The Effects of Watershed Urbanization on Stream Hydrologic Characteristics and Riparian Vegetation of Los Peñasquitos Creek, California

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1.0 INTRODUCTION

There is increasing interest in the effects of urbanization on natural systems (Pickett et al. 2001, Paul and Meyer 2001). Among the variety of observed effects, urbanization has long been recognized as affecting hydrological characteristics of streams and rivers (e.g., see reviews in Poff et al. 1997, 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 riparian system. These coastal river systems in southern California have received little attention in the literature.

Urbanization within a watershed increases the area of impervious surfaces (Paul and Meyer 2001). Increasing the area of impervious surfaces generally decreases infiltration of rainfall 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 increased runoff from storms increases peak discharges and flood flows (Dunne and Leopold 1978). However, floods with long recurrence intervals may be less affected than floods of shorter recurrence intervals (Hirsch et al. 1990). Reduced infiltration of precipitation to groundwater aquifers may reduce groundwater recharge and stream baseflow (Paul and Meyers 2001). It is possible that importing water into an urban watershed for landscaping irrigation may offset the reduced groundwater recharge, thereby mitigating potential reductions of stream baseflow (Hirsch et al. 1990, Paul and Meyers 2001).

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). The distribution of many native riparian plant species along streams in the southwestern United States is a function of the autecology of these species relative to stream hydrology. Woody riparian plant species establish in positions along streams 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, at varying spatial scales, of species and age class composition produced by spatial and temporal variations in stream discharge patterns (Auble and Scott 1998, Stromberg et al. 1997, Shafroth et al. 1998).

Poff et al. (1997) have discussed the concept of the “natural flow regime” of riverine systems as the critical determinant of their biological structure. The flow regime can be described by five important characteristics: magnitude, frequency, duration, timing, and rate of change of discharge (Poff et al. 1997). Modifications to the natural flow regime by river regulation and impoundments have well-documented effects on riparian plant species and 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 Meyers 2001). As urbanization of watersheds can modify the natural flow regime of stream systems, it is expected that riparian vegetation communities would be affected as well.

Our study was conducted in the Los Peñasquitos Creek watershed, San Diego County, California. The objectives of this research were to:

1. Document the urbanization of the watershed over time;
2. Describe the hydrologic characteristics of Los Peñasquitos Creek, and evaluate potential urbanization-induced changes in these characteristics; and
3. Map and quantify changes in the distribution of the riparian vegetation community in the lower Los Peñasquitos Creek watershed over time, and evaluate whether these distribution patterns are consistent with observed hydrologic changes.

2.0 METHODS

2.1 STUDY AREA

The Los Peñasquitos Creek watershed encompasses approximately 60,415 acres of drainage area, extending east to Iron Mountain (elevation 2,696 ft above mean sea level) and draining west to Los Peñasquitos Lagoon at the coast. The Los Peñasquitos Creek watershed is comprised of three distinct subwatersheds associated with the Los Peñasquitos, Carroll, and Carmel creek systems, which drain from east to west (Figure 1A). The sizes of these subwatersheds are 38,924, 11,290 and 10,201 acres, respectively. The Los Peñasquitos Creek subwatershed can further be divided into upper and lower portions (Figure 1B). The upper portion of the subwatershed is relatively steep, and stream channels run through narrow and deep valleys, whereas the lower portion of the subwatershed is less steep, and stream channels cut through relatively broad valleys (Prestegaard 1979). A prominent Jurassic-age sedimentary rock outcropping traverses Los Peñasquitos Creek (Abbott 1999) and forms a waterfall in the lower Peñasquitos Creek subwatershed (Figure 1B).

Runoff in the Los Peñasquitos Creek watershed is closely associated with rainfall patterns. Rainfall in low-elevation, coastal San Diego County is largely derived from winter storm systems. These storm systems produce an average of approximately 10 inches of rainfall during the period from October to March each year, recorded at San Diego Lindbergh Field airport. Annual rainfall totals and timing are highly variable, with totals at Lindbergh Field ranging from about 3.5 inches to over 26 inches during the period 1851-2000. Annual rainfall totals in the region are generally higher farther inland, due to increasing elevations.

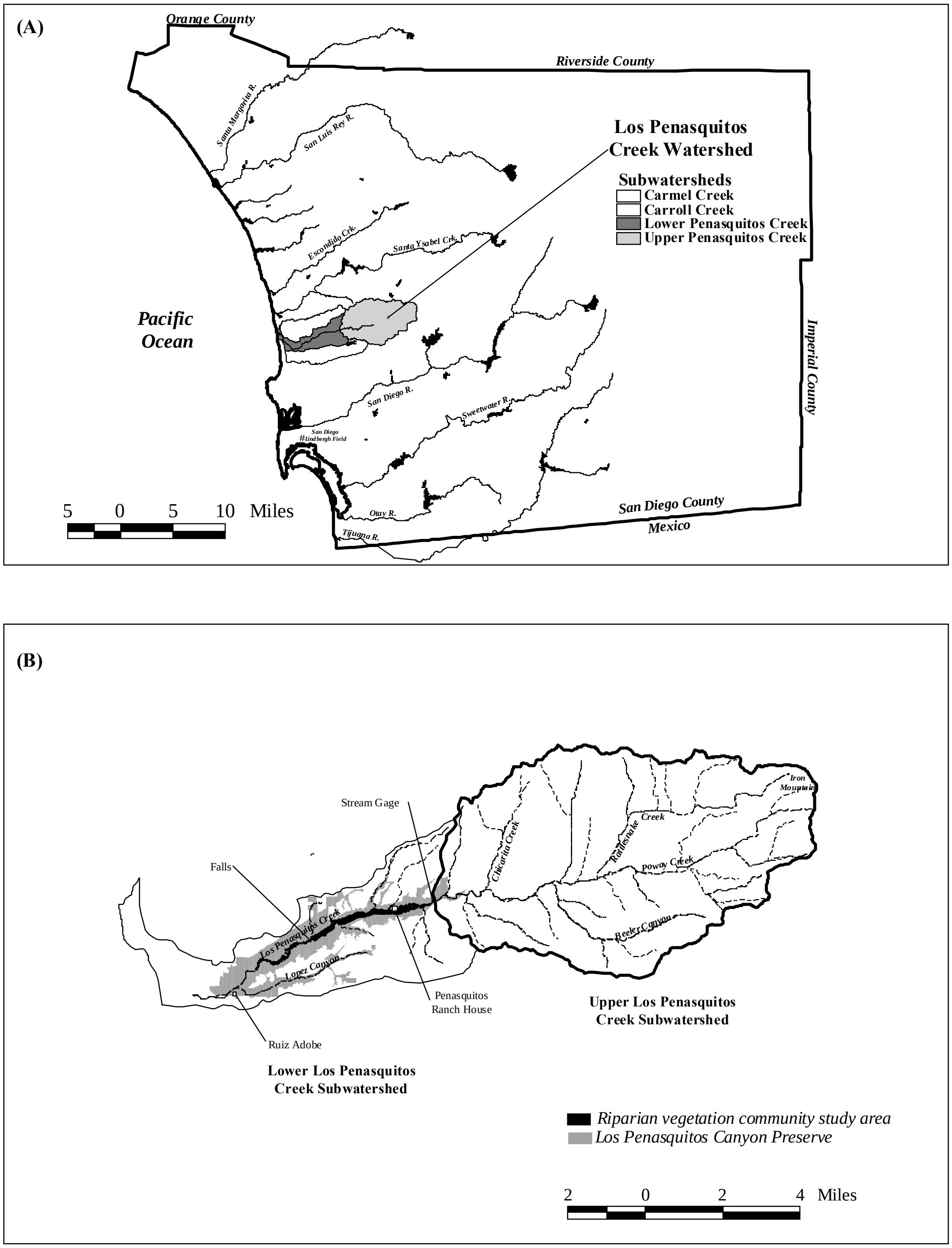


Figure 1. (A) Location of the Los Peñasquitos Creek watershed and major coastal drainages within San Diego County. (B) Streams and landmarks within the Upper and Lower Los Peñasquitos Creek subwatersheds.

Vegetation communities consist primarily of coastal sage scrub and chaparral on the upland slopes of the watershed. In draws and bottoms of tributary canyons, oak trees are a dominant component of the vegetation. Along stream courses, oaks intermingle with sycamore trees and willows within the riparian vegetation community (see Section 3.3).

This study focused on the Upper and Lower Los Peñasquitos Creek subwatersheds. The U.S. Geological Survey (USGS) has operated a streamflow gaging station on Los Peñasquitos Creek (station number 11023340) continuously since October 1, 1964 (Figure 1B). Since 1964, significant urbanization has occurred in the Los Peñasquitos Creek subwatersheds. Los Peñasquitos Creek flows through, and is an important feature of, the Los Peñasquitos Canyon Preserve, which is a natural open space reserve within the City of San Diego. Therefore, understanding the dynamics of the riparian vegetation community in this area is important for future habitat management efforts. We hope that the results of this study will stimulate examination of urbanization patterns in other watersheds and the effects on the ecology of these watersheds.

2.2 AERIAL IMAGES AND IMAGE PROCESSING

We analyzed the temporal and spatial patterns of land use and riparian vegetation communities using historic and current 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, Thibault and Zipperer 1994, Johnston 1994, Syphard and Garcia 2001). Aerial photographs provide a synoptic view and contain historic information that allows for vegetation change detection studies. A series of aerial photographs and, where available, digital orthophotos covering the boundaries of the Los Peñasquitos Creek watershed was obtained from commercial vendors and the City of San Diego (Table 1). The photos cover the period from 1928 to 2000. Digital orthophotos were available for the study site for 1994, 1996, 1999, and 2000. All of the digital orthophotos are in California State Plane (Zone 6) projection, utilizing the North American Datum (NAD) 1983. In addition, a 1945 aerial photograph of Los Peñasquitos Creek was obtained but was not geo-referenced, as discussed below.

