Los Peñasquitos Creek watershed within San Diego County, California. (B) Detailed view of the watershed, showing the boundary between the upper and lower basins and the location of the stream gage (cross symbol). The two rectangular cross-hatched areas are the Ranch House and Falls reaches. Changes in urbanization were measured in the upper basin, and riparian vegetation changes were measured in the lower basin.

the vegetation communities on the upland slopes of the watershed, and oaks intermingle with sycamores and willows along the margins of streams and in floodplains. The watershed can be divided further into upper and lower basins, 10,997 ha and 4762 ha in size, respectively (Fig. 1B). In the lower watershed basin, a prominent sedimentary rock outcropping in the creek forms a waterfall (“Falls”; Fig. 1B).

Runoff in the Los Peñasquitos Creek watershed is closely associated with rainfall patterns. Rainfall in coastal San Diego County is derived largely from fall and winter storm systems generated in the Gulf of Alaska, which produces an annual average of approximately 25 cm of rainfall (recorded at San Diego Lindbergh Field airport), with the majority falling during the period from October to March each year. The region also receives periodic summer (June–September) rainfall events. Annual rainfall totals and timing are highly variable, with totals at Lindbergh Field ranging from about 9 cm to over 66 cm during the period 1851–2000.

The U.S. Geological Survey (USGS) has operated a streamflow gaging station on Los Peñasquitos Creek (station number 11023340), at the bottom of the upper basin of the watershed, continuously since October 1, 1964 (Fig. 1B). All water flowing from the upper watershed basin to the lower basin is measured by the stream gage. Since 1964, there has been significant urbanization in the Los Peñasquitos Creek watershed. In addition, the Pomerado Waste Water Treatment Plant, located approximately 2500 m upstream from the USGS gaging station, discharged treated wastewater to the creek from 1962 to 1972. In this study, we quantified land cover changes in the upper basin of the watershed, assessed stream flow changes at the stream gage during the same period, and mapped changes in the riparian vegetation community in the lower basin. This allowed us to assess the effect of urbanization on riparian vegetation via altered stream hydrology.

2.2. Aerial images and image processing

We analyzed the temporal and spatial patterns of land use and riparian vegetation communities using aerial photos of the Los Peñasquitos Creek watershed. Aerial photography has long been used to map and assess changes to wetlands (Cowardin and Myers, 1974; Lyon and Greene, 1992; Johnston, 1994; Thibault and Zipperer, 1994; Syphard and Garcia, 2001). We obtained aerial photographs and, where available, digital orthophotos covering the boundaries of the Los Peñasquitos Creek watershed for the period from 1928 to 2000 (Table 1). Digital orthophotos were available for the study site for 1992, 1994, 1996, 1999, and 2000. The remaining aerial photographs were black-and-white or color prints (Table 1).

Photographs were scanned and geo-referenced to the existing digital imagery by “rubber-sheeting” the images using common pairs of invariant features (e.g., road intersections, houses, bridges, and unique topographic features) present in both the digital images and scanned photographs (Cook and Pinder, 1996). Individual pairs of points with high root mean square errors (RMSE) were discarded and replaced until an acceptable overall RMSE was achieved. The RMSE quantifies the distortion between a scanned aerial image and a rectified, geo-referenced base map such as a digital ortho quarter quad. The average RMSE for the overall study was 6.50 pixels or 7.73 m (Table 1).

2.3. Land use patterns

There are few spatially explicit maps showing historic land use information for the city and county of San Diego. Some of the most comprehensive historic land use maps come from the California Department

Table 1
Aerial photographs used in the study, showing the date (month/day/year), photograph type, pixel resolution, root mean square errors (RMSE), and number of ground control points (GCP)

Image date	Type	Pixel resolution (m)	RMSE (pixels)	RMSE (m)	Number of GCPs
–/–/1928	B&W photo	1.58	5.22	8.25	33
10/02/1969	B&W photo	1.26	7.94	10.05	13
01/31/1977	B&W photo	1.26	11.72	14.84	10
09/05/1982	B&W photo	1.26	8.10	10.26	10
11/26/1988	CIR photo	1.26	14.24	18.02	12
06/02/1990	Color photo	1.26	7.80	9.88	9
10/–/1992	DOQQ	0.32	0.75	0.24	–
08/–/1994	DOQQ	1.00	0.95	0.90	–
09/–/1996	DOQQ	1.00	6.23	5.92	–
04/–/1999	DOQQ	1.00	2.00	1.90	–
09/–/2000	CIR DOQQ	1.00	–	–	–

B&W: black-and-white photograph, CIR: color infrared image, and DOQQ: digital orthophoto quarter quads. The symbol "–" indicates unknown or not applicable.

of Water Resources (DWR), which we used, in combination with aerial photographs, to determine land use changes in the Los Peñasquitos Creek watershed. DWR land use maps, printed on USGS 7.5-min quadrangle base maps, are available for 1966, 1975, 1986, and 1998 (DWR, 1968, 1978, 1987, 1998). The DWR maps are produced via aerial photograph interpretation, followed by intensive field verifications. Digital Geographic Information System (GIS) land use layers for 1990 and 1995 were obtained from the San Diego Association of Governments.

