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IMPACTS OF CLIMATE VARIABILITY AND LAND USE ALTERATIONS ON FREQUENCY DISTRIBUTIONS OF TERRESTRIAL RUNOFF LOADING TO COASTAL WATERS IN SOUTHERN CALIFORNIA[1]

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ABSTRACT: The transport of water, sediment, dissolved and particulate chemicals, and bacteria from coastal watersheds affects the nearshore marine and estuarine waters. In southern California, coastal watersheds deliver water and associated constituents to the nearshore system in discrete pulses. To better understand the pulsed nature of these watersheds, frequency distributions of simulated runoff events are presented for: (1) three land use conditions (1929, 1998, 2050); (2) three time periods (all water years 1989-2002), only El Nino years (1992, 1993, 1995, 1998); and only non-El Nino years; and (3) three regions (watershed, uplands, and lowlands). At the watershed scale, there was a significant increase (>200%) in mean event runoff from 1929 to 2050 (0.4-1.3 cm) due to localized urbanization, which shifted the dominant sources of runoff from the mountains in 1929 (78% of watershed runoff) to the coastal plane for 2050 conditions (51% of watershed runoff). Inter-annual climate variability was strong in the rainfall and runoff frequency distributions, with mean event rainfall and runoff 66 and 60% larger in El Nino relative to non-El Nino years. Combining urbanization and climate variability, 2050 land conditions resulted in El Nino years being five times more likely to produce large (>3.0 cm) runoff events relative to non-El Nino years. Combining frequency distributions of event runoff with regional nutrient export relationships, we show that in El Nino years, one in five events produced runoff ≥2.5 cm and temporary nearshore nitrate and phosphate concentrations of 12 and 1.4 μM, respectively, or approximately 5-10 times above ambient conditions.

(KEY TERMS: climate; event; frequency distribution; nutrients; risk; runoff; urbanization.)

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INTRODUCTION

The delivery of streamflow, which includes sediment, dissolved and particulate chemicals, and bacteria from coastal watersheds occurs in both base flows and discrete pulses of storm runoff. The effect of any one pulse on nearshore and estuarine ecosystems depends on both the magnitude of the pulse and the pattern of its dispersal (Mertes and Warrick, 2001; Warrick *et al.*, 2004). It is possible to reason qualitatively from a hydrological and geomorphological perspective that the relative magnitude of the contributions from storm pulses should be larger for

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particulate constituents than for dissolved load, larger for smaller watersheds, and should depend on the frequency distributions of rainfall characteristics and the condition of the watershed. Transport of particulates and microbes should be further modulated by processes and changes in transiently closed lagoons near the river mouth (Steets and Holden, 2003).

However, it is not straightforward to predict quantitatively the frequency distribution of event runoff that characterizes small, mountainous, chaparral-covered basins in a Mediterranean climate. Nor is it possible to predict from first-order principles, the magnitude of the hydrologic impacts resulting from urbanizing such watersheds or the influence of persistent weather fluctuations such as the El Nino Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO) on this frequency distribution. Monteverdi and Null (1997) showed that El Nino years usually have above-average rainfall in southern California. However, there is an increasing recognition that the response of rainfall and streamflow to the establishment of El Nino is partly contingent on the state of the Pacific Decadal Oscillation (Gershunov *et al.*, 1999; Pizarro and Lall, 2002). In this paper, we consider only the affects of ENSO conditions.

In coastal southern California, there is a clear development pattern: bottom-up, where urbanization begins in the coastal plane, migrates inland and is pushed upward into the mountainous headwaters (Beighley *et al.*, 2003). Numerous efforts have documented the increase in runoff magnitude and degraded water quality due to increasing imperviousness and urban land uses (Leopold, 1968; Dunne and Leopold, 1978; Jennings *et al.*, 1994; Schueler, 1994; Beighley and Moglen, 2002). However, few studies have investigated how the spatial distribution of urbanization within a watershed can shift the dominant source of runoff (e.g., from upland to lowland regions). In coastal southern California, there is a noticeable difference between the upland and lowland ecosystems, specifically, in the riparian corridors (Faber *et al.*, 1989). This difference combined with the basic impacts of urbanization will probably alter the composition of nutrients, sediments, and pollutants delivered to the coastal ecosystem. Currently, the Santa Barbara Coastal-Long Term Ecological Research Project (SBC-LTER) is studying the long-term impacts of changes in terrestrial export caused by climatic and land use changes on giant kelp forests located in the nearshore region. The potential impacts of altered terrestrial export to coastal ecosystems due to changes in the dominant sources of runoff is poorly understood and requires further empirical study to quantify how land surface transformations load the coastal wetlands and ocean with contaminants and nutrients.

In this paper, we have explored the impact of watershed characteristics, transient weather regimes, and land conversion on the frequency distributions of event runoff from coastal watersheds in southern California. We have used a generalized rainfall-runoff model (Beighley *et al.*, 2003), calibrated and then verified against local hydrometric records, to simulate the impacts of land use change (i.e., differences in storm runoff distributions from historical, current and future land use conditions) and interannual climatic variability (i.e., ENSO events) using a recent 14-year precipitation series (October 1, 1988-September 30, 2002). This paper presents: (1) simulated frequency distributions of event runoff for three different land use conditions (1929, 1998, and 2050) in a typical southern California coastal watershed representing three time periods: the complete 14 years of record, El Nino years (1992, 1993, 1995, 1998), and non-El Nino years; (2) a quantitative assessment of the difference in event runoff characteristics for El Nino *vs.* non-El Nino years, predevelopment land use *vs.* postdevelopment land use conditions, and mountainous vs. lowland/coastal lands; and (3) simulated frequency distributions for terrestrial runoff events and the resulting nitrate and phosphate concentration in the nearshore ecosystem along coastal Santa Barbara, California. Our methodology provides a basis for the risk analysis of the terrestrial delivery of nutrients and contaminants to coastal waters.

STUDY LOCATION AND CHARACTERISTICS

Our primary study watershed is drained by Atascadero Creek and its tributaries and is part of the Goleta Slough system, draining the southern coast of California between Goleta and Santa Barbara into the Pacific Ocean (Figures 1 and 2; Table 1). Its topography is representative of coastal watersheds draining into the ocean from the Santa Ynez Mountains (approximately 50 coastal watersheds ranging in size from <10 to $\sim$500 km^2), with mountainous headwaters and mild sloping coastal plane separated by transitional foothills.

