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Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River

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Abstract

The Santa Clara River delivers nutrient rich runoff to the eastern Santa Barbara Channel during brief (~1–3 day) episodic events. Using both river and oceanographic measurements, we evaluate river loading and dispersal of dissolved macronutrients (silicate, inorganic N and P) and comment on the biological implications of these nutrient contributions. Both river and ocean observations suggest that river nutrient concentrations are inversely related to river flow rates. Land use is suggested to influence these concentrations, since runoff from a subwatershed with substantial agriculture and urban areas had much higher nitrate than runoff from a wooded subwatershed. During runoff events, river nutrients were observed to conservatively mix into the buoyant, surface plume immediately seaward of the Santa Clara River mouth. Dispersal of these river nutrients extended 10s of km into the channel. Growth of phytoplankton and nutrient uptake was low during our observations (1–3 days following runoff), presumably due to the very low light levels resulting from high turbidity. However, nutrient quality of runoff (Si:N:P = 16:5:1) was found to be significantly different than upwelling inputs (13:10:1), which may influence different algal responses once sediments settle. Evaluation of total river nitrate loads suggests that most of the annual river nutrient fluxes to the ocean occur during the brief winter flooding events. Wet winters (such as El Niño) contribute nutrients at rates approximately an order-of-magnitude greater than "average" winters. Although total river nitrate delivery is considerably less than that supplied by upwelling, the timing and location of these types of events are very different, with river discharge (upwelling) occurring predominantly in the winter (summer) and in the eastern (western) channel.

Keywords: river nutrients; nitrate; Santa Clara River; Santa Barbara Channel; California

1. Introduction

Eastern boundary upwelling regions are very productive coastal ecosystems due to the introduction of nutrients from depth (Summerhayes et al., 1995; Hill et al., 1998). River nutrient inputs are generally ignored in these regions since these contributions are assumed to be small compared to upwelling and other sources of vertical mixing. However, river discharge can influence coastal water biogeochemistry and primary production especially near river mouths (Drinkwater and Frank, 1994; Smith and Hitchcock, 1994). For example, the Columbia River is known to influence ocean concentrations of nutrients and chlorophyll for 100s of km from the river mouth (Stefansson and Richards, 1963; Hobson, 1966; Pruter and Alverson, 1972). Further, historic changes in river discharge quantity or qualities have forced significant changes to other coastal ecosystems (Humborg et al., 1997; Chen, 2000; NRC, 2000; Schilman et al., 2001; Scrivner et al., 2004).

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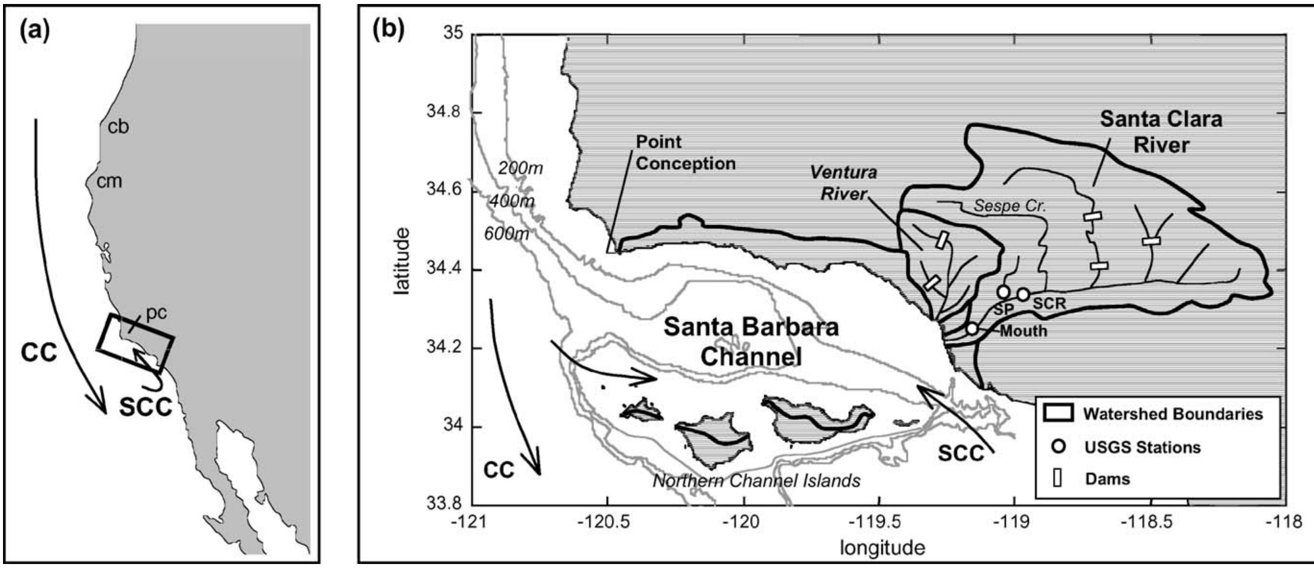

Fig. 1. (a) A generalized map of the California Current (CC) and the Southern California Countercurrent (SCC) of the northeastern Pacific Ocean. Also identified are Cape Blanco (cb), Cape Mendocino (cm) and Point Conception (pc). The rectangle shows the area shown in (b). (b) The Santa Barbara Channel and rivers discharging directly into the channel. Three USGS river gauging sites utilized in this work are identified with circles and include 'SCR' (USGS 11113300, Santa Clara River near Santa Paula), 'SP' (USGS 11113500, Santa Paula Creek near Santa Paula), 'Mouth' (USGS 11114000, Santa Clara River at Montalvo).