We used the DWR land use maps to quantify historic land uses in the Los Peñasquitos Creek watershed for 1966, 1975, and 1986. We quantified land use for 1999 by refining and updating the 1998 DWR land use data layer using 1999 digital imagery. To map land use for 1982, 1990, and 1996, we interpreted and classified 1982 black-and-white photos, 1990 color aerial photos, and 1996 digital orthophotos through on-screen digitizing. We used San Diego Association of Governments GIS land use layers for 1990 and 1995 to facilitate interpretation of land uses from these images. The maps were scanned and incorporated into the GIS database as ArcView shape files with appropriate land use attributes. All land use/land cover classes were aggregated into four superclasses—urban, agriculture, graded, or undeveloped. The urban superclass consisted of residential and commercial development. We used these superclasses in this study, as they were the most comparable categories among the various data sources.

2.4. Hydrologic patterns

We obtained daily mean and annual instantaneous peak discharges for the Los Peñasquitos Creek gage from the USGS National Water Information System (USGS, 2001). This gage is located at the boundary between the upper and lower basins of the Los Peñasquitos Creek watershed and thus measures discharge from the upper watershed only. We used data for water years 1965–2000, where a water year extends from October 1 to September 30 (Gordon et al., 1992). Rainfall data for water years 1851–2000 were obtained from the Western Regional Climate Center and National Climatic Data Center for the San Diego Lindbergh Field (airport) station, which is approximately 22 km southwest of the Los Peñasquitos Creek gage.

2.4.1. Annual hydrologic statistics

For the gage's period of record (1965–2000), we calculated maximum, median, and minimum annual discharges; total annual and total dry-season (June 1–September 30) runoff volume; and total annual and total dry-season precipitation. Annual discharge statistics were derived from daily mean discharge records ($m^3\,s^{-1}$) for the Los Peñasquitos Creek gage. Maximum and minimum annual discharges are the single daily mean maximum and minimum discharge values ($m^3\,s^{-1}$) for each water year, respectively. Median annual discharges are the daily mean discharge value with an equal number of higher discharge values above it and lower discharge values below it for each water year. Annual runoff was estimated by averaging the mean daily discharges for each day of the water year and converting this annualized mean daily discharge into a total annual flow volume (m^3 per year). Dry-season runoff was estimated in the same way, except days only during the period from June 1 to September 30 each year were used in the calculation. Annual discharge statistics were plotted on a logarithmic scale after adding a constant of $3 \times 10^{-4}\,m^3\,s^{-1}$ to each datum, which is the minimum measurable discharge at the gage. Using this constant allowed undetectable discharges to be plotted on a logarithmic scale. Annual and dry season runoff were plotted on a logarithmic scale without addition of a constant.

Temporal trends in annual hydrological summary statistics were estimated with a linear regression model:

$$\log(D) = a + b\mathrm{Y}$$

where D is discharge, Y the year, a the y-intercept, and b is the regression coefficient. To assess hydrologic changes in response to increasing urbanization, regression analyses used only hydrologic summary statistics from the period 1973 to 2000 (i.e., excluded hydrologic records from the period when the Pomerado Waste Water Treatment Plant was in operation). The slope of the regression equation (i.e., regression coefficient) was tested for significance with an ANOVA. The regression analyses are not intended to be used for predicting future discharge values but rather are used as an aid in identifying trends in discharge over the period of record of the gage. The back-transformed regression coefficient (B):

$$B = 10^b - 1$$

provides an estimate of the percent increase in discharge per year, over the period considered in the regression analysis.

Annual precipitation and dry-season precipitation were estimated for each year by summing daily rainfall totals for the entire water year and for the period from June 1 to September 30, respectively. Days reported with “trace” amounts of rainfall were treated as zeros in these calculations. Annual summary statistics were plotted on a logarithmic scale. Precipitation data were plotted after adding a constant of 0.025 cm to each datum, which is the minimum measurable rainfall at the gage.