The region's Mediterranean climate provides more than 80% of the annual rainfall in winter (Decmber-March). The south sloping orientation of the watershed, the flow of moisture from south-southwest during winter storms, and the steep mountainous terrain contribute to significant orographic precipitation (NOAA, 2001). Based on the data from the County of Santa Barbara rainfall gauge network (CSBCA, 2005), mean annual precipitation over the past

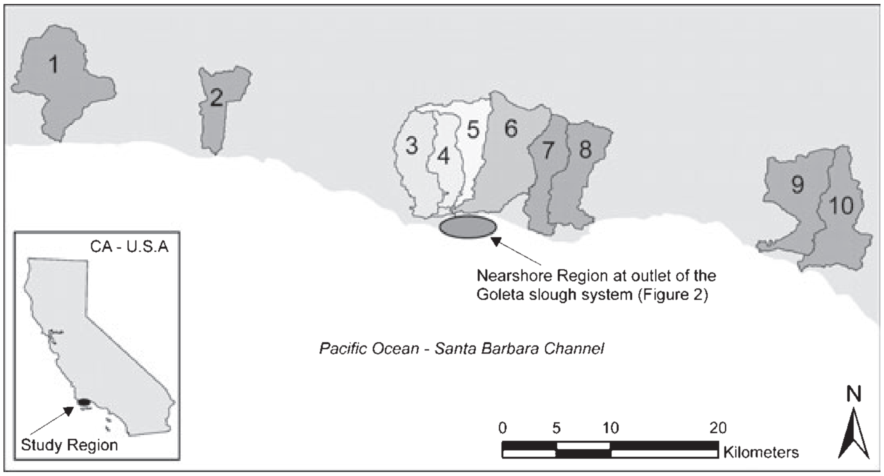

FIGURE 1. Site Map Showing General Location for the Study Region, Watershed Boundaries, and Location of Nearshore Region (see Figure 2 for expanded view of Watersheds 3 to 6).

TABLE 1. Watershed Characteristics and 1998 Land Use Conditions for the Watersheds Shown in Figures 1 and 2.

ID (n/a)	Watershed Name	Area (ha)	Mean Elevation (m)	Relief (m)	Slope (%)	Urban (%)	Agr. (%)	Undeveloped (%)
1	Gaviota	5220	287	850	30	2	0	98
2	Refugio	2080	349	980	28	9	10	81
3	Tecolotito	2930	193	930	19	23	20	57
4	San Pedro	1980	182	870	17	36	17	47
5	San Jose	2300	363	930	26	16	20	64
6	Atascadero	5040	310	1130	23	38	8	54
6-(A)	Watershed	4890	316	1125	25	39	9	52
6-(B)	Uplands	2990	476	1110	34	14	6	80
6-(A-B)	Lowlands	1900	65	330	10	78	14	7
7	Arroyo Burro	2370	306	1195	29	39	7	54
8	Mission	2990	383	1200	26	53	2	45
9	Carpinteria	3850	520	1405	40	5	15	80
10	Rincon	1900	65	330	10	78	14	7

40 years was approximately 50 cm (ranging from 20 to 120 cm) in the coastal plane and 85 cm (30-225 cm) in the mountains corresponding to a mean annual watershed rainfall of 61 cm (ranging from 22 to 156 cm). Based on U.S. Geological Survey streamflow data (USGS, 2005c), mean annual watershed runoff over the past 60 years was approximately 10 cm (ranging from 0.1 to 53 cm).

The 14-year period selected for this study is representative of the long-term variability in rainfall and runoff, with a mean annual watershed rainfall and runoff of 65 cm (ranging from 21 to 145 cm) and 15 cm (ranging from 3 to 50 cm), respectively. El Nino (1992, 1993, 1995, 1998) and non-El Nino years were determined based on an analysis of ocean surface temperature in the tropical Pacific: high/low values of the Bivariate El Niño Southern Oscillation Time series "BEST" Index (Smith and Sardeshmukh, 2000). In general, most of the precipitation and corresponding runoff occurs in only a few large events resulting in high peak discharges and a rapid return to near base-flow conditions (Beighley *et al.*, 2003). For example, a runoff event in March 2001 produced approximately 50 and 90% of the annual export of dissolved and particulate nitrogen, respectively, from Atascadero Creek in 48 hours (Beighley *et al.*, 2004).

The type and spatial distribution of land uses within the watershed are consistent with the region's development pattern: urbanization from Santa Barbara is expanding west towards Goleta and upslope into the foothills. In 1998, the distribution of land use was 38, 8, and 54% urban, agricultural, and undeveloped, respectively (Table 1). Since 1929, urban land area has increased sevenfold and agricultural area has decreased by 70% (Table 2). It is projected that urbanization will continue through 2050 (SBCPD, 2000; CADOF, 2001; Candau, 2002). The spatial distribution

TABLE 2. Land Use Characteristics for Study Watershed: Watershed 6-(A), Uplands 6-(B), and Lowlands 6-(A-B) as Shown in Figure 2.

Land Use Conditions – Spatial Unit	Urban	Agricultural	Undeveloped
1929 – Watershed	5	27	68
1929 – Uplands	2	10	89
1929 – Lowlands	11	55	34
1998 – Watershed	39	9	52
1998 – Uplands	14	6	80
1998 – Lowlands	78	14	7
2050 – Watershed	50	2	48
2050 – Uplands	23	3	74
2050 – Lowlands	93	1	6

of land use is also correlated with the topographic characteristics: mountains are covered with shrub/brush (i.e., chaparral) while the lowlands contains agricultural (i.e., orchards) and urban lands (commercial and low-density to high-density residential).

METHODS

Determining Event Runoff

In southern California, coastal watersheds typically discharge into estuaries, which drain into the Pacific Ocean. Most of these estuaries contain tidal wetlands, and many of them have been degraded by a recent acceleration in sedimentation. Given the Mediterranean climate, streamflow entering the estuaries for much of the year is characterized as base flow, which is minor relative to event flows, and the estuary-ocean exchange is tidally driven. During short, intense runoff events, streamflow overwhelms the estuaries, and freshwater plumes extend into the ocean. Because of the importance of storm-flow quantity and quality entering the estuary and nearshore ecosystems, we focus our efforts on quantifying event runoff characteristics (frequency and magnitude).