Photographs were scanned using a flatbed desktop scanner at a resolution of 300 dots-per-inch (dpi), except for the 1945 photograph which was scanned at 1,000 dpi. The scanned images were geo-referenced in order to register them to existing digital orthophoto quarter quads (DOQQs). Geo-referencing was performed using Environmental Systems Research Institute's (ESRI) ArcView geographic information system (GIS) software. To geo-reference the aerial photographs, ArcView's Image Analysis extension was used to "rubbersheet" the images by selecting common points between the scanned aerial photographs and the geo-referenced digital orthophotos (Cook and Pinder 1996). These points are referred to as ground control points (GCP) and were selected based on discrete and invariant features between the aerial photograph and the digital orthophoto (e.g., road intersections, houses, bridges, unique topographic features). The aerial photographs were registered to the digital orthophotos, thereby simultaneously geo-referencing them. Individual GCPs with high root mean square errors (RMSE) were discarded and replaced until an acceptable overall RMSE was achieved. The RMSE

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). The symbol "--" indicates unknown or not applicable.

Image Date	**Type**	**Pixel Resolution (ft)**	**RMSE (Pixels)**	**RMSE (ft)**	**Number of GCPs**
--/--/1928	B&W Aerial Photo	5	5.22	26.09	33
10/02/1969	B&W Aerial Photo	4	7.94	31.76	13
01/31/1977	B&W Aerial Photo	4	11.72	46.88	10
09/05/1982	B&W Aerial Photo	4	8.10	32.41	10
11/26/1988	CIR Aerial Photo	4	14.24	56.94	12
06/02/1990	Color Aerial Photo	4	7.80	31.22	9
10/--/1992	Digital Orthophoto	1	0.75	0.75	
08/--/1994	Digital Orthophoto	3	0.95	2.85	--
09/--/1996	Digital Orthophoto	3	6.23	18.70	--
04/--/1999	Digital Orthophoto	3	2.00	6.00	--
09/--/2000	Digital Orthophoto	3	--	--	--

quantifies the distortion between a scanned aerial image and a rectified, geo-referenced base map such a digital DOQQ. The average RMSE for the overall study was 6.50 pixels or 25.36 ft (Table 1).

2.3 LAND USE PATTERNS

While tabular information and statistics of land use and population are readily available for various geographic regions of the City and County of San Diego via the federal census, spatially explicit historic information on land use (i.e., maps) is very limited. Some of the most comprehensive information comes from the California Department of Water Resources (DWR), which has generated and utilized land use maps to estimate present and future water demands. Land use maps on United States Geological Survey (USGS) 7.5-minute quadrangles are available for 1966, 1975, 1986, and 1998 (DWR 1968, 1978, 1987, 1998). The DWR maps are based on aerial photograph interpretation, followed by intensive field verifications. Digital GIS land use layers for 1990 and 1995 were obtained from the San Diego Association of Governments (SANDAG).

The DWR land use maps were used to quantify historic land uses in the Los Peñasquitos Creek subwatersheds for 1966, 1975, and 1986. Land use in 1999 was quantified by refining and updating the 1998 DWR land use data layer using 1999 digital imagery. To map land use for 1982, 1990, and 1996, 1982 black-and-white photos, 1990 color aerial photos, and 1996 digital orthophotos were interpreted and classified using a process of on-screen digitizing. SANDAG GIS coverages depicting 1990 and 1995 land use facilitated interpretation of historic land uses from these images. All land use/land cover classes were aggregated into four superclasses consisting of urban, agriculture, newly graded, or native vegetation. These superclasses were used in this study, as they were the most comparable categories among the various data sources. Aerial photographs and digital images of the watershed were examined to help rectify any inconsistencies that appeared on the maps. The maps were scanned and incorporated into the GIS database as ArcView Shape files with appropriate land use attributes. Much of the land use information for the Los Peñasquitos Creek watershed was compiled in a previous study conducted by Greer (2001).

2.4 HYDROLOGIC PATTERNS

Discharge data for Los Peñasquitos Creek were obtained via the Internet from the USGS National Water Information System (USGS 2001) for the Los Peñasquitos Creek gage (station number 11023340). This gage is located at the boundary between the Upper and Lower Los Peñasquitos Creek subwatersheds and thus measures discharge from the upper subwatershed. Daily average discharges and annual instantaneous peak discharges in cubic feet per second (cfs) were obtained and are displayed by water year. A water year extends from October 1 of the previous calendar year to September 30 of the current year (Gordon et al. 1992). Data for water years 1965-2000 were used in this study.

Rainfall quantities can be extremely variable geographically, given the variability of storm behaviors and topographic effects. Rainfall data for this study were obtained from the Western Regional Climate Center and National Climatic Data Center for the San Diego Lindbergh Field (airport) station, which is approximately 14 miles from the Los Peñasquitos Creek gage (Figure 1B). While this climate station may not provide an accurate estimate of rainfall in the Los Peñasquitos Creek subwatersheds, the Lindbergh Field station has a period of record that overlaps with the discharge record for the Los Peñasquitos Creek gage and is considered to provide a reasonable estimate of annual trends in rainfall. Rainfall records were obtained for water years 1851-2000.

2.4.1 Annual Hydrologic Statistics

Annual hydrologic summary statistics, including maximum, median, and minimum annual discharges; annual and dry-season flow volumes; and annual and dry-season precipitation, were estimated for the gage's period of record (1965-2000). Annual discharge statistics were obtained from mean daily discharge records for the Los

Peñasquitos Creek gage. Maximum and minimum annual discharges are the single mean daily maximum and minimum discharge values for each water year, respectively. Median annual discharges are the mean daily discharge value with an equal number of higher discharge values above it and lower discharge values below it. Annual runoff for the Los Peñasquitos Creek subwatersheds was estimated by averaging the mean daily discharges for each water year. This average annual discharge (cfs) was then converted into a total annual discharge in acre-feet per year (afy). Dry-season flow was estimated in the same way, except only days during the period from June 1 to September 30 each year were used in the calculation. Annual summary statistics were plotted on a logarithmic scale after adding a constant of 0.01 to each datum (no constant was added to annual and dry-season flow volumes), which is the minimum measurable discharge at the gage.

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

$$\log(D) = a + bY$$

where D is discharge, Y is the year, a is the y-intercept, and b is the regression coefficient. The regression analysis used only hydrologic summary statistics from the period 1973-2000 (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 (i.e., significantly different from zero) with an ANOVA. The regression analysis is not intended to provide an accurate prediction of future discharge values but is used as an aid in identifying trends in discharge over time. The back-transformed regression coefficient (B):

$$B = 10^{b} - 1$$

provides an estimate of the percent increase in discharge per year, as predicted by the regression equation.

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 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 0.01 to each datum.

2.4.2 Flood Frequency

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):

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

Therefore, a 1-in-10-year flood event has a recurrence interval of 10 years and a 10% probability of being equaled or exceeded in any year.

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 interval (RI) of each peak discharge was calculated as (Leopold 1994):

$$RI = \frac{n+1}{m}$$

where *n* is the number of discharge values ranked and *m* is the rank number of each discharge value. Recurrence intervals were calculated separately for peak discharges within three distinct time periods (i.e., segments of the period of record for the gage): 1965-1972, 1973-1987, 1988-2000. The three time periods were distinguished by differences in the percent urbanization in the subwatersheds (see Section 3.1.2). This allowed us to compare the magnitude of floods of similar return intervals between three periods characterized by differences in land use. Discharge values and recurrence intervals were plotted on logarithmic scales, and flood magnitudes were estimated from linear regression lines calculated with the logarithmically transformed data.

2.4.3 Flow Duration

Flow duration was compared among the three time periods to evaluate relationship of flow duration to degree of urbanization. Flow duration curves were constructed to determine the percentage of a given period of time in which flows were above or below a particular discharge (or benchmark value, see below). Flow duration curves were constructed from average daily discharges for each of the three time periods, and the cumulative frequency distribution of average daily discharge values was determined without regard to the temporal pattern of the discharges (Gordon et al. 1992, Leopold 1994). Discharge values were transformed by adding a constant value of 0.01 to each datum. A duration curve was then plotted as discharge as a function of the percentage of time that the discharge value was equaled or exceeded during the time period, with discharge on a logarithmic scale.

We conducted two analyses to test for differences among the flow duration curves for the three time periods, which are distinguished by differences in percent urbanization in the subwatersheds. We selected two benchmark values to use in the analyses: (1) the average daily flow for the period 1965-2000 and (2) the average daily flow for the dry-season only for the period 1965-2000. Using these benchmarks, we calculated the following for each year within each of the three time periods: (1) the number of days equal to or above the first benchmark value (average daily discharge), and (2) the number of days below the second benchmark value (average daily discharge for the dry-season only). Using ANOVA, we evaluated differences among the three time periods with respect to the numbers of days equal to or above the first benchmark and number of days below the second benchmark. Data were natural logarithmically transformed after adding a constant of 1, prior to performing the ANOVA, to homogenize the variances among the groups. Differences among the means of the three time periods were compared with pair-wise t-tests on the transformed data.

2.5 RIPARIAN VEGETATION COMMUNITY PATTERNS

Changes in the spatial distribution of the riparian vegetation community along Los Peñasquitos Creek were quantified from digital imagery in an area extending from near the USGS stream gage located just east of Black Mountain Road, west approximately 6 linear miles to near the confluence with Lopez Canyon (Figure 1B). Riparian vegetation community mapping was conducted initially on 2000 color infrared DOQQ, using a process of on-screen digitizing to create a GIS coverage (i.e., ArcView Shape files). To increase the reliability of on-screen digitizing, a variety of image enhancement techniques (e.g., contrast enhancements) and feature extractions, using a spatial-spectral region-growing technique, were applied to the scanned digital images. The seed tool function of ArcView's Image Analysis extension was used for these techniques (Lillesand and Kiefer 1994, ESRI 1998). The resulting vegetation map was then revised in the field using a plot of the vegetation map overlaid on the 2000 orthophoto. The high spatial resolution of the 2000 imagery (3 ft ground resolution element), coupled with the color infrared nature of the imagery and our ability to field-verify the resulting vegetation type map, provided a high degree of certainty regarding the vegetation classification. This method is similar to that used by O'Leary et al. (1994) for mapping vegetation and land cover types on Marine Corps Air Station Miramar, San Diego.