2.4.2. *Flood frequencies*

To estimate the frequency of flood flows (i.e., a 1-in-N-year flood event), the recurrence intervals of the peak annual stream discharges during the period of record were determined. Flood recurrence interval (T) is the reciprocal of flood probability (P) (Gordon et al., 1992):

$$T = \frac{1}{P}$$

To determine recurrence intervals, annual instantaneous peak stream discharges during the period of interest were ranked from highest to lowest (i.e., the highest discharge receives a rank of 1). Recurrence intervals were calculated using a Weibull plotting position formula (Gordon et al., 1992):

$$T = \frac{(n+1)}{m}$$

where n is the number of discharge values ranked and m is the rank of each discharge value. Recurrence intervals were calculated separately for three distinct time periods (i.e., segments of the period of record for the gage): 1965–1972, 1973–1987, and 1988–2000, which represent periods with different levels of urbanization in the watershed (e.g., <15%, 15–25%, and >25% of watershed urbanized, respectively). This allowed us to compare the magnitude of floods of similar return intervals at periods of time with different levels of watershed urbanization. Discharge values and recurrence intervals were plotted separately for each of the three time periods on logarithmic scales, and flood magnitudes were estimated from linear regression lines calculated with the logarithmically transformed data.

2.5. *Riparian vegetation community patterns*

We quantified changes in the extent and distribution of the riparian vegetation community along Los Peñasquitos Creek from digital imagery in an area extending from near the USGS stream gage to approximately 9.6 linear km downstream. We delineated riparian vegetation community boundaries on a 2000 color infrared (CIR) digital orthophoto, using a process of on-screen digitizing to create a GIS coverage (i.e., ArcView shape file). We then ground-truthed the resulting vegetation map in the field, using a plot of the vegetation map overlain on the 2000 orthophoto, and made adjustments to the GIS coverage, as necessary.

After completing mapping from the 2000 imagery, we interpreted and mapped the images from the remaining dates, starting with the 1996 orthophoto and then working sequentially back to 1928, using the 2000 vegetation map as an interpretation aid. As the riparian vegetation in the imagery was visually distinct from non-riparian vegetation and bare ground by brightness and texture differences, classification accuracy was considered high even with the historic black-and-white photography. Due to their indistinct signatures in the aerial photographs, herbaceous species and young riparian trees were difficult to distinguish from non-riparian vegetation communities; therefore, the resulting maps may under-represent areas where these elements dominate the riparian vegetation community. The area occupied by the riparian vegetation community was quantified from the GIS coverage for each year.

To help illustrate the temporal changes we observed in the entire riparian vegetation community, we documented the changes in its extent and distribution in two reaches of Los Peñasquitos Creek, one in the vicinity of the Peñasquitos Ranch House and the other in the vicinity of the Falls. In these two reaches, we quantified the area occupied by riparian vegetation during the years 1928, 1969, and 2000 and illustrated the nature of the changes using aerial photographs. We also used the photographs in these years to visually assess apparent changes in channel morphology in these two reaches (e.g., shift from braided to entrenched channel). No field measurements of geomorphology were made for this study.

3. Results

3.1. Land use patterns

3.1.1. Cattle grazing

Cattle were first introduced into the lower basin of the Los Peñasquitos Creek watershed in 1823, and, presumably, settlers altered the riparian vegetation community by clearing trees for firewood and charcoal and to create agricultural fields in floodplain areas (Pourade, 1969). Cattle were grazed continuously in the lower Los Peñasquitos Creek watershed until 1989, when they were removed to eliminate conflicts between ranging cattle and increasing vehicular traffic in the area. During the 166-year period that cattle were present in the lower Los Peñasquitos Creek watershed, they likely had access to most of the riparian vegetation in the lower basin. The extent of any historical modifications to the riparian vegetation community of Los Peñasquitos Creek from cattle grazing and other agricultural operations is unknown. However, cattle are known to consume riparian vegetation, and have significantly reduced vegetation biomass in other riparian systems in the western U.S. (Belsky et al., 1999).

3.1.2. Urban development

The amount of urban development within the upper Los Peñasquitos Creek watershed (i.e., area above the stream gage) increased substantially during the period 1966–1999. When expressed as percentages of the total watershed area, the amount of undeveloped land fell from 87% to 57%, while the amount of urbanized land increased from 9% to 37% (Fig. 2). In addition, the Pomerado Waste Water Treatment Plant discharged treated wastewater effluent into Los Peñasquitos Creek, upstream of the gaging station from 1962 to 1972. The annual quantities of effluent discharged by the plant were not available.

Based on these development patterns, we divided the period of record for the Los Peñasquitos Creek gage into three periods: (1) 1965–1972, the period of treated wastewater discharge and low urbanization (<15% urbanization of the watershed); (2) 1973–1987, the period

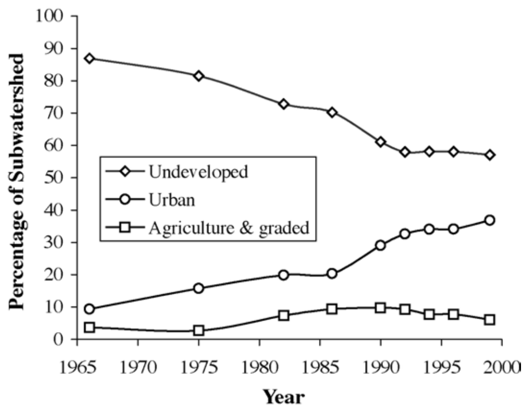

Fig. 2. Changes in the percentage of the Upper Los Peñasquitos Creek watershed in urban and undeveloped land use categories during the period 1966–1999.