In this study, event runoff is determined by separating hourly streamflow series into individual storm events and calculating the watershed runoff (cm) for the storm duration. Given the distinct contrast between storm flow and base flow and the rapid return to near base-flow conditions following a storm, the duration of individual runoff events was determined in a two-step process. Initially, runoff events were defined as starting when discharge exceeded a specified threshold and ending when discharge dropped below the same threshold. For our study watershed, a threshold of 0.1 m^3/s (3.5 cfs) was used. For much of the year, streamflow is near zero. The threshold value was set slightly above what appeared to be daily fluctuations in base flow to filter initial storm flow from daily base-flow variability. To separate back-to-back rainfall and corresponding runoff events that did not drop below the specified threshold, the time between hydrograph peaks was evaluated. If the time between two peaks exceeded 15 hours, then the storms were separated at the time when the later peak began to rise. This process separates continuous periods of high discharge into multi-peaking hydrographs and separate runoff events. The majority of event hydrographs were separated by weeks with peaks returning to near base-flow conditions within 24 hours. The 15-hour separation basis was obtained from manually reviewing multi-peaking hydrographs and used to separate few storms. For example, only 25% of all events were classified as back-to-back, and of the back-to-back events, the mean duration of the leading event was approximately 48 hours. Overall, the selection process was not sensitive to the selected threshold discharge and peak separation duration due to the large magnitude and rapid response time of the event hydrographs.

To determine the event runoff series representing the three land use configurations 1929, 1998, and 2050, the U.S. Army Corps of Engineers' Hydrologic Modeling System (HEC-HMS) model was used to simulate continuous streamflow for the Atascadero Creek watershed using the same 14-year precipitation series from October 1, 1988, to September 30, 2002. HEC-HMS is a lumped parameter model, where the spatial pattern of development is incorporated into the model by subdividing the watershed into subareas that are approximately homogeneous in land use, soil type, slope, etc. (USACE, 2000). For our analysis, the watershed was subdivided into 31 subareas, with a mean model unit area of 1.6 km^2 ranging from 0.2 to 3.3 km^2. The variation in mean subarea elevation (15-900 meters) and ground slope (3-54%) captures the contract between the mountainous headwaters and coastal plane. The selected loss model was "initial loss, constant rate," where runoff is generated under two conditions: (1) the soil storage reservoir is full and the rainfall rate exceeds the infiltration rate, or (2) rainfall occurs on impervious area. The kinematic wave methodology was used for routing overland and channel flow.

Model parameters were largely obtained from the spatial analysis and processing of a 30-meter Digital Elevation Model (DEM) (USGS, 2005a), known stream locations (USGS, 2005b), Soil Survey Geographic Database (NRCS, 2005), and varying land use datasets. The DEM was processed to obtain flow directions and the corresponding drainage network and watershed boundaries using ArcGIS 9.1. Spatial watershed characteristics were obtained by overlaying the derived boundaries on the land use and soils datasets. The 1929 land use was obtained by scanning aerial photographs and hand digitizing the watershed into three categories: agricultural, urban, and undeveloped (Beighley *et al.*, 2003). The 1998 land use was also developed using aerial photographs and hand digitizing, but land uses were based on the Anderson Level III categories (Anderson *et al.*, 1976). As described in Candau (2002), the projected 2050 land use coverage was determined using the SLEUTH model, a modified cellular automaton urban growth model named for the input data used to initialize the model: Slope, Land Use, Exclusion, Urban, Transportation, and Hillshade and described by Clarke and Hoppen (1997). Beighley *et al.* (2003) provided a detailed description of the model parameterization, calibration, and assessment processes.

Event Runoff Analysis

For consistency, the discharge series generated with the 2050 land use conditions was used to define the maximum time window for each runoff event. The 2050 land use conditions (most urban scenario) resulted in event runoff starting earlier (i.e., less initial losses) and ending later (lower constant loss rate) relative to both the 1929 and 1998 conditions. Using the discharge series most impacted by urbanization provided the most extreme variations between storm flow and base flow, and thus simplified the runoff event separation process. Using the time windows obtained from analyzing the 2050 runoff series, hourly runoff values for each event simulated with 1929, 1998, and 2050 conditions were obtained. Because the 1929 and 1998 events were selected based on the 2050 durations, the exact event duration for these events is unknown. In this work, only event runoff volume was required. Based on a preliminary assessment, the event durations for 1929 and 1998 conditions were the same or shorter by only a few hours relative to the 2050 events.

For the 14-year period, 240 storm events were selected. The mean number of events per year was 17 ranging from 9 to 25. In El Nino years, the average number was 21 events per year, and non-El Nino years included an average of 16 events per year. For the 2050 conditions, the mean storm-flow event duration was 48 hours ranging from 6 hours to 5 days. The longer events were verified as being periods of relatively consistent rainfall with intermittent periods of intense rainfall. While it is possible that separate storm systems continued to pass over the region, their short separation intervals caused the hydrograph to remain well above flood level. In terms of our research focus, the pulsed loading of water and associated constituents to the ocean, these long durations represent extended periods of significant export that must be accommodated by the nearshore and estuary systems and were retained in our analysis. Using the specified duration for each event, runoff was calculated for all storms under the three land use conditions and for three physiographic settings: whole watershed, mountains, and coastal plane (Figure 2 and Table 2). This process resulted in a total of nine event runoff series: 1929, 1998, and 2050 for each of the three landscape regions.

Terrestrial Export of Nutrients

Building on the runoff frequency analysis, it is possible to combine relationships between event runoff (cm) and event nutrient export (kg/ha) to evaluate the risk of a given runoff event resulting in degraded water quality (i.e., nutrient concentrations exceeding a specific threshold) in known water volumes (i.e., estuary, lagoons, and/or nearshore region). In this study, we relate event runoff to nitrate and phosphate concentration in the nearshore region at the mouth of the Goleta Slough near Santa Barbara (Figures 1 and 2). The Goleta Slough receives streamflow from four watersheds: Atascadero, San Jose, San Pedro and Tecolitito Creeks, with a combined

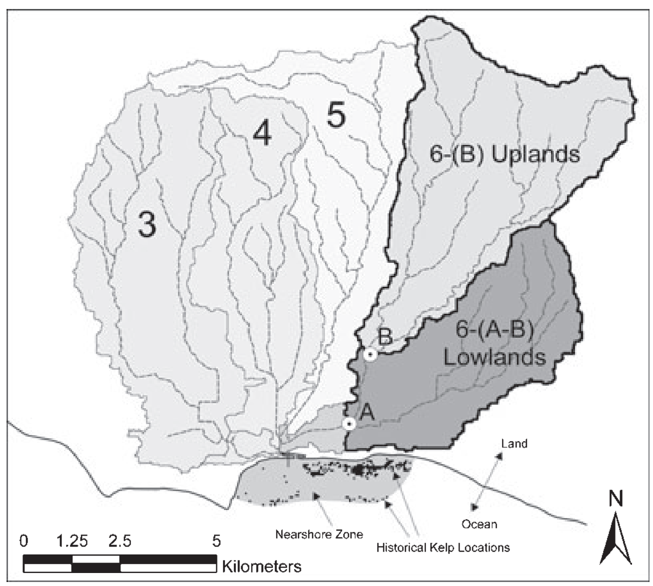

FIGURE 2. Goleta Slough Drainage System With Contributing Watershed Boundaries (IDs 3-6) and Near-Shore Zone Highlighted in Gray; Historical Kelp Locations Shown in Black; and the Study Watershed: Atascadero Creek (ID 6), Where the Land Draining to Point *A* Represents the Watershed Region (6-A), Land Draining Point *B* Represents Upland Region (6-B), and Land Draining to Point *A* Minus Land Draining to Point *B* Represents Lowland Region (6-[A-B]); Refer to Table 1 for Watershed Characteristics.

drainage area of 12,300 ha (47.5 mi^2); Table 1 lists general watershed characteristics.