After completing mapping from the 2000 imagery, the images from the remaining dates were interpreted and mapped, starting with the 1996 orthophoto and then working sequentially back to 1928, using the 2000 vegetation map as an interpretation aid. Starting with the 2000 image and vegetation map (i.e., the most recent imagery) and working sequentially backwards increased the reliability and consistency of the vegetation classification and mapping, because the 2000 imagery was easily field-verified. 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 generally considered high even with the historic black-and-white photography. Due to their indistinct signatures in the aerial photographs, herbaceous species and young trees are difficult to distinguish from non-riparian vegetation communities; therefore, the resulting maps may under-represent areas where these elements dominate the riparian community. The quality of the 1945 aerial photography was considered too poor to reliably develop a map of the riparian vegetation community over the entire study area. Therefore, the use of this image was restricted to visual interpretation of channel and vegetation community characteristics in specific sections of the study area.

3.0 RESULTS

3.1 LAND USE PATTERNS

3.1.1 Cattle Grazing

In 1823, Captain Francisco Maria Ruiz was awarded the first land grant in San Diego County for the 8,486-acre Los Peñasquitos Rancho (Pourade 1969). Rancho Los Peñasquitos encompassed the lower Los Peñasquitos Creek subwatershed from near Sorrento Valley, upstream to an area east of the present day Interstate-15 freeway. Captain Ruiz first introduced cattle into the valley and, presumably, altered the riparian vegetation community in other ways by clearing trees for firewood and charcoal and to create agricultural fields. However, the extent of these habitat modifications is unknown. Two brief historic descriptions of the riparian habitat in the valley were found in archival newspaper clippings. A reporter for the San Diego Union (1869) provided the following description:

> *The road was in fine condition, and the ride was exceedingly exhilarating. Along lovely valleys it passed, crossing, sometimes, gurgling streams of water, shaded by large trees, filled with birds of silvery voices, and among flowers of the most beautiful hues. We were but a little more than two hours in making the trip. No pen can describe the beauties of the scenery by which the house is surrounded. Situated in a valley, near a little stream skirted by tall and graceful cottonwood, and slender willows; on either hand the hills roll back in graceful undulations covered with verdure and flowers of every color.*

A reporter for The Daily World (1873) recorded the following observation of the lower portion of the Los Peñasquitos Creek subwatershed, which indicates that the riparian habitat was fairly extensive in 1873.

> *This ridge is covered by a luxuriant growth of Chapparal* (sic). *Inumerable sycamores and live oaks, which make the whole valley almost a grove, creep to the foot of this range. It is enclosed on the north side by oat-hills of considerable heighth* (sic).

Cattle were grazed continuously in the lower Los Peñasquitos Creek subwatershed until 1989, when cattle 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 subwatershed, they likely had access to most of the riparian vegetation in the lower valley.

3.1.2 Urban Development

The amount of urban development within the Upper Los Peñasquitos Creek subwatershed above the stream gage has changed substantially since 1966. When expressed as percentages of the total subwatershed area, the amount of undeveloped land fell from 87% to 57%, while the amount of urbanized land increased from 9% to 37% (Figure 2).

During the period 1966 to 1999, the acreage of undeveloped land in the subwatershed decreased by 34%, while the acreage of urbanized land increased by 290% (Appendix A)

Also, treated sewage effluent was discharged into Los Peñasquitos Creek, upstream of the gaging station, by the Pomerado Waste Water Treatment Plant. This “live stream discharge” of waste water effluent occurred from 1962 to 1972. The annual quantities discharged by the plant were not available.

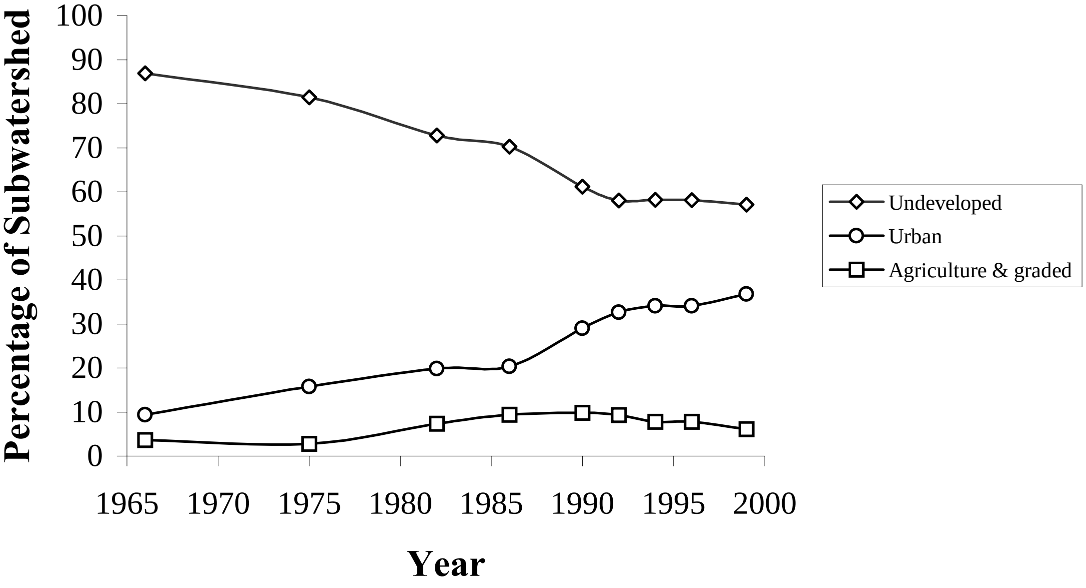


Figure 2. Changes in the percentage of the Upper Los Peñasquitos Creek subwatershed in urban and undeveloped land use categories during the period 1966-1999.

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 live stream discharge and low urbanization (<15% urbanization); (2) 1973-1987, the period of moderate urbanization (15%≤ urbanization <25%); and (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 increased significantly from 1973-2000 (Figure 3, Appendix A). The influence of sewage effluent discharges to the stream can be seen in the elevated minimum and median annual discharge values in the years prior to 1973. While there was a slightly increasing trend of maximum discharges from 1973-2000, it was not statistically significant (Figure 3).

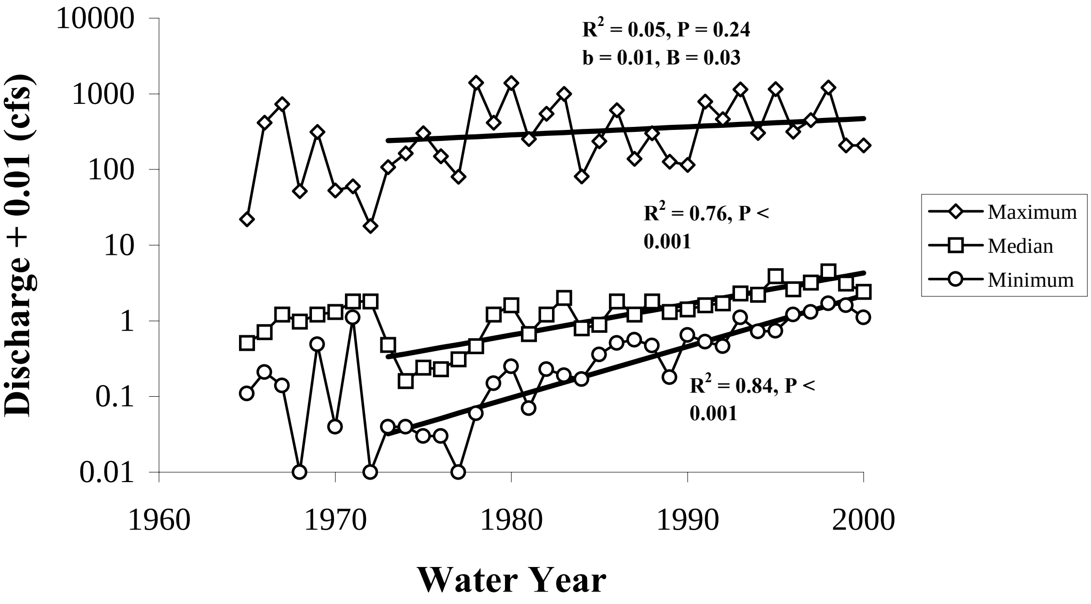


Figure 3. Annual maximum, median, and minimum discharges recorded at the Los Peñasquitos Creek gage during the period 1965-2000. Discharge is plotted on a logarithmic scale. Lines are values predicted by the linear regression equations of the 1973-2000 data. R^2 = coefficient of determination, b = regression coefficient, P = significance of regression coefficient, B = back-transformed regression coefficient.

The total annual runoff in the Upper Los Peñasquitos Creek subwatershed exhibited a high degree of inter-annual variation but showed a significant increasing trend during the period of 1973-2000 (Figure 4). The back-transformed regression coefficient of the trend line predicts an increase in total annual runoff of 4% per year from the 27,163-acre subwatershed above the stream gage. Total dry-season runoff also exhibited a significant increasing trend over the same time period (Figure 4). Total dry-season runoff increased at an estimated rate of 13% per year. However, during the same time period, there was no significant trend in total annual rainfall or in total dry-season precipitation (Figure 5). During the period 1965-2000, average daily flow was 10.52 cfs, average daily dry-season flow was 1.36 cfs, and mean annual precipitation (water year basis) was 10.7 inches. For the entire period of record for rainfall at Lindbergh Field, the mean annual (water year) precipitation was 10.0 inches (Figure 6).