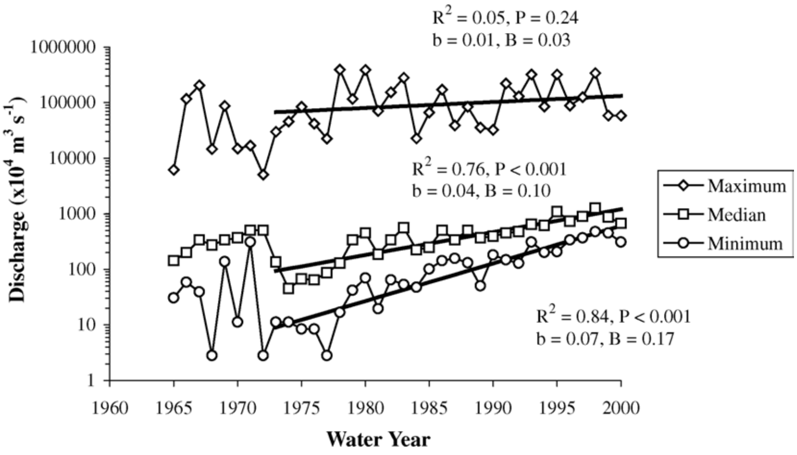

Fig. 3. Annual maximum, median, and minimum discharges recorded at the Los Peñasquitos Creek gage during the period 1965–2000. Discharge is plotted on a logarithmic scale after adding a constant of 3×10^{-4} m^3 s^{-1}. Lines are values predicted by the linear regression equations of the 1973–2000 data. R^2: coefficient of determination; b: regression coefficient; P: significance of regression coefficient; B: back-transformed regression coefficient.

of moderate urbanization (15% ≤ urbanization < 25%); (3) 1988–2000, the period of high urbanization (≥25% urbanization). We used these periods to analyze hydrologic patterns, as discussed below.

3.2. *Hydrologic patterns*

3.2.1. *Annual hydrologic statistics*

Annual minimum and median discharges in Los Peñasquitos Creek increased significantly from 1973 to 2000 ($P < 0.001$; Fig. 3). While there was a slightly increasing trend of maximum discharges from 1973 to 2000, it was not statistically significant (Fig. 3). The influence of wastewater effluent discharges on streamflow can be seen in the elevated median annual discharges in the years prior to 1973 (when effluent discharges to the stream were terminated). Median discharges were significantly higher during the 8 years with wastewater discharges than the first 8 years following the termination of wastewater discharges ($\Delta\bar{x} = 189\,\text{m}^3\,\text{s}^{-1};\ P = 0.007$). Minimum discharges were, on average, lower and more variable in the 8 years prior to 1973 than in the 8 years following termination of wastewater discharges, but the differences were not statistically significant.

The total annual runoff in the upper Los Peñasquitos Creek watershed exhibited a high degree of inter-annual variation but showed a marginally significant increasing trend during the period 1973–2000 ($P = 0.06$; Fig. 4). The back-transformed regression coefficient of the trend line estimates an average increase in total annual runoff of 4% per year from the upper watershed basin. Total dry-season runoff also exhibited a significant increasing trend over the same time period ($P < 0.001$; Fig. 4), increasing at an average rate of 13% per year. During the same time period, there were no

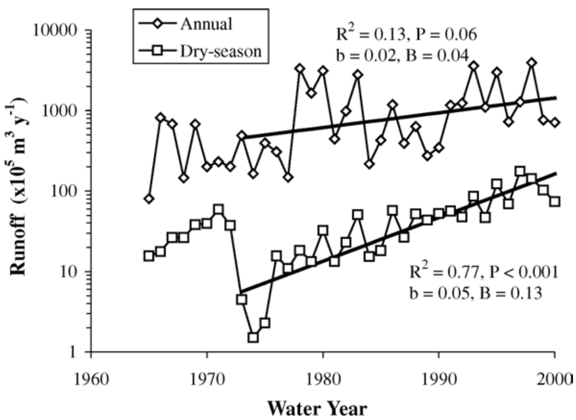

Fig. 4. Annual and dry-season runoff for 1965–2000 at the Los Peñasquitos Creek gage. Runoff is plotted on a logarithmic scale. Lines are values predicted by the linear regression equations of 1973–2000 data. R^2: coefficient of determination; b: regression coefficient; P: significance of regression coefficient; B: back-transformed regression coefficient.