At the outlet of the Goleta Slough system, the following assumptions were made to define the nearshore receiving volume. The extent of the nearshore ecosystem was defined by historical kelp forests located within approximately 1 km of the coastline, extending 5 km along the shore, and having an average depth of 5 meters ranging from 0 to 10 meters (Figure 2). This approximation, which is only intended to illustrate the applicability of our work, is generally supported by Warrick *et al.* (2004, 2005) who found a significant drop in terrestrial plume concentrations within 1 km of the shore and below depths of 2-8 meters. Given the importance of defining the receiving water volume, the SBC-LTER is actively investigating this issue through stream, ocean, and nearshore event sampling and modeling. For the purpose of this paper, we also assumed that the nearshore region retains the freshwater plume for the duration of the runoff event prior to mixing with the surrounding waters, which is reasonable given the relatively short event durations with export highly concentrated for only a few hours. Based on the above assumption, the total volume of the nearshore region was approximated as 25×10^6 m^3. The hydrodynamics of freshwater plumes mixing in the nearshore zone are complex, poorly understood, and beyond the scope of this paper. In this paper, we assumed the freshwater plume was mixed with ambient ocean waters within the nearshore volume. Based on the results of Warrick *et al.* (2005), we assumed that ambient ocean nitrate and phosphorous concentrations were approximately 2 and 0.25 μM, respectively.

Next, regression-based relationships between nitrate and phosphate export (kg/ha) and event runoff (cm) were developed using water quality data collected by the SBC-LTER in water years 2001-2005 from seven coastal watersheds: Gaviota, Refugio, Atascadero, Arroyo Burro, Mission, Carpinteria, and Rincon Creeks (Figure 1 and Table 1). These relationships were then combined with the derived runoff frequencies, the assumed nearshore water volume, and mixed with ambient ocean waters to develop frequency distributions for nearshore nitrate and phosphate concentrations due to terrestrial event runoff.

RESULTS AND DISCUSSION

Defining the Sources of Runoff

The overall goal of this study was to quantify the impacts of varied climatic, land use, and physiographic conditions on the frequency distribution of event runoff. While it is useful for management purposes to quantify the frequency distribution of event runoff at a watershed's outlet to the coastline, knowing the frequency distributions for both upland (mountains) and lowland (coastal plane) areas provides a better understanding of the risk associated with the potential delivery of bacteria, nutrients, and sediments to the ocean from different parts of the landscape. For example, the bulk of nutrients delivered to the ocean originate from the agricultural and urban lands in the coastal plane and not from the undeveloped mountainous lands (Beighley *et al.*, 2004; Robinson *et al.*, 2005).

To generate runoff event characteristics for the three physiographic regions (watershed, mountains, and coastal plane), simulation results for points A and B in Figure 2 were used. Watershed runoff was determined as the total runoff draining to point A. The mountainous or upland runoff was obtained from the total runoff draining to point B. The coastal plane or lowland runoff was determined by separating the upland runoff fraction from the watershed runoff by subtracting the flow at point B from the flow at point A. Tables 1 and 2 provide landscape characteristics for these regions (watershed, upland, and lowland).

Spatial Distribution of Event Rainfall for Varied Climate Conditions

Table 3 lists the 14-year rainfall statistics, and Figure 3 shows the frequency distributions of rainfall for the three physiographic regions. At the watershed scale, the mean event rainfall for all storms over the 14-year period was 3.6 cm ranging from 3.0 cm in non-El Nino years to 4.9 cm in El Nino years (1992, 1993, 1995, 1998). These findings are consistent with other studies (Monteverdi and Null, 1997) that showed El Nino years usually have above-average rainfall in southern California.

Comparing the difference in mean (2.9 *vs.* 4.2 cm) and maximum (33 *vs.* 48 cm) event rainfall between the lowlands and uplands highlights the importance of quantifying the orographic enhancement of runoff response, which is a significant complication because of the sparseness of rainfall measurements and the limited calibrations of radar rainfall monitoring systems. For example, mean event rainfall over the 14-year period was 1.3 cm (46%) larger in uplands relative to the lowlands. There was also a noticeable difference in event rainfall between non-El Nino and El Nino years. For example, mean event rainfall was 2.0 cm (66%) larger in El Nino years relative to non-El Nino years at the watershed scale.

TABLE 3. Simulation Results for Study Watersheds: Watershed 6-(A), Uplands 6-(B), and Lowlands 6-(A-B) as Shown in Figure 2, Where *P* Is Event Rainfall, *Q* Is Event Runoff, and *Q*:*P* Is the Event Runoff-Rainfall Ratio.

		Watershed		**Uplands**		**Lowlands**	
Land Use Conditions – Period	**Hydrologic Quantity**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**
N/A – All years	*P* (cm)	3.6	42	4.2	48	2.9	33
N/A – Non-El Nino years	*P* (cm)	3.0	24	3.4	28	2.3	18
N/A – El Nino years	*P* (cm)	4.9	42	5.7	48	3.9	33
1929 – All years	*Q* (cm)	0.4	14	0.5	19	0.2	7.0
1929 – Non-El Nino years	*Q* (cm)	0.2	5.7	0.3	8.3	0.1	2.0
1929 – El Nino years	*Q* (cm)	0.8	14	1.1	19	0.5	7.0
1998 – All years	*Q* (cm)	0.9	19	0.7	20	1.2	16
1998 – Non-El Nino years	*Q* (cm)	0.6	8.7	0.4	9.2	0.9	7.9
1998 – El Nino years	*Q* (cm)	1.4	19	1.2	20	1.7	16
2050 – All years	*Q* (cm)	1.3	22	1.0	23	1.6	20
2050 – Non-El Nino years	*Q* (cm)	0.9	11	0.6	12	1.2	10
2050 – El Nino years	*Q* (cm)	2.0	22	1.7	23	2.5	20
1929 – All years	*Q*:*P* (cm/cm)	0.06	0.61	0.06	0.77	0.05	0.40
1929 – Non-El Nino years	*Q*:*P* (cm/cm)	0.04	0.37	0.04	0.48	0.04	0.15
1929 – El Nino years	*Q*:*P* (cm/cm)	0.09	0.61	0.10	0.77	0.08	0.40
1998 – All years	*Q*:*P* (cm/cm)	0.20	0.73	0.09	0.79	0.38	0.76
1998 – Non-El Nino years	*Q*:*P* (cm/cm)	0.18	0.49	0.07	0.51	0.37	0.76
1998 – El Nino years	*Q*:*P* (cm/cm)	0.24	0.73	0.13	0.79	0.40	0.71
2050 – All years	*Q*:*P* (cm/cm)	0.33	0.82	0.19	0.84	0.57	0.90
2050 – Non-El Nino years	*Q*:*P* (cm/cm)	0.30	0.60	0.17	0.57	0.56	0.89
2050 – El Nino years	*Q*:*P* (cm/cm)	0.38	0.82	0.24	0.84	0.59	0.90