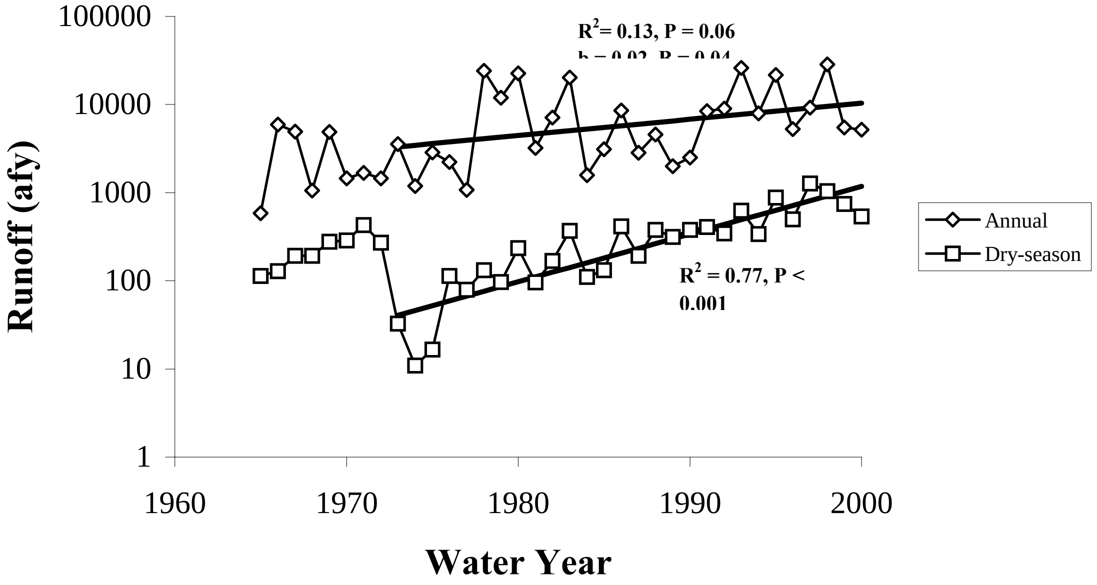


Figure 4. Annual and dry-season runoff for 1965-2000 at the Los Peñasquitos Creek gage. Runoff is plotted on a logarithmic scale. Lines are values predicted by the linear regression equations of 1973-2000 data. R^2 = coefficient of determination, b = regression coefficient, P = significance of regression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

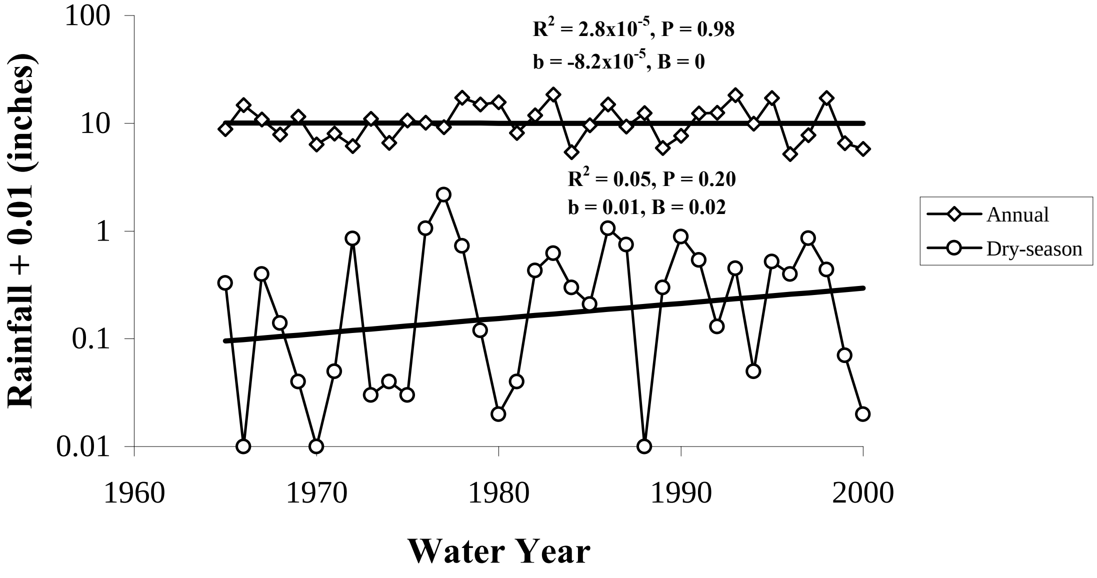


Figure 5. Annual and dry-season precipitation measured at San Diego Lindbergh Field during the period 1965-2000. Lines are values predicted by the linear regression equations of the respective data. R^2 = coefficient of determination, b = regression coefficient, P = significance of regression coefficient, B = back-transformed regression coefficient.

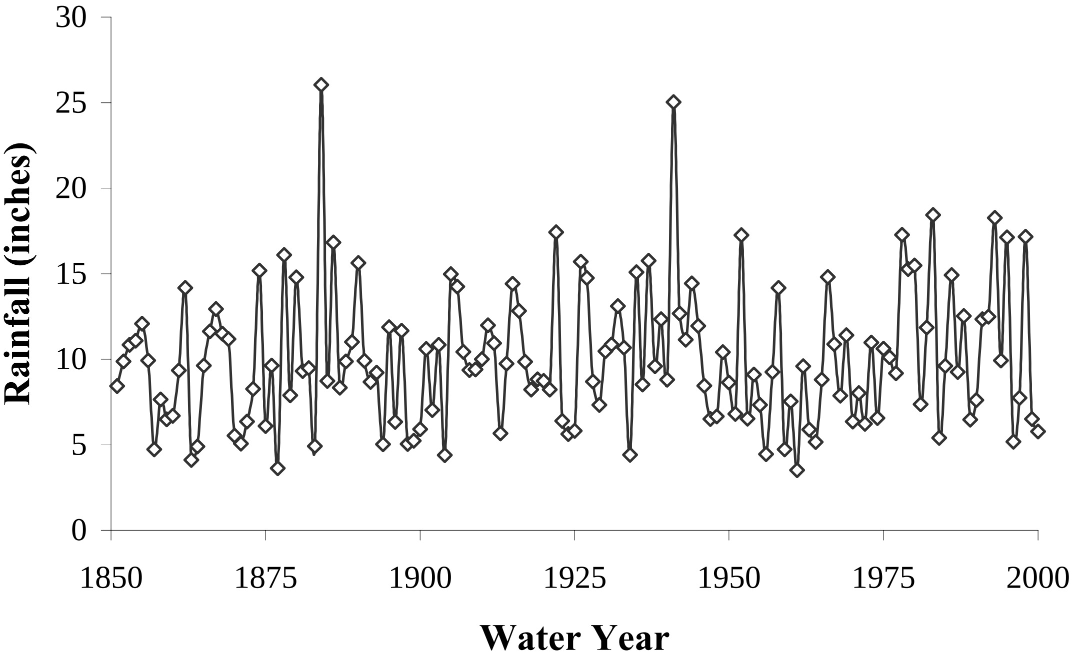


Figure 6. Annual precipitation measured at San Diego Lindbergh Field during the period 1851-2000.

3.2.2 Flood Frequencies

The magnitude of floods of varying return intervals varies greatly between the three time periods characterized by different levels of urbanization (Figure 7). For all return intervals of less than 5 years, annual peak discharges of a given return interval were always ordered from low to high as 1965-1972, 1973-1987, and 1988-2000. For example, the estimated 1-in-2-year flood was 229 cfs during the period 1965-1972, 745 cfs during the period 1973-1987, and 1274 cfs during the period 1988-2000. Differences in the flood magnitudes diminished at higher return intervals (e.g., approaching the 1-in-10-year flood).

3.2.3 Duration Curves

The patterns of mean daily discharge duration also varied between the three time periods characterizing urbanization (Figure 8). The period 1988-2000 was shifted upwards to higher discharges and to the right to higher durations relative to the duration curves for the other two time periods, except at extremely high discharges (i.e., over 1,000 cfs). Thus, during 1988-2000 the stream experienced a greater proportion of time at higher discharges than during the other two time periods, except that during the period 1973-1987 the stream experienced a greater proportion of time over 1,000 cfs. The duration curves for the periods 1965-1972 and 1973-1987 cross at approximately 1.7 cfs (32% of days equaling or exceeding this flow). These curves illustrate that, for discharges above 1.7 cfs, the period 1973-1987 experienced a greater percentage of time at higher discharges than did the period 1965-1972. At discharges below 1.7 cfs, the period 1973-1987 experienced a lower percentage of time at higher discharges than did the period 1965-1972.

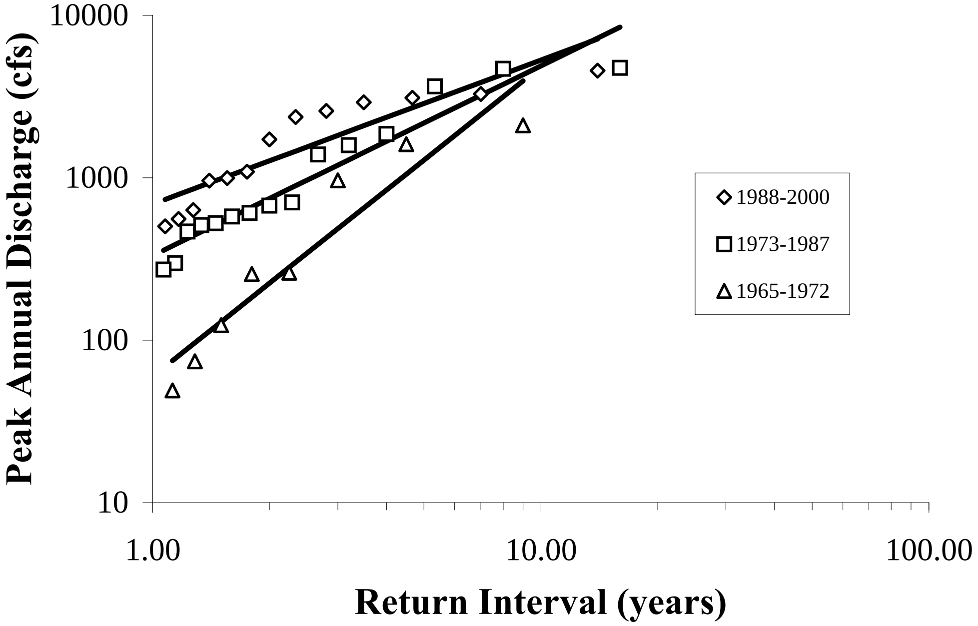


Figure 7. Flood frequencies during three time intervals: 1965-1972, 1973-1986, and 1987-2000 at the Los Peñasquitos Creek gage. Lines are values predicted by the linear regression equations of the respective data. All regressions are statistically significant ($P < 0.001$). Coefficients of determination (R^2) are as follows: 1988-2000 = 0.82, 1973-1987 = 0.92, and 1965-1972 = 0.90.