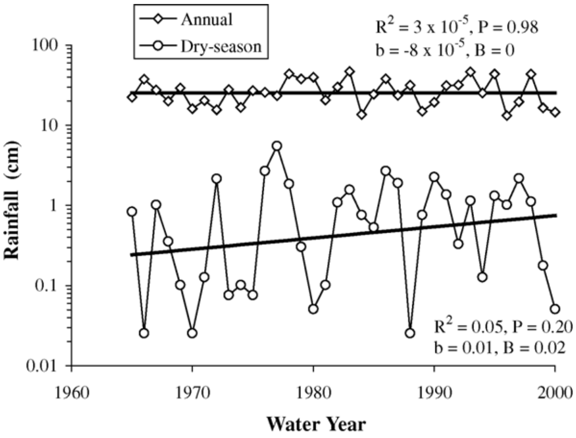

Fig. 5. Annual and dry-season precipitation measured at San Diego Lindbergh Field during the period 1965–2000. Precipitation is plotted on a logarithmic scale after adding a constant of 0.025 cm. Lines are values predicted by the linear regression equations of the respective data. R^2: coefficient of determination; *b*: regression coefficient; *P*: significance of regression coefficient; *B*: back-transformed regression coefficient.

significant increases or decreases in total annual or total dry-season precipitation (Fig. 5).

3.2.2. Flood frequencies

Flood magnitudes in Los Peñasquitos Creek have increased with increasing urbanization in the watershed, and increases were greatest for floods with low return intervals (Fig. 6). For return intervals of >5 years, flood magnitude was always highest during 1988–2000, lowest during 1965–1972, and intermediate during 1973–1987. For example, the estimated 1-in-2-year flood was 6.41 $m^3 s^{-1}$ during the period 1965–1972, 20.86 $m^3 s^{-1}$ during the period 1973–1987, and 35.67 $m^3 s^{-1}$ during the period 1988–2000. Differences in the flood magnitudes diminished at higher return intervals (e.g., approaching the 1-in-10-year flood); although, the low number of years during each of the three time periods prevented confident estimation of the magnitude of higher return interval events.

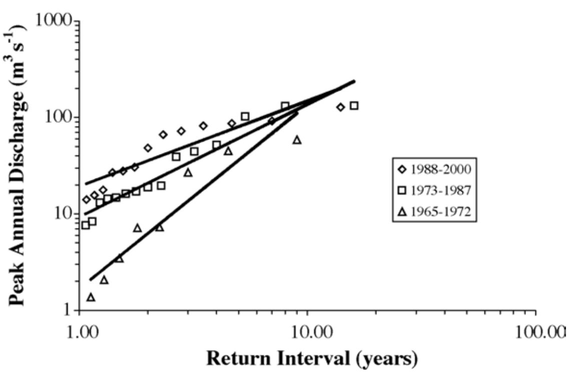

Fig. 6. Flood frequencies during three time intervals: 1965–1972, 1973–1987, and 1988–2000 at the Los Peñasquitos Creek gage. Lines are values predicted by the linear regression equations of the respective data. All regressions are statistically significant ($P < 0.001$). Coefficients of determination (R^2) are as follows: 1965–1972 = 0.90, 1973–1987 = 0.92, and 1988–2000 = 0.82.

3.3. Riparian vegetation community patterns

The historic composition of the riparian vegetation community along Los Peñasquitos Creek is unknown. Two newspaper articles published in 1869 and 1873 describe the riparian vegetation community as dominated either by willows and cottonwoods or sycamores and live oaks. The existing riparian vegetation community associated with lower Los Peñasquitos Creek is comprised of dense stands of willows, primarily arroyo willow (*Salix lasiolepis* Benth.) and black willow (*Salix goodingii* C. Ball), large western sycamores (*Platanus racemosa* Nutt.), and coast live oaks (*Quercus agrifolia* Nee). Willow species are dominant along the active stream channel, while sycamores and oaks occur more frequently in floodplain areas adjacent to the channel. There are a relatively small number of Fremont cottonwoods (*Populus fremontii* S. Watson) in the lower watershed, many of which apparently were planted as part of recent riparian restoration efforts.

Table 2
Estimated area of riparian vegetation associated with lower Los Peñasquitos Creek from 1928 to 2000 within the Ranch House reach, the Falls reach, and the entire study area

Date	Riparian vegetation (ha)		
	Ranch House reach	Falls reach	Total study area
1928	6.4	9.8	44.9
1969	15.2	14.3	78.2
1977	13.3	16.3	70.2
1982	15.1	14.5	78.2
1988	17.7	17.9	100.4
1996	19.9	18.0	102.6
2000	17.0	16.8	97.8

The acreage of the riparian vegetation community in the lower Los Peñasquitos Creek watershed has more than doubled since 1928 (Table 2). The smallest area of riparian vegetation (45 ha) was mapped for 1928. Relative to 1928, the area of riparian vegetation in the lower watershed increased by 56–74% between 1969 and 1982, and increased by 118–129% between 1988 and 2000. The Ranch House reach exhibited a large proportional increase in riparian vegetation because it had large unvegetated areas available to colonize (Fig. 7). For example, in 1928 riparian vegetation was sparsely distributed around a broad, unvegetated, braided channel; by 1969 there is a distinct channel with riparian vegetation beginning to establish along the margins; and in 2000 dense riparian vegetation has developed along the length of the channel. A similar sequence occurs in the Falls reach (Fig. 8), but relatively less unvegetated substrate existed in this reach in 1928. Thus, riparian vegetation increased differentially in these two reaches as the watershed urbanized, with a 164% increase in the Ranch House reach and only a 71% increase in the Falls reach (Table 2).