Combining both climatic and physiographic conditions, Figure 3 shows that the frequency of a rainfall event exceeding 4 cm ranges from 15% in a non-El Nino year in the lowlands to 44% (~1 in 2 events) in an El Nino year in the uplands. For large events (>10 cm), the frequency ranges from 3 to 16%. At the watershed-scale, the mean event rainfall exceeded 4 cm in approximately one in four storms selected as producing separable storm flow, with only one in ten storms exceeding 10 cm. The 4-cm threshold of rainfall is referenced because on average 4 cm of rainfall yields 1 cm of runoff based on the mean watershed event runoff-rainfall ratio of approximately 0.25 for the 14-year dataset with current land use conditions.

Effects of Climate Variations on Runoff

The effect of climate variability on runoff was driven by the spatial distribution of rainfall and contrast between El Nino and non-El Nino years described above. For 1998 conditions, the mean event runoff for the watershed, uplands, and lowlands was 0.6, 0.4, and 0.9 cm in non-El Nino years and 1.4, 1.2, and 1.7 cm in El Nino years, respectively. For the watershed, runoff events were 60% larger in El Nino relative to non-El Nino years. In terms of event frequency, events were more frequency in El Nino relative to non-El Nino years. The largest range in event frequency was for events exceeding 1 cm: 53% (one in two events) from the lowlands in El Nino years compared with only 6% (1 in 16 events) from the uplands in non-El Nino years. The watershed dampened this variability resulting in 33% of events exceeding 1 cm in El Nino years and 11% in non-El Nino years. For large events (>3 cm), the patterns are similar but the events are less frequent. At the watershed, the frequency of a runoff event exceeding 3 cm was 11% (one in nine events) in El Nino years and 3% (1 in 40 events) in non-El Nino years; nine events in the four El Nino years relative to only four events in the ten non-El Nino years.

Effects of Urbanization on Runoff

The mean event runoff for predevelopment (1929), recent development (1998) and future development (2050) conditions at the watershed scale was 0.4, 0.9, and 1.3 cm over the 14-year periods, respectively (Table 3). Thus, there was a 200% increase in event runoff from 1929 to 2050. Comparing the two extremes (1929 and 2050), this increase was primarily due to changes at the local scale, where the localized urbanization increased lowlands runoff from 0.2 cm in 1929 to 1.6 cm in 2050. In terms of relative magnitude, the localized increase in runoff due to urbanization was four times greater in the lowlands relative to the uplands. For example, mean event runoff from the uplands doubled between 1929 and 2050 (0.5-1.0 cm), while the lowlands experienced a 600% increase. The larger relative increase in runoff