The results of an ANOVA comparing the three time periods with respect to the number of days each year where average daily discharge equaled or exceeded the long-term (1965-2000) average annual daily discharge (10.52 cfs) and the number of days each year where average daily discharge was less than the long-term (1965-2000) average dry-season daily discharge (1.36 cfs) are provided in Table 2. As expected, the patterns seen in the three duration curves are also reflected in the ANOVAs. Significant differences were detected both for numbers of days exceeding 10.52 cfs and numbers of days below 1.36 cfs. The period 1965-1972 had statistically fewer days each year above 10.52 cfs than did either 1973-1987 ($P = 0.03$, $t = 2.52$, $df = 13$) or 1988-2000 ($P = 0.004$, $t = 3.17$, $df = 12$), which were not statistically different from one another. Likewise, the period 1988-2000 had statistically fewer days below 1.36 cfs than did the period 1965-1972 ($P = 0.002$, $t = 3.34$, $df = 18$) or the period 1973-1987 ($P < 0.001$, $t = 4.53$, $df = 12$), which were not statistically different from one another.

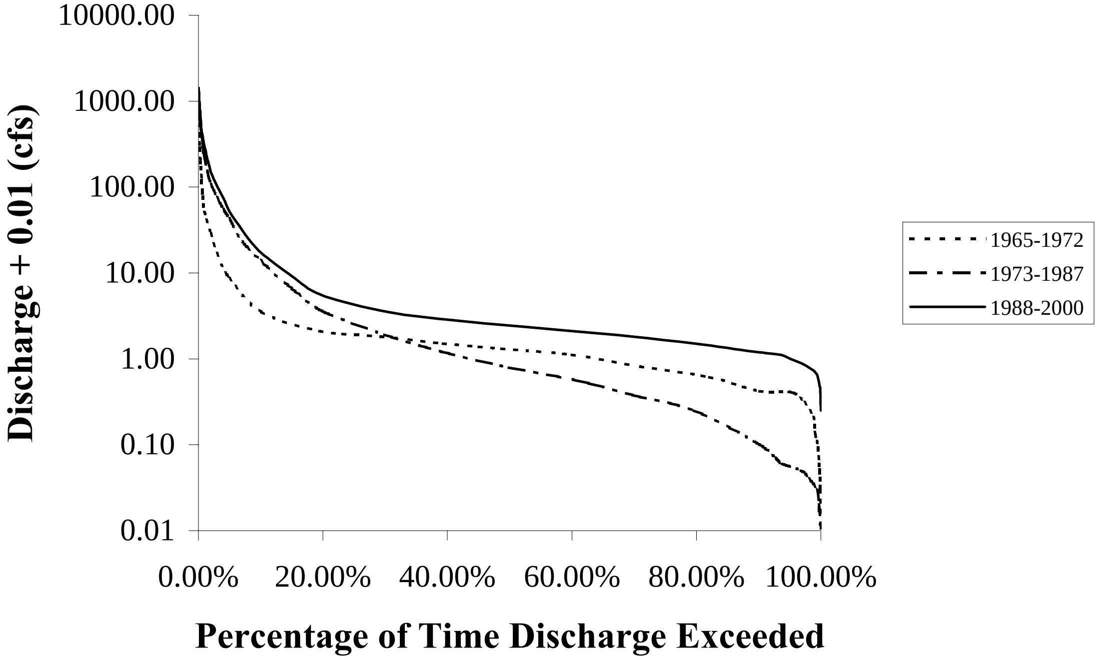


Figure 8. Duration curves for flows during three time periods: 1965-1972, 1973-1987, and 1988-2000 at the Los Peñasquitos Creek gage. Discharge is plotted on a logarithmic scale.

Table 2. Analysis of variance on the number of days with flows equaling or exceeding mean annual daily discharge (10.52 cfs) and the number of days with flows less than mean annual dry-season discharge (1.36 cfs) in three time periods: 1965-1972, 1973-1987, and 1988-2000 (df = degrees of freedom, SS = sums of squares, MS = mean square, F = F statistic).

Days ≥ 10.52 cfs	***df***	***SS***	***MS***	***F***	***Significance***
Between Groups	2	7.9	4.0	6.1	0.006
Within Groups	33	21.5	0.6		
Total	35	29.4			
Days < 1.36 cfs	***df***	***SS***	***MS***	***F***	***Significance***
Between Groups	2	44.4	22.2	14.5	< 0.001
Within Groups	33	50.5	1.5		
Total	35	94.9			

3.3 RIPARIAN VEGETATION COMMUNITY PATTERNS

The existing riparian vegetation community associated with lower Los Peñasquitos Creek is generally comprised of dense stands of willows, primarily arroyo willow (*Salix lasiolepis*) and black willow (*Salix goodingii*), western sycamores (*Platanus racemosa*), and coast live oaks (*Quercus agrifolia*). Willow species are dominant along the active stream channel, while sycamores and oaks are more frequently in floodplain areas adjacent to the channel. There are a relatively small number of Fremont cottonwoods (*Populus fremontii*) in the eastern portion of the lower subwatershed in the vicinity of the Peñasquitos Ranch House, many of which have been planted as part of riparian revegetation efforts (M. Kelly, personal communication). Information generated from aerial photographs shows that the current acreage and distribution of the riparian vegetation community have changed substantially from that in 1928, and the changes have occurred differentially across the lower subwatershed.

Since 1928, the overall acreage of the riparian vegetation community has more than doubled. The smallest area of riparian habitat (111 acres) was mapped in 1928, an intermediate acreage (174 to 193 acres) was mapped between 1969 and 1982, and the greatest acreage (242-253 acres) was mapped between 1988 and 2000 (Table 3).

Table 3. Acreage of riparian vegetation associated with lower Los Peñasquitos Creek from 1928-2000.

Date	Riparian Vegetation (acres)
1928	111
1969	193
1977	174
1982	193
1988	248
1996	253
2000	242

The distribution of riparian vegetation along Los Peñasquitos Creek changed with the increase in acreage. These changes are illustrated in Figure 9, where the footprint of the vegetation community in 1928 is superimposed on the footprint of the community in the year 2000. Thus, the portions of the 2000 vegetation community footprint that are visible in Figure 9 outside of the 1928 footprint represent areas of expansion of the community since 1928. In general, this figure shows riparian vegetation expanding into the eastern end of the study area, into the northern portion of the study area upstream of the falls, and below the falls at the western end of the study area.

The nature of these changes is apparent from inspection of the aerial photographs. In Figures 10, 11, and 12, portions of the aerial photographs from 1928, 1945, 1969, and 2000 are shown that cover three reaches of the creek, respectively: the eastern end of the

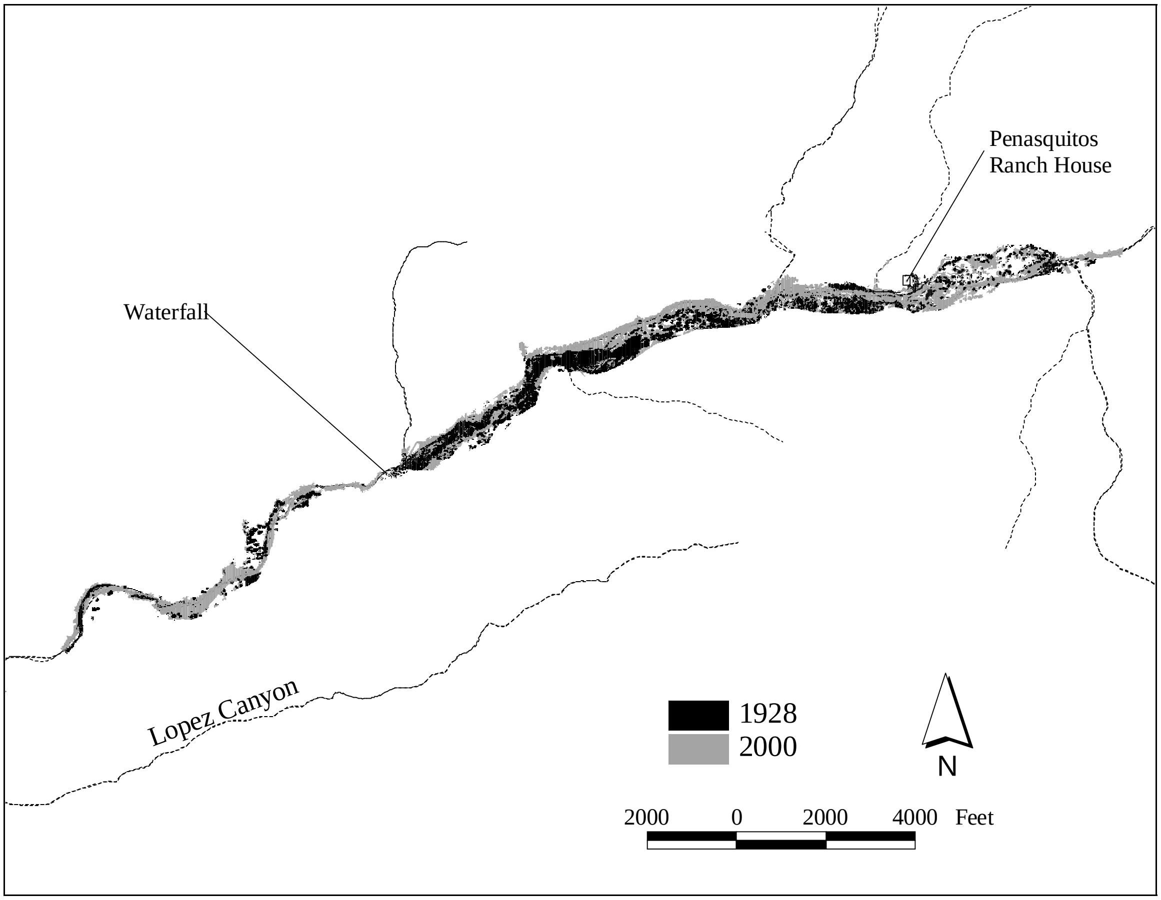
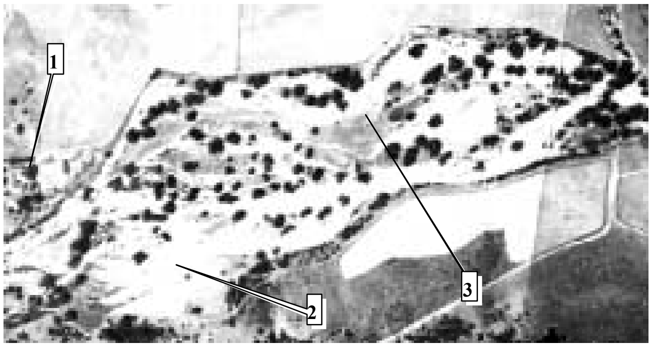


Figure 9. Distribution of the riparian vegetation community along lower Los Peñasquitos Creek in 1928 and 2000. The footprint of the 1928 vegetation community is superimposed on the footprint of the vegetation community in 2000.

study area (near the Peñasquitos Ranch House), the vicinity of the falls, and the western end of the study area. The four dates shown in these figures provide a good time series for documenting the changes in riparian vegetation communities along the stream.