4. Discussion

Previous research has estimated runoff increases of 200–500% where impervious surface cover exceeds

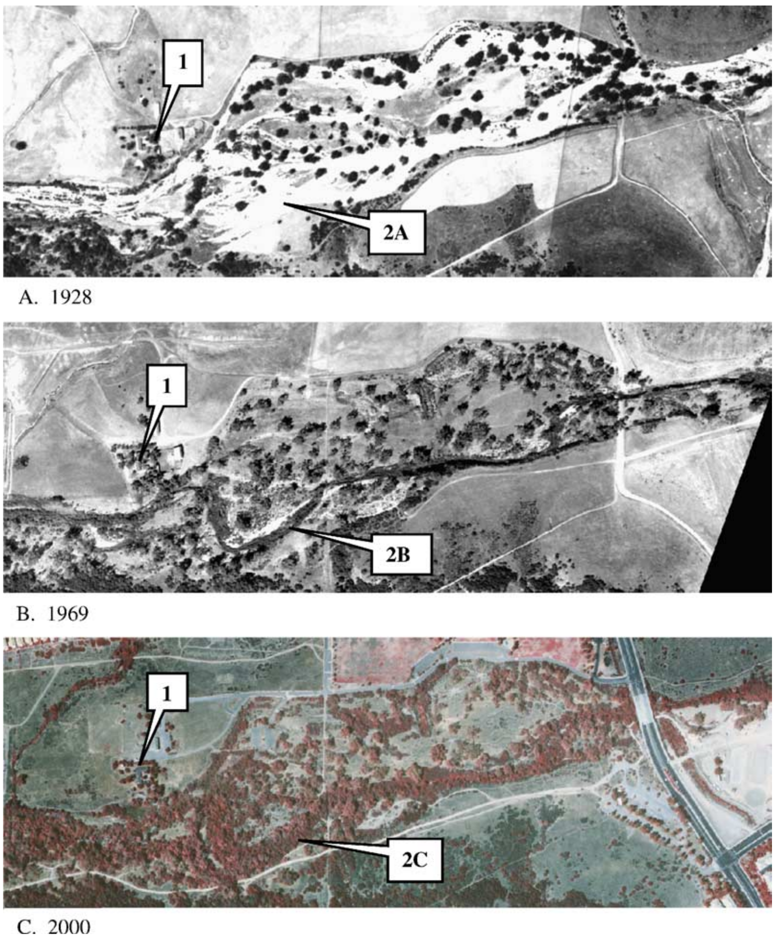

Fig. 7. Aerial photographs of the Ranch House reach of Los Peñasquitos Creek from: 1928 (A), 1969 (B), and 2000 (C), showing changes in channel characteristics and the distribution of riparian vegetation. (1) Ranch House buildings; (2A) sparsely vegetated, braided channel; (2B) narrow channel with riparian vegetation along the margins; (2C) narrow channel with dense riparian vegetation.