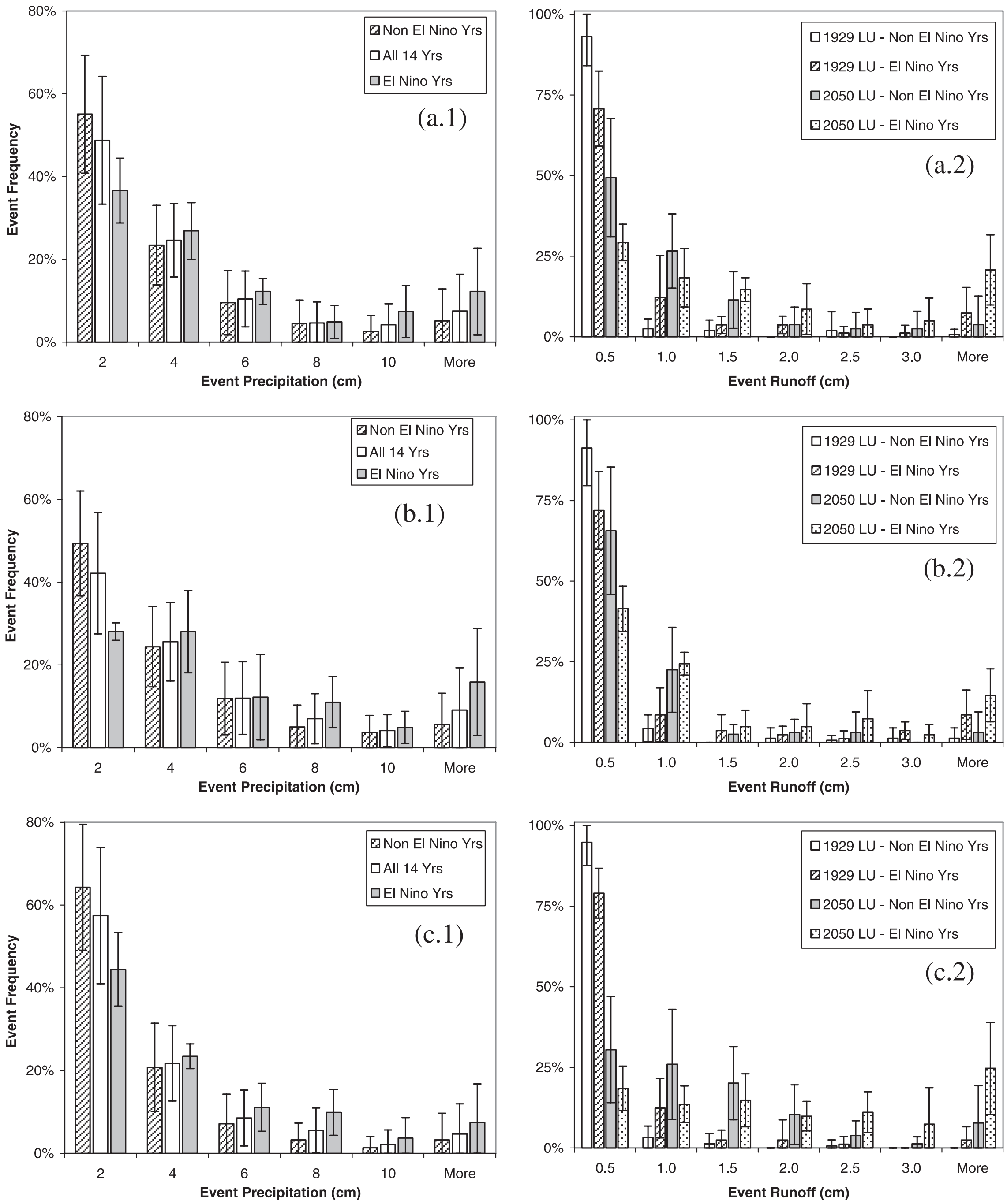

FIGURE 3. Frequency of Event Precipitation (1) and Runoff (2) for the Three Regions: (a) Watershed, (b) Uplands, and (c) Lowlands, Shown in Figure 2, Where Vertical Error Bars Represent One Standard Deviation of the Event Frequencies From Each Year.

from the lowlands was due the high concentration of total watershed development in the coastal plane, which was only 5% urban in 1929 and expected to be 50% urbanized by 2050 (Table 2).

The change in the spatial distribution of runoff production can be summarized by two key points: (1) the mean event runoff from the coastal plane for the projected 2050 land use conditions (1.6 cm) is approximately six times larger than in 1929 (0.2 cm) and (2) there is a shift in the dominant source of event runoff leaving the watershed from the uplands in 1929 to the lowlands for projected 2050 conditions. For example, the uplands (61% of the watershed drainage area) produced on average 78% of a given runoff event in 1929 but only 49% for 2050 conditions. Thus, there is a fundamental change in the dominant mechanisms and pathways of storm runoff, with 1929 conditions producing mostly interflow and infiltration excess runoff from undeveloped mountainous lands (Beighley *et al.*, 2005) and 2050 conditions resulting in mostly impervious surface runoff from the highly urbanized coastal plane. This shift is due to the regional development pattern, which has tended to concentrated significant development in the lands closest to the ocean. The localized urbanization near the watershed outlet compounds the impacts of increased runoff from the coastal plane because of the relatively short flowpath lengths to the estuary and nearshore ecosystems. These short flowpaths result in little nutrient uptake, storage or attenuation prior to entering the coastal ecosystem.

In terms of the frequency of small events (>1 cm), there were large differences for upland *vs.* lowland and predevelopment *vs.* future development conditions. In the uplands, the frequency of a runoff event exceeding 1 cm increased from 10% (one in ten events) for 1929 conditions to 19% (one in five events) in 2050. In the lowlands, the frequency of a runoff event exceeding 1 cm increased from 4% (1 in 24 events) for 1929 conditions to 52% (one in two events) in 2050. Relative to the frequency of small events, large events (>3 cm) were less likely, especially for 1929 conditions in the uplands. In the uplands, the frequency of a runoff event exceeding 3 cm increased from 1% (1 in 100 events) for 1929 conditions to 14% (one in seven events) in 2050. In the lowlands, the frequency increased from 4% (1 in 27 events) for 1929 conditions to 7% (1 in 14 events) in 2050. In terms of the number of larger events (>3 cm) from the watershed over the 14-year period, there were seven events for 1929 conditions compared with 23 events in 2050.

Effects of Combined Climate Variations and Urbanization on Runoff

The mean event runoff for predevelopment (1929), recent development (1998), and future development (2050) conditions at the watershed scale was 0.2, 0.6, and 0.9 cm in non-El Nino years and 0.8, 1.4, and 2.0 cm in El Nino years, respectively. As shown for the 14-year period, the impact of coastal development on runoff was significant. This change was further amplified when comparing changes in event runoff in non-El Nino years. Comparing 1929 and 2050 land use conditions, lowlands runoff increased from 0.1 to 1.2 cm (~11× increase) in non-El Nino years and from 0.5 to 2.5 cm (~4× increase) in El Nino years.

Figure 3 shows the frequency of a runoff event exceeding a given value in both El Nino and non-El Nino years. For the predevelopment conditions in 1929, the distribution of event runoff was similar for both upland and lowland regions in both El Nino and non-El Nino years. The vast majority of storms yielded <1 cm of runoff with the right tail of the distribution strongly skewed. As the watershed urbanized, the coastal plane received a disproportionately high percentage of the development, resulting in a significant difference in the runoff distributions from the upland and lowland regions. In the lowlands, the frequency of a runoff event exceeding 1 cm increased from 9% (1 in 11 events) for 1929 conditions to 68% (two of three events) for 2050 conditions in El Nino years and from 2 to 44% in non-El Nino years. However, the large change in runoff frequency from the coastal plane (i.e., lowlands) was muted at the watershed outlet when combined with the less impacted upland contributions. At the outlet, the frequency of a runoff event exceeding 1 cm increased from 17% (one in six events) for 1929 conditions to 52% (one in two events) for 2050 conditions in El Nino years and from 4 to 24% in non-El Nino years.

For large events (runoff >3 cm), the effects of climate conditions was largest in the uplands. For example, the frequency of an event exceeding 3 cm for 1929 conditions was 1% in non-El Nino years and increased to 9% in El Nino years (i.e., 8× increase). Similarly, for 2050 conditions, there was a 4× increase in El Nino years. In the lowlands, in the increase in the frequency of large events in El Nino relative to non-El Nino years was only about 2× for both 1929 (1-3%) and 2050 (8-25%) conditions. This difference was primarily due to the spatial distribution of rainfall (Figure 3). At the watershed scale for 2050 conditions, large events were approximately five times more likely in El Nino years (one in five events) relative to non-El Nino years (1 in 26 events). For predevelopment (1929) conditions, large events were approximately 11 times more likely in El Nino and non-El Nino years, with <1 in 100 events resulting in more then 3 cm of runoff in non-El Nino years. In terms of the number of events at the watershed outlet, 1929 conditions resulted in six events in the four El Nino years compared with only one event in the ten non-El Nino years. For 2050 conditions, the number of events in the four El Nino and ten non-El Nino years increased to 17 (~4 per year) and 6 (~1 per 2 years), respectively.

Effects of Combined Climate Variations and Urbanization on Event Runoff-Rainfall Ratios

In addition to understanding how runoff changes with climate variations and urbanization, it is useful to characterize the change in event runoff-rainfall ratios, which can be used to assess the impacts of future climate scenarios on runoff. For the 1929 conditions, the mean watershed event runoff-rainfall ratio was 6% over the 14-year period ranging from 9% in El Nino years to 4% in non-El Nino years. For 2050 conditions, the mean event ratio increased to 33%.