The eastern portion of the study area (Figure 10) exhibits the most dramatic changes of the entire study area. In 1928, riparian vegetation was sparsely distributed around a broad, braided channel. A similar pattern appears in 1945, although image quality is poor. In the 1969 photograph, there is a distinct channel with riparian vegetation along the margins. By 2000, dense riparian vegetation has developed along the length of the channel. In both 1969 and 2000, riparian vegetation is less dense in the floodplain area north of the stream channel.

The area upstream of the falls did not exhibit the same degree of change as did the eastern portion of the study area (Figure 11). In 1928, there was relatively dense riparian vegetation immediately upstream of the rock outcropping forming the falls and in a swath extending farther upstream. However, an open channel adjacent to the stand of riparian vegetation is

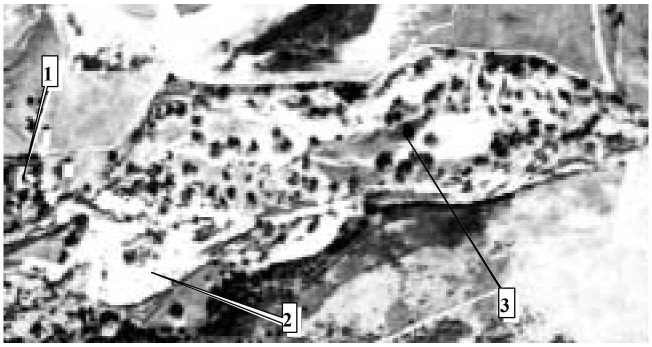


1928

1 - Penasquitos Ranch House

2 - Sparsely vegetated, braided channel

3 - Braided channels in floodplain

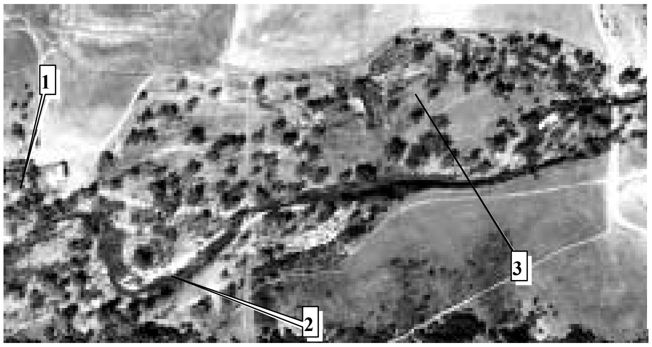


1945

1 - Penasquitos Ranch House

2 - Sparsely vegetated channel

3 - Braided channels in floodplain

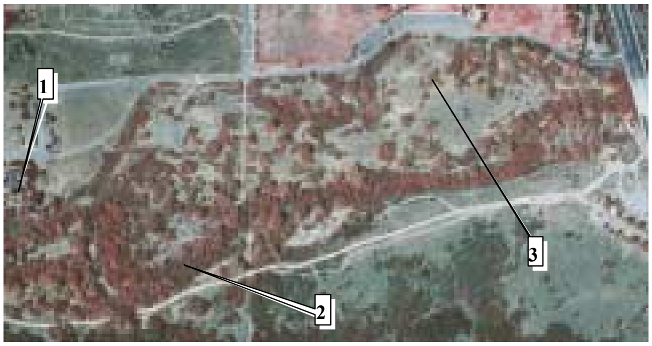


1969

1 - Penasquitos Ranch House

2 - Narrowed channel with riparian vegetation along the margins

3 - Few channels apparent in floodplain



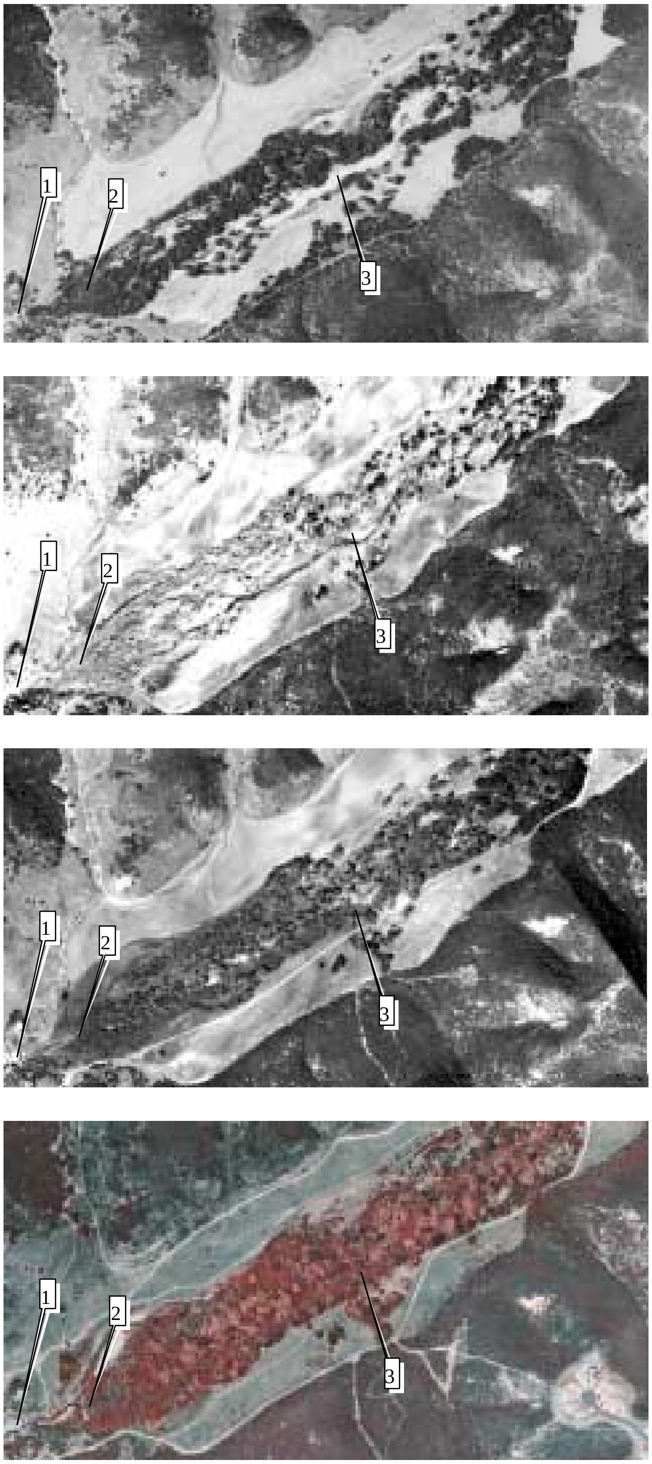
2000

1 - Penasquitos Ranch House

2 - Narrowed channel with dense riparian vegetation

3 - No channels apparent in floodplain

Figure 10. Aerial photographs of a reach of Los Peñasquitos Creek upstream of the Ranch House in 1928, 1945, 1969, and 2000, showing changes in channel features and the distribution of riparian vegetation.