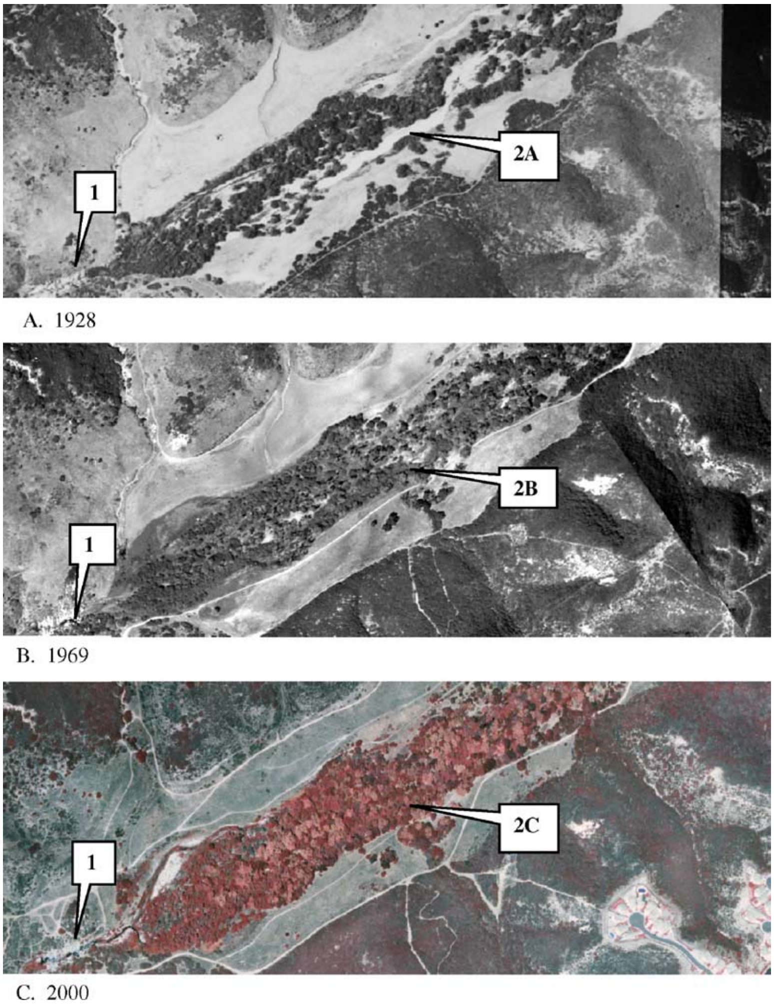

Fig. 8. Aerial photographs of the Falls reach of Los Peñasquitos Creek from 1928 (A), 1969 (B), and 2000 (C), showing changes in channel characteristics and the distribution of riparian vegetation. (1) The rock outcropping that forms the Falls; (2A) unvegetated channel; (2B) vegetation established in unvegetated channel; (2C) dense riparian vegetation obscures channel.

10% of the watershed (Arnold and Gibbons, 1996; Paul and Meyer, 2001). The results of this study are consistent with these findings. As urbanization in the Los Peñasquitos Creek watershed increased from 9% to 37% (Fig. 2), total runoff increased by an average of 4% per year (Fig. 4), representing an increase of over 200% from 1973 to 2000. During the same time period, there was no change in rainfall (Fig. 5). Although we did not measure impervious cover per se, impervious cover has been shown to represent 40–95% of the area occupied by small lot residential, industrial, and commercial land uses (Arnold and Gibbons, 1996), which comprised the majority of the urban land use superclass we used to represent urbanization.

Urbanization has also been shown to increase peak discharges and flood magnitudes, particularly floods with lower return intervals (Hollis, 1975; Hirsch et al., 1990; Leopold, 1994; Schueler, 1994; Paul and Meyer, 2001; Konrad and Booth, 2002). These results are also consistent with the hydrologic changes documented for Los Peñasquitos Creek. We estimate that (1) floods of return intervals of 1.5–3 years, which are considered to be the bank-full flood in Los Peñasquitos Creek (Prestegaard, 1979), have increased from 350% to over 700% as a result of increasing urbanization in the watershed; (2) the influence of urbanization on flood magnitude appeared to diminish with increasing return intervals (Fig. 6).

While some portions of Los Peñasquitos Creek are fed by natural springs, records at the gage and interpretation of historic aerial photographs (e.g., Fig. 7A) indicate that the majority of lower Los Peñasquitos Creek historically exhibited only intermittent flow. However, wastewater discharges and increasing urbanization in the watershed have significantly increased dry-season flows. The influence of wastewater discharges on dry-season base flows is reflected in the elevated annual median discharges and dry-season runoff during the period 1965–1972 and their rapid reduction in the years immediately following the termination of the sewage discharges in 1972. After wastewater discharges to the stream were terminated, dry-season hydrologic changes were driven by urbanization in the watershed. From1973 to 1975, annual minimum discharges increased at a rate of 17% per year, and dry-season runoff increased at a rate of 13% per year.

Urbanization-induced increase in the dry-season streamflow of Los Peñasquitos Creek is the most dramatic hydrologic effect we observed in this study. A decrease in dry-season stream base flow resulting from decreased infiltration of precipitation to groundwater aquifers is frequently cited as an effect of watershed urbanization and increased impervious surface cover (Hall, 1984; Paul and Meyer, 2001; National Research Council, 2002). However, urbanization can also increase dry-season base flows due to septic system drainage, leaky water or sewage pipes, and irrigation of lawns and landscaping (Hirsch et al., 1990; DeWalle et al., 2000; Konrad and Booth, 2002; Greer and Stow, 2003). Excess irrigation water conveyed to the stream network via the municipal stormwater system is likely responsible for the increased dry-season flows observed in Los Peñasquitos Creek with increasing watershed urbanization. The municipal water supply used for irrigating urban landscaping within the watershed is derived entirely from outside the watershed, and any water not lost to evaporation or transpiration eventually augments its natural water budget. There is now permanent dry-season flow in Los Peñasquitos Creek, and we project that flow will continue to increase as urbanization of the watershed continues.