For 1929 conditions, the watershed was nearly homogeneous in terms of urbanization, which allows us to compare the fundamental differences between rainfall and runoff in the coastal plane and mountains. The uplands have relatively thin soils, steep slopes, and receive more rainfall relative to the lowlands. Thus, the two regions have very different hydrologic characteristics. However, the event runoff-rainfall ratios were similar (Table 3), with average ratios in uplands and lowlands of 6 and 5%, respectively, for 1929 conditions over the 14-year period. Given that the two regions convert a similar fraction of rainfall to runoff in the absence of urbanization, we combined the results from all three regions to assess the impacts of urbanization on event runoff-rainfall ratios. Figure 4 illustrates the variation of event runoff-rainfall ratio in relation to the percentage of urban area. Until urban land area exceeded approximately 10%, the natural runoff processes yielded on average approximately 5% of the rainfall. Above 10% urbanization, each 1% increase in urban land use resulted in approximately 0.6% increase in event runoff-rainfall ratio. The 0.6 factor is likely due to the impervious fraction of the urban land, which are mostly a mix of medium-density to high-density residential and commercial. These land uses generally are found to contain approximately 40 to 80% impervious area (Haan *et al.*, 1994).

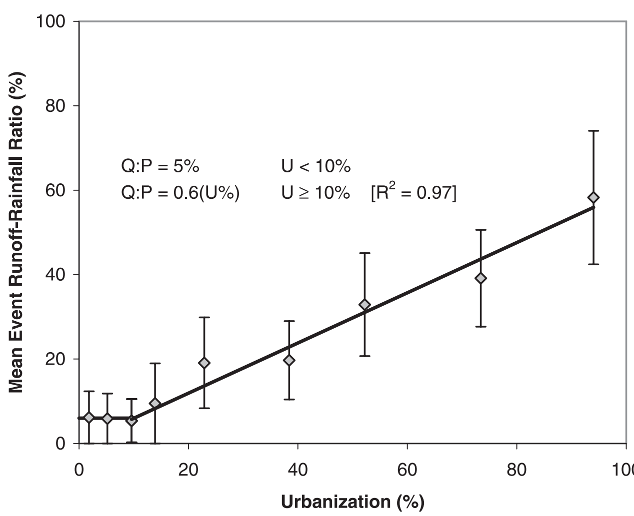

FIGURE 4. Relationship Between Mean Event Runoff-Rainfall Ratios and Urbanization for the Atascadero Creek Watershed Developed Using Simulated Results From 1929, 1998, and 2050 Land Use Conditions; Vertical Error Bars Represent One Standard Deviation for the Simulated Event Ratios.

Comparison Between Event Rainfall and Runoff Distributions

The pattern of rainfall was the dominant signal in the streamflow series. However, the distribution of event runoff shows a greater tendency towards smaller events. For example, at the watershed scale, the skewness of event rainfall was 3.6 compared with 5.5, 6.2, and 7.1 for the event runoff from 2050, 1998, and 1929 land use conditions, respectively. The difference between the rainfall and runoff frequency distributions was primarily due to pre-storm soil moisture conditions, which affects the ability of the watershed to absorb significant rainfall at the onset of the rainy season prior to the generation of appreciable runoff. The importance of initial conditions in the generation of runoff from nonimpervious surfaces was also reflected in the skewness of the runoff distributions, with the predevelopment (1929) conditions resulting in the larges skewness or greatest tendency towards smaller events.

Terrestrial Export to Nearshore Waters

The SBC-LTER sampled approximately 82 events between 2001 and 2005 from seven watersheds: Gaviota, Refugio, Atascadero, Arroyo Burro, Mission, Carpinteria, and Rincon (Table 1 and Figure 1). The sampling was performed a temporal resolution (i.e., hourly on rising limb and ~3-4 hours on the falling limb) sufficient to quantify event export for nitrate and phosphate. Figure 5 shows the relationship between event runoff and nutrient export based on these 82 events. For consistency with the frequency distributions discussed previously, the analysis was limited to events resulting in at least 0.5 cm of runoff (i.e., ~12 events per watershed). The event export relationships for nitrate and phosphate were $N = 0.11Q$ and $P = 0.03Q$ where N and P represent nutrient yield (kg/ha) and Q is event runoff (cm). It should be noted that the presented relationships do not reflect the eventual limitation of available nutrients for export due to the range of available event data (i.e., limitations not observed for range of events sampled).

Given the similarity urban and agricultural land uses in the Goleta Slough drainage areas and the SBC-LTER sample watersheds, the relationships in Figure 5 were used to approximate the nitrate and phosphate export from the Goleta Slough to the ocean for given runoff events. Combining drainage areas,

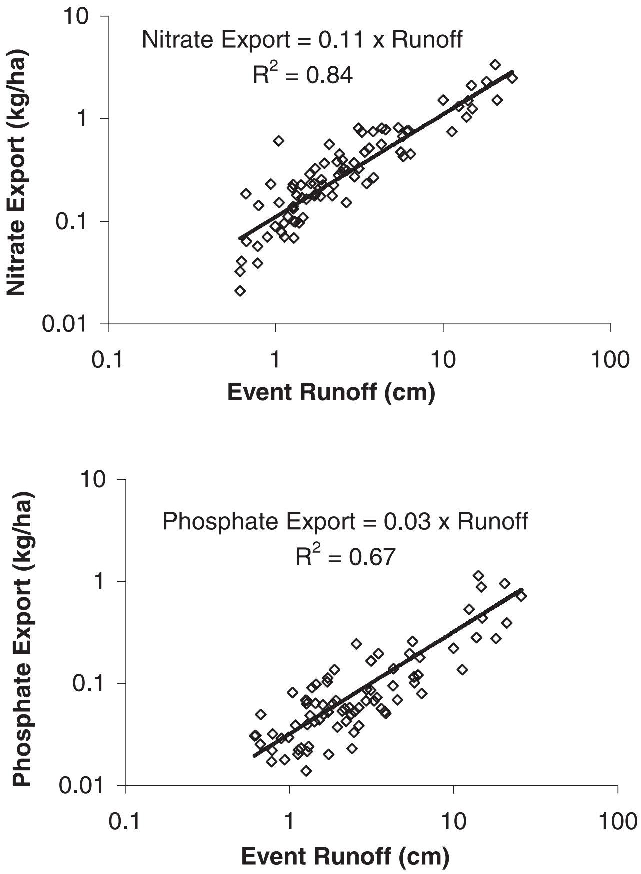

FIGURE 5. Nitrate and Phosphate Export (kg/ha) in Response to Event Runoff From Coastal Watersheds in Southern Santa Barbara County (for period 2001-2005; event runoff >0.5 cm; watershed area >1500 ha; n = 85; from watersheds listed in Table 1: Gaviota, Refugio, Atascadero, Arroyo Burro, Mission, Carpinteria, and Rincon).