1928

1 - Rock outcropping forming waterfall

2 - Dense vegetation immediately upstream of the rock outcropping

3 - Unvegetated channel

1945

1 - Roack outcropping forming waterfall

2 - Dense vegetation immediately upstream of the rock outcropping

3 - Distinct channel

1969

1 - Rock outcropping forming waterfall

2 - Dense vegetation immediately upstream of the rock outcropping

3 - Completely vegetated channel

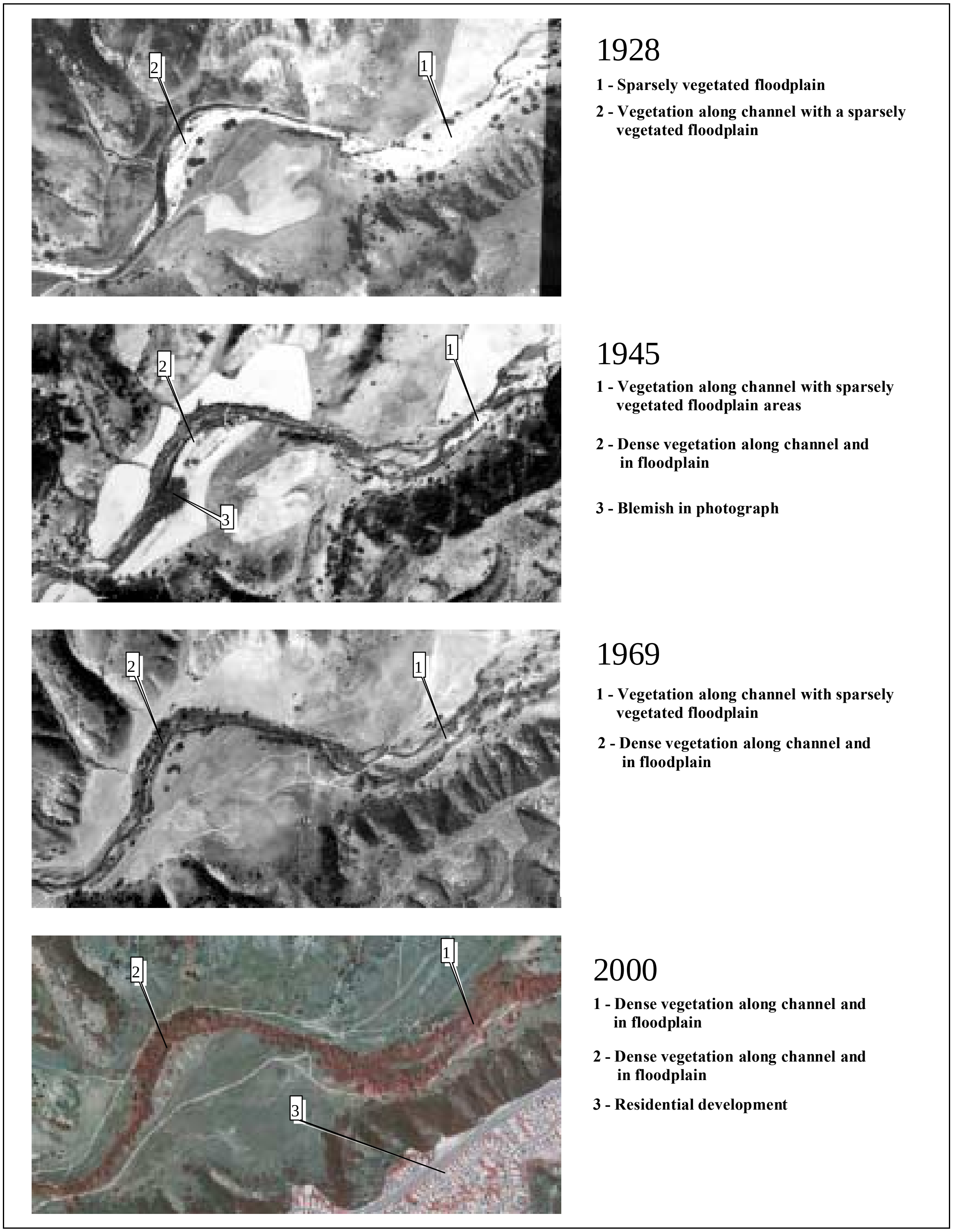
2000

1 - Rock outcropping forming waterfall

2 - Dense vegetation immediately upstream of the rock outcropping

3 - Dense riparian vegetation obscures channel

Figure 11. Aerial photographs of a reach of Los Peñasquitos Creek upstream of the rock outcropping forming the waterfall in 1928, 1945, 1969, and 2000, showing changes in channel features and the distribution of riparian vegetation.



1928

1 - Sparsely vegetated floodplain

2 - Vegetation along channel with a sparsely vegetated floodplain

1945

1 - Vegetation along channel with sparsely vegetated floodplain areas

2 - Dense vegetation along channel and in floodplain

3 - Blemish in photograph

1969

1 - Vegetation along channel with sparsely vegetated floodplain

2 - Dense vegetation along channel and in floodplain

2000

1 - Dense vegetation along channel and in floodplain

2 - Dense vegetation along channel and in floodplain

3 - Residential development

Figure 12. Aerial photographs of a reach of Los Peñasquitos Creek at the western end of the study area in 1928, 1945, 1969, and 2000, showing changes in channel features and the distribution of riparian vegetation.

still visible. In 1945, a distinct narrow channel is visible where the broader open channel was present in 1928, and there is relatively dense riparian vegetation adjacent to the channel. By 1969, riparian vegetation has obscured the channel, but the ground is still visible in a few areas where the vegetation is less dense. In the 2000 photograph, dense vegetation has obscured most of the bare areas visible in 1969.

The eastern portion of the study area appeared to behave in a fashion intermediate between the two other areas discussed above (Figure 12). In 1928, areas of broad, sparsely vegetated channel and floodplain were visible, as was a section of vegetated channel in the downstream portion of the photograph. In 1945, a distinct channel with vegetation along its margin is visible at the upstream end of the photograph, and the vegetation in the downstream end of the photograph has expanded laterally. The 1969 photograph appears very similar to the 1945 photograph, although the area of bare ground is reduced. By 2000, vegetation cover has increased and the area of bare ground has been reduced.

4.0 DISCUSSION

This study documents urbanization-induced changes of the hydrologic characteristics of Los Peñasquitos Creek. Total annual runoff exhibited a significant rising trend for the Los Peñasquitos Creek gage following the termination of sewage effluent discharges in 1972 (Figure 4). A regression analysis of the discharge data for the post-1972 period showed an estimated increase in total runoff of 4% per year. During the same time period, there was no significant trend in rainfall (Figure 5). However, the increase in runoff occurred while the percentage of urbanization in the catchment for the gage rose from 9% to 37% (Figure 2). This estimated increase in runoff is less than results from similar studies in the literature, where increases in runoff from 2-fold to 5-fold in watersheds where percent impervious surface cover exceeds 10% have been reported (Arnold and Gibbons 1996, Paul and Meyer 2001). Although we did not measure impervious cover *per se*, impervious cover has been shown to be associated with residential, industrial, and commercial land uses (Arnold and Gibbons 1996), which we aggregated into the urban land use superclass to represent degree of urbanization in this study.

Urbanization has also been shown to result in increased peak discharges and floods of a given return interval, particularly those with lower return intervals (Hirsch et al. 1990, Leopold 1994, Paul and Meyer 2001). Flood magnitudes in Los Peñasquitos Creek also increased as urbanization in the watershed increased (Figure 7). Bankfull floods fill the stream channel to the top of the bank and are thought to shape and maintain the morphology of stream channels (Leopold 1994). The bankfull flood in Los Peñasquitos Creek has been estimated to occur at a return interval of 1.5-3 years (Prestegaard 1979), which is consistent with other rivers (Leopold 1994). In Los Peñasquitos Creek, floods of return intervals from 1.5-3 years are estimated to have increased by 3.5-fold to over 7-fold (Figure 7) during the period of record. In addition, while changes of maximum average daily discharges over time were not significant (Figure 3), the duration of high discharges increased over time (Figure 8), so that the stream has been subjected to higher discharges a greater proportion of the time with increasing urbanization. Thus, a geomorphic response by the stream channel (enlarging channel volume) to the increasing flows over this time period would be expected.

Anecdotal evidence suggests that some reaches of Los Peñasquitos Creek historically had permanent flow. The San Diego Union (1869) describes substantial springs in the vicinity of the Peñasquitos Ranch House, which flow to this day. Based on records at the gage and historic aerial photographs, however, lower Los Peñasquitos Creek flowed intermittently in many reaches. The results of this study confirm significant changes in dry-season flows in the gage reach of the stream that are associated with treated sewage discharges and increasing urbanization in the watershed. During the period 1965-1972, the influence of live stream discharges of sewage effluent on dry-season base flows are evident in the elevated annual minimum discharges (Figure 3), dry-season runoff (Figure 4), and the duration of low value discharges (Figure 8) relative to later time periods. There were 2 years, 1972 and 1977, where minimum annual flows at the gage fell to zero, but the post-1972 trend in minimum flows increased at a rate of 17% per year. Similarly, dry-season runoff was at its lowest magnitude over the period of record for the gage from 1973-1975; but dry-season runoff increased at a rate of 13% per year with continued urbanization of the watershed. During the period of greatest urbanization from 1988-2000, discharges were greater than 1 cfs 95% of the time, whereas during the period 1973-1987, discharges exceeded or equaled 1 cfs only 43% of the time (Figure 8).

A classic effect of watershed urbanization is a decrease in dry-season baseflow as a result of decreased infiltration of precipitation to groundwater aquifers (Leopold 1994). Several studies have demonstrated that decreased infiltration and consumptive use of groundwater result in decreased dry-season flows (Klein 1979, Medina 1990, Barrenger et al. 1994). However, as recognized by Hirsch et al. (1990) but not well documented in the literature, urbanization can also increase baseflows due to septic system drainage, leaky water or sewage pipes, and irrigation of lawns and landscaping. The latter factor is likely responsible for the increased dry-season flows observed in Los Peñasquitos Creek as watershed urbanization increased. All water used for irrigating urban landscaping within the Los Peñasquitos Creek subwatershed is derived from outside of the subwatershed and, to a large degree, outside of the southern California region. Therefore, any water applied to urban landscaping that is not lost to evaporation or transpiration will eventually move to groundwater aquifers or surface water within the subwatershed, augmenting the natural water budget of the watershed. Dry-season flows in Los Peñasquitos Creek are now permanent, and we project them to continue to increase as development of the watershed proceeds in the future. Urbanization-induced changes in the dry-season hydrologic characteristics of Los Peñasquitos Creek are the most dramatic hydrologic effects we observed in this study.

While geomorphological characteristics of the Los Peñasquitos Creek channel were not measured in this study, changes in channel morphology and associated riparian vegetation distribution were apparent in aerial photographs of the stream. In 1928 and 1945 photographs, portions of the stream channel, particularly at the eastern end of the study area, were relatively broad and braided, whereas by 1969 a distinct incised channel was present. After 1969, the lateral position of the channel in the floodplain appeared to change little, but riparian vegetation adjacent to the channel increased in density. Because significant human land uses (e.g., cattle grazing, agriculture, and wood cutting) occurred in the Los Peñasquitos Creek subwatershed from the late 1800s until 1989 when cattle grazing was terminated, it is unlikely that these land uses were responsible for the differences between pre-1969 conditions and conditions observed in 1969 and later years.

A potential explanation for the apparent changes is that high magnitude flood flows in the years preceding the 1928 and 1945 photographs scoured the channel and floodplain and reduced the distribution of the riparian vegetation community. As stream discharge data are not available prior to 1964, we have reviewed annual rainfall data in the years preceding each photograph used to evaluate riparian vegetation community distribution and channel morphology (Table 4). The 2 years preceding both 1928 and 1945 had annual rainfall totals significantly above the long-term average, implying that the stream may have experienced high magnitude discharges. However, at least 2 other years (1982 and 1996) had annual rainfall totals significantly above the long-term average in the year preceding the year of the photograph, but a scoured channel or floodplain was not visible in these photographs. In fact, dense vegetation lined the channel in both of these years.