Bank-full floods shape and maintain the morphology of stream channels (Leopold, 1994), and geomorphic changes of stream channels in response to urbanization have been documented in other watersheds (Hirsch et al., 1990; Booth and Henshaw, 2001). Channel incising was evident in portions of the Los Peñasquitos Creek channel that were braided in 1928 (Figs. 7 and 8). Channel geomorphic changes appeared to be initiated by wastewater discharges and maintained by urbanization-driven increases in flood magnitudes once wastewater discharges were terminated. These geomorphic changes were accompanied by dramatic increases in flood magnitudes, dry-season runoff, and a shift from an intermittent to a perennial flow pattern.

The extent of the riparian vegetation community in the lower watershed significantly increased in area as the watershed became increasingly urbanized (Table 2). Cattle grazing occurred throughout the majority of the study period (until 1989), and cattle grazing generally results in a decrease in the density and cover of riparian vegetation (Belsky et al., 1999) rather than the increase observed in this study. Thus, cattle grazing is unlikely to be responsible for the observed results. However, stream hydrologic patterns and fluvial geomorphological processes play an important role in the ecology of riparian vegetation communities (Stromberg, 1993; Scott et al., 1996, 1997), and have been altered significantly by urbanization in the Los Peñasquitos Creek watershed. The riparian vegetation community appears to have responded to increasing flood discharges and dry-season discharges by expanding into areas of the channel and floodplain that were unvegetated prior to the initiation of wastewater discharges and significant urbanization (Figs. 7 and 8).

In Southern California, sycamores and coast live oaks often dominate along intermittent and ephemeral streams, and willows along the wetter banks of perennial streams (Faber et al., 1989). From our field observations and review of aerial photography, riparian vegetation along the channel is currently dominated by willow species, while oaks and sycamores dominate in floodplain areas farther from the current channel. These willow-dominated areas were largely unvegetated in 1928. The increase from intermittent to perennial streamflow has favored the establishment of willow-dominated riparian vegetation along the unvegetated remnants of the historic braided channel adjacent to the newly configured channel. This mechanism appears to be responsible for the increase of riparian vegetation in the lower Los Peñasquitos Creek watershed.

Anecdotal observations of other drainages in San Diego County indicate that a shift to perennial streamflow and willow-dominated riparian habitats following upstream urbanization is common, which has significant implications for natural resources protection in the face of an urbanizing landscape. Many local governments in Southern California are developing land use plans that attempt to balance the need for expanding urban areas with protecting natural resources. These land use plans require the protection and management of threatened and endangered species and their habitats, including streams and riparian habitats, in exchange for regulatory authorizations under federal and California Endangered Species Acts. These land use plans often target stream and riparian habitats for protection, but generally do not consider the indirect effects of watershed urbanization on hydrologic processes. Thus, as watersheds are urbanized upstream of protected riparian areas, hydrologic regimes in these reaches are modified and the habitats and species originally targeted for protection may no longer be supported by the altered conditions. Land use plans must consider the indirect effects of urbanization on ecosystem processes, such as watershed-scale hydrological regimes, to effectively protect natural resources. These effects can extend far beyond the footprint of the urban areas themselves. For stream and riparian resources, the most effective approach to conserving hydrological processes, and thus downstream habitat character and quality, is to concentrate development in watershed basins with existing urbanization and ensure that undeveloped watershed basins or subbasins and their associated streams and riparian areas remain undeveloped.

5. Conclusions

We assert that the increase in urbanization of Los Peñasquitos Creek watershed has resulted in (1) significant increases in annual median and minimum discharges and dry season runoff; (2) increases in flood magnitudes; (3) geomorphic changes to stream channel morphology; (4) hydrologic changes favoring the expansion of a willow-dominated riparian vegetation community. We attribute the changes to an increased conveyance of storm runoff from the greater impervious surface area and increased dry-season runoff of imported landscaping irrigation water that are associated with expanding urbanization.

The stream and riparian communities of Los Peñasquitos Creek are typical of many coastal drainages in Southern California. Historic conditions in many streams in the region have been greatly modified as increasing urban runoff transforms intermittent and ephemeral drainages into perennial streams with elevated flood discharges. The urbanization-induced hydrologic changes that have altered stream and riparian vegetation communities also likely affect the native wildlife species associated with them. Given coastal Southern California watersheds are urbanizing at a rapid pace, the hydrologic characteristics of streams in these watersheds will continue to change. Species that prefer these altered hydrologic conditions will continue to replace species that prefer historic conditions, resulting in a shift in community composition associated with urbanization. Protecting the historic character and conditions of Southern California's natural resources in the face of these changes is extremely difficult, and can only be accomplished by land use planning that protects ecosystem processes, such as watershed-scale hydrologic regimes.

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