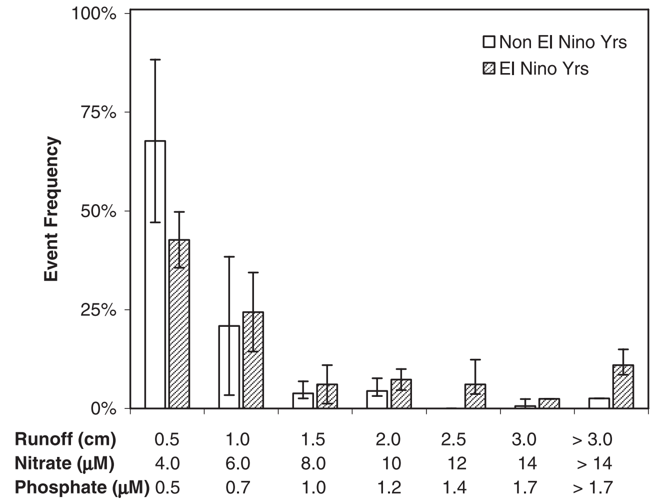

FIGURE 6. Frequency Distributions for Event Runoff (cm) and Resulting Short-Term Nitrate and Phosphate Concentrations (μM) in the Nearshore Region Shown in Figures 1 and 2, Where Vertical Error Bars Represent One Standard Deviation of the Event Frequencies From Each Year.

export relationships, runoff frequencies, nearshore water volume, ambient ocean N and P concentrations ($\sim$2 and 0.25 μM), and assumed mixing method, Figure 6 shows the probability of a runoff event resulting in specific nearshore nitrate and phosphate concentrations. For example, the frequency of a storm event, which produces runoff $\geq$2.5 cm (1 inch) and a nearshore nitrate concentration greater than 12 μM (μM/l) and phosphate concentration greater than 1.4 μM ranges from 3% in non-El Nino years to 20% in El Nino years. These results show that in El Nino years approximately one in five storm events (or $\sim$3 in each El Nino year) would have increased the nearshore nitrate and phosphate concentrations $\sim$5-10 times above ambient conditions. These approximations are consistent with ocean nitrate concentrations (8-12 μM) obtained from sampling terrestrial event runoff plumes 1-3 km offshore between 1997 and 1998 in the Santa Barbara Channel (Warrick *et al.*, 2005). The main point of Figure 6 is to illustrate how both the magnitude and frequency of terrestrial export events impact short-term constituent loading to nearshore kelp forests and beaches.

CONCLUSIONS

In southern California, coastal watersheds deliver water and associated constituents to the nearshore marine and estuarine waters in discrete pulses. To better understand these systems, it is critical to quantify the impacts of urbanization and climate variability on these runoff pulses or events. In this paper, a rainfall-runoff model was used to simulate the impacts of urbanization and inter-annual climatic variability on the distribution of event runoff from the Atascadero Creek watershed using a 14-year precipitation series (October 1, 1988-August 31, 2002). Simulated event runoff frequency distributions were presented for the following: land use conditions (1929, 1998, and 2050), weather sequences (complete 14 years period, El Nino [1992, 1993, 1995, 1998], and non-El Nino years), and regions (watershed, uplands, and lowlands).

The two primary drivers of runoff variability in this effort were rainfall and land use conditions. The spatial distribution of rainfall reflected the topographic gradient in the watershed. In general, event rainfall was 46% larger in the mountains relative to the coastal plane. Climate conditions contributed additional variability with the mean rainfall event in El Nino years approximately 66% larger than in non-El Nino years. Over the 14-year period, one in four rainfall events, which resulted in detectable runoff, exceeded 4 cm. These rainfall patterns were also reflected in the event runoff series. Mean event runoff was 60% larger in El Nino relative to non-El Nino years. For large runoff events (>3 cm), there were nine events in the four El Nino years relative to only four events in the ten non-El Nino years.

In terms of urbanization, there was a 200% increase in the mean event runoff from the watershed between 1929 and 2050 conditions, due to concentrated development in the coastal plane. This localized urbanization resulted a 600% increase in mean event runoff from the coastal plane, which shifted the dominant source of watershed runoff from the mountains in 1929 (78% of the watershed runoff) to the coastal plane for 2050 conditions (51% of the watershed runoff). Urbanization also affected the number of large runoff events from the watershed. Using the 14-year climate series, predevelopment conditions resulted in only seven runoff events >3 cm compared with 23 event for 2050 conditions (>200% increase). When combining both urbanization and climate variability, event runoff from the coastal plane in non-El Nino years was most affected, increasing by 11× (0.1-1.2 cm) from 1929 to 2050 conditions. At the watershed scale, the full range of variability is evident when comparing the frequency of large runoff events (>3 cm) in non-El Nino years for 1929 conditions (1% or 1 in 100 events) to El Nino years for 2050 conditions (20% or one in five events). Looking at both rainfall and runoff, the mean event runoff-rainfall ratio increased by approximately 0.6% for each 1% increase in urbanization, which reflects the impervious fraction of the added urban lands: medium- density to high-density residential. Overall, the mean event runoff-rainfall ratio increased from 6% for 1920 conditions to 33% for 2050.

To illustrate the potential usefulness of event runoff frequency distributions, this paper combines frequency distributions of event runoff with regional relationships for nutrient export to estimate the risk of elevated nitrate and phosphate concentrations in the nearshore ecosystem, near Santa Barbara. For the study site, runoff events ≥ 2.5 cm (1.0 in) had an occurrence frequency of 20% (one in five events) in El Nino years and resulted in a temporary nearshore nitrate and phosphate concentration of 12 and 1.4 μM, respectively, which equates to approximately ~5-10 times above ambient conditions. In non-El Nino years, the frequency decreased to only 3% (1 in 32 events).

While this study focuses on nitrate and phosphate, the methodology provides a basis for a risk analysis of the delivery of contaminants to the nearshore region. Given sufficient resources, it may also be possible to develop similar relationships for sediments, bacteria or metals enabling one to assess the risk of a given runoff event resulting in coastal water quality measures exceeding specified limits that may represent human health dangers. Regardless of the index measures, this study highlights an approach that land use planners and managers can use to assess the potential impacts of land use change or climate variability on coastal water quality following storm events. The approach can also be used to assess the potential frequency of beach closures for either current or future land use and climate conditions.

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