Annual rainfall totals may not provide a complete picture of the potential for flood-induced changes caused by large single-storm or successive-storm rainfall events. For example, while the year preceding the 1928 photograph (i.e., 1927) had nearly 15 inches of rain, over 6 inches fell in February. February 14, 1927 had the highest single-day total for the year at 1.84 inches, but an additional 1.73 and 1.48 inches were recorded on February 15 and 16, respectively. However, there were significant single-day rainfall totals preceding the date of photographs taken in later years that do not support flood scour prior to the 1928 and 1945 photographs as an explanation for reduced riparian vegetation cover relative to later photographs. For example, January 14, 1969 totaled 2.01 inches, February 8, 1976 totaled 1.71 inches, March 17, 1982 totaled 2.03 inches, and January 4, 1995 totaled 2.24 inches (representing year prior to the aerial photograph or year of the photograph). While, the assessment of flood scour potential from rainfall events is complicated by both the spatial and temporal patterns of rainfall and the vegetative and geomorphic conditions of the stream channel, rainfall data do not support storm-induced scour events as an explanation for observed changes in riparian vegetation cover in Los Peñasquitos Creek.

Table 4. Annual rainfall totals (inches) in the water years preceding the aerial photographs used to quantify riparian vegetation measured at San Diego Lindbergh Field.

	Water Year Preceding Photograph				
Photo Year	**1**	**2**	**3**	**4**	**5**
1928	14.74	15.70	5.82	5.62	6.39
1945	14.43	11.14	12.68	25.03	8.80
1969	7.87	10.87	14.81	8.81	5.16
1977	10.11	10.62	6.57	10.97	6.22
1982	7.37	15.48	15.28	17.28	9.17
1988	9.25	14.92	9.61	5.40	18.43
1996	17.13	9.93	18.26	12.48	12.33
2000	6.51	17.16	7.74	5.18	17.13

Therefore, while cattle grazing and high magnitude stream discharges do not appear to explain the observed changes in the character of the stream channel, we know that live stream discharge of sewage effluent began in 1962, and we have documented that the Upper Los Peñasquitos Creek subwatershed was 9% urbanized by 1966. Therefore, we suggest that the presence of the distinct low flow channel in all photographs from 1969 to 2000 reflects change in channel geomorphology associated with changes in hydrology from effluent discharges and urban runoff. Furthermore, the hydrologic characteristics associated with the newly formed channel appeared to be conducive to the establishment of riparian vegetation.

Stream hydrologic patterns and fluvial geomorphological processes play an important role in the ecology of riparian vegetation communities (Stromberg 1993, Scott et al. 1996, Scott et al. 1997). Changes in the amount and distribution of the riparian vegetation community appear to be associated with the large urbanization-induced changes in stream discharge characteristics and channel morphology in Los Peñasquitos Creek. The acreage of riparian vegetation in the study area more than doubled from 1928 to 2000 (Table 3 and Figure 9). The increasing acreage was a result of two factors: (1) increasing canopy area from maturing trees and (2) the establishment of new vegetation in areas unoccupied by vegetation in 1928.

Many willow species are recognized as “pioneer species” that are among the first to colonize newly exposed substrates along streams, and, in the Mediterranean climate zones of coastal California, riparian tree species tend to follow a dominance gradient with willows occurring on lower, wetter sites and sycamores and coast live oaks on higher, dryer stream terraces (Walters et al. 1980). In Southern California, sycamores and coast live oaks are reported to dominate intermittent and ephemeral streams, whereas willows dominate the banks of perennial streams (Faber et al. 1989). Along Los Peñasquitos Creek, the majority of new vegetation established along the incised channel present in photographs from 1969-2000 (Figures 10, 11, and 12) rather than in floodplain areas farther from the channel (e.g., Figure 10). Based on field observations, riparian vegetation along the channel is currently dominated by willow species, while oaks and sycamores dominate in floodplain areas farther from the channel. These willow-dominated areas were largely unvegetated in photographs taken prior to 1969, where in most areas an incised stream channel was not visible.

Exceptions to this general pattern were seen in the areas immediately upstream of the rock outcrop forming the waterfall (Figure 11) and at the extreme western portion of the study area (Figure 12). Prestegaard (1979) characterized the reach above the waterfall as an aggrading reach with a relatively wide and shallow channel, whereas the reaches immediately above and below had incised channels. Prestegaard (1979) also suggested that Los Peñasquitos Lagoon, which is approximately 2 miles from the reach of the stream at the extreme western end of the study area, controls the base level of the channel bottom, thereby preventing the channel from incising below this elevation and creating a zone of sediment deposition. Thus, these two areas appear to be sediment depositional areas and may have geological (rock outcrop) and hydraulic (lagoon water surface) features that historically maintained surface flow and relatively high groundwater elevations, which favored the establishment of willow-dominated riparian vegetation communities.

To summarize, increasing urbanization of the Los Peñasquitos Creek subwatershed has been shown to be associated with significant hydrologic changes in the stream, the most obvious of which are increasing peak flood flows and dry-season runoff. These changes appear to have produced an incised stream channel in order to accommodate the increased volume of runoff. Along the newly incised channel, the establishment of willow-dominated riparian vegetation has been facilitated by the modified flow characteristics. The establishment of the willow-dominated community along the incised channel altered the distribution and composition of the riparian vegetation community in the lower Los Peñasquitos Creek subwatershed relative to historic conditions. Prior to the development of the incised channels, sycamores and live oaks dominated the community. In areas where geological and hydrological features form depositional zones and maintain surface flow and high groundwater elevations (e.g., at the falls and downstream end of the study area), willow-dominated communities appear to have been present historically.

While the focus of this study was the riparian vegetation community, many aquatic and riparian-associated wildlife species presumably have been affected by the urbanization-induced changes as well. Unitt (1984) described different bird communities characteristic of willow, sycamore, and live oak-dominated riparian habitats. Various terrestrial insect species are also specific to particular riparian host plants (Emmel and Emmel 1973). In addition, many aquatic species respond directly or indirectly to changes in hydrologic regimes as a result of changes in substrate composition and water quality or the establishment of non-native species, which is often facilitated under the modified hydrologic conditions. Thus, changes in stream hydrologic characteristics and species composition of riparian vegetation communities may potentially affect habitat suitability for riparian-dependent wildlife species.

The stream and riparian communities of many of the coastal drainages in San Diego County evolved under a greatly different set of conditions than exist today. The historic diversity of stream conditions is becoming increasingly diminished as increases in urban runoff transform intermittent and ephemeral drainages into perennial systems with elevated flood discharges. The urbanization-induced hydrologic changes that can alter riparian vegetation communities also likely affect the native ecosystems associated with them. Given that continued watershed urbanization is projected in the future, the current hydrologic characteristics of coastal streams will likely continue to change, and species that are favored under these modified conditions will continue to increase at the expense of those species better suited to historic conditions.

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APPENDIX A

DATA AND ANALYSIS TABLES

Table A-1. Acreage of land uses in the Upper Los Peñasquitos Creek subwatershed over time.

Date	Urban	Graded	Agriculture	Undeveloped
1966	2,555	0	997	23,611
1975	4,285	0	743	22,135
1982	5,395	1,203	793	19,772
1986	5,529	1,542	1,012	19,080
1990	7,890	1,525	1,144	16,605
1992	8,864	2,092	445	15,761
1994	9,257	1,666	445	15,794
1996	9,270	1,624	494	15,776
1999	10,004	1,220	438	15,501

Table A-2. Regression analyses of maximum, median, and minimum annual discharges (Q) during the period of record at the Los Peñasquitos Creek gage (df = degrees of freedom, SS = sums of squares, MS = mean square, F = F statistic).

Maximum Q	***df***	***SS***	***MS***	***F***	***Significance***
Regression	1	4.5×10^5	4.5×10^5	2.8	0.101
Residual	34	5.4×10^6	1.6×10^6		
Total	35	5.9×10^6			
Median Q	***df***	***SS***	***MS***	***F***	***Significance***
Regression	1	18.7	18.7	35.4	9.95×10^{-7}
Residual	34	18.0	0.5		
Total	35	36.8			
Minimum Q	***df***	***SS***	***MS***	***F***	***Significance***
Regression	1	4.3	4.3	38.0	5.24×10^{-7}
Residual	34	3.9	0.1		
Total	35	8.2			

Table A-3. Regression analyses of maximum, median, and minimum annual discharges (Q) during the period of record at the Los Peñasquitos Creek gage (df = degrees of freedom, SS = sums of squares, MS = mean square, F = F statistic).

Maximum Q	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	4.5×10^5	4.5×10^5	2.8	0.101
Residual	34	5.4×10^6	1.6×10^6		
Total	35	5.9×10^6			
Median Q	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	18.7	18.7	35.4	9.95×10^{-7}
Residual	34	18.0	0.5		
Total	35	36.8			
Minimum Q	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	4.3	4.3	38.0	5.24×10^{-7}
Residual	34	3.9	0.1		
Total	35	8.2			

Table A-4. Regression analyses of annual and dry-season runoff during the period 1965-2000 (df = degrees of freedom, SS = sums of squares, MS = mean square, F = F statistic).

Annual	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	3.2×10^8	3.2×10^8	5.8	0.02
Residual	34	1.9×10^9	5.6×10^7		
Total	35	2.2×10^9			
Dry-Season	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	1.4×10^6	1.4×10^6	30.6	3.50×10^{-6}
Residual	34	1.5×10^6	4.4×10^4		
Total	35	2.9×10^6			

Table A-5. Regression analyses of annual and dry-season precipitation measured at San Diego Lindbergh Field during the period 1965-2000 (df = degrees of freedom, SS = sums of squares, MS = mean square, F = F statistic).

Annual	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	1.8	1.8	0.1	0.74
Residual	34	561.3	16.5		
Total	35	563.1			
Dry-Season	*df*	*SS*	*MS*	*F*	*Significance*
Regression	1	0.04	0.04	0.2	0.65
Residual	34	7.0	0.2		
Total	35	7.0			