The Santa Barbara Channel (Fig. 1) has a unique eastern boundary coastal setting, because it receives inputs from both nutrient-rich and nutrient-depleted circulation sources and ephemeral terrestrial runoff. Upwelled California Current waters can enter the western Santa Barbara Channel along the Northern Channel Islands (Fig. 1b), which promotes primary productivity in the western portion of the channel (Dugdale and Wilkerson, 1989). The eastern Santa Barbara Channel generally receives water from the Southern California Countercurrent (Fig. 1), which transports warmer waters poleward through the Southern California Bight (Hickey, 1998). These warmer countercurrent waters have low concentrations of macronutrients and are therefore less productive than the recently upwelled waters of the western channel. Hence, the average circulation patterns suggest that the Santa Barbara Channel should have greater productivity in the western, upwelling-dominated section than in the eastern, countercurrent dominated section.

Satellite ocean color observations of Santa Barbara Channel reveal that chlorophyll pigments are greatest in the western and central sections of the channel especially following upwelling conditions (Otero and Siegel, in press), which is consistent with the inferred productivity patterns described above. These SeaWiFS remote sensing observations, however, also reveal consistently high chlorophyll in the eastern channel extending 5–10 km from the shoreline throughout the year. If these ocean color observations are accurately portraying chlorophyll patterns, nutrient sources in the eastern channel are required to support this algal biomass.

Here we evaluate the influence of river discharge, which occurs dominantly in the eastern channel (Fig. 1b), on the spatial and temporal distribution of macronutrients (silicate and inorganic N and P) and chlorophyll pigments in the Santa Barbara Channel. This work focuses on the Santa Clara River, since it the dominant source of discharge to the Channel. Our data show that the Santa Clara River does introduce a significant source of nutrients to the channel, especially during the winter season. Although these contributions are significantly less than upwelling inputs to the channel, they are highly pulsed and supply nutrients in significantly different proportions and at different times of the year compared to upwelling.

1.1. Study area

The Santa Barbara Channel is the northernmost ocean basin of the Southern California Bight and generally receives inputs from the California Current (CC) on its western boundary and the Southern California Countercurrent (SCC) on its eastern boundary. Circulation through and within the Santa Barbara Channel, however, is complex and dynamic, as it responds to both regional alongshore pressure gradients and local wind stresses (Harms and Winant, 1998; Chen and Wang, 2000; Oey et al., 2001). Surface currents are commonly cyclonic within the channel, especially during the spring and summer. During periods of intense upwelling wind stresses, circulation can be equatorward in both the western and eastern ends of the channel, and during periods of wind relaxation, currents can be strongly poleward.

The CC is dominated by upwelling especially from late spring to early fall, which enriches the surface waters in macronutrients and enhances primary productivity (Hickey, 1998). Coastal headlands along the CC tend to increase upwelling rates and encourage coastal jets that transport surface waters offshore. One such headland system exists near Point Conception at the western end of the Santa Barbara Channel (Fig. 1a) where high rates of upwelling occur both due to the headland and especially strong wind stresses (Dugdale et al., 1997; Dorman and Winant, 2000). The intensity of this upwelling is influenced by El Niño/La Niña cycles (Chavez et al., 2002) and has increased somewhat during the past 50 years due to increasing wind stresses (Schwing and Mendelssohn, 1997).

Although upwelled waters are replete in macronutrients, recent work suggests that primary production rates in the CC can be seasonally and/or geographically limited by the micronutrient iron (Hutchins et al., 1998; Johnson et al., 1999). Iron is largely supplied to the CC from continental-shelf sediments and is generally more abundant in regions with broad shelves than regions with narrow shelves (Bruland et al., 2001). Iron concentrations vary widely in the CC, however, and diverse biologic and biogeochemical responses can be expected from somewhat subtle levels of this iron limitation (Hutchins et al., 1998).

Domoic acid producing toxic algal blooms are also known to occur in the surface waters of the CC, although no coupling processes with upwelling or other mechanisms have been identified to date (Trainer et al., 1998). In light of this, nutrients from river discharge have been shown to influence red tide bloom dynamics in southern California and may influence blooms of other harmful algae (Kudela and Cochlan, 2000).

The Santa Barbara Channel receives river discharge from approximately 6000 km^2 of mainland and Channel Island drainage area as shown in Fig. 1b. The Santa Clara River is the major drainage to the channel, as it incorporates 71% of total watershed area and discharges over 50% of the annual average fresh water to the channel (Warrick, 2002). Another major drainage is the Ventura River (Fig. 1b), which incorporates 9.8% of the total watershed area and discharges approximately 20% of the annual discharge. The remaining 19% of the watershed area is represented by numerous, small (10–50 km^2) drainages of the mainland and Channel Islands, which on average are cumulatively responsible for $<30\%$ of discharge.

River discharge in the study area is ephemeral with the majority occurring after brief, intense winter rainstorms. This produces an average flow–duration relationship in which over half of the water runoff occurs in $<1\%$ of the time (on average, ~ 3 days/year; Warrick, 2002). Further, during much of the year ($\sim 70\%$ of the year on average) the Santa Clara River has negligible discharge, which is characteristic of the warm, dry conditions of summer and early fall, when coastal upwelling is greatest. Annual variability of discharge is also high largely due to the location of the Jet Stream and tropical precipitation sources related to El Niño processes (Mo and Higgins, 1998). Wet, El Niño years can have appreciably more discharge ($500–1000 \times 10^6\ m^3\ yr^{-1}$) than dry, La Niña years ($<10 \times 10^6\ m^3\ yr^{-1}$), although not all El Niño years are associated with large floods (Inman and Jenkins, 1999).

The focus of this work is the large Santa Clara River, since it is the single largest source of river discharge to the channel ($>50\%$). Discharge generated within the Santa Clara River basin is derived from a number of sources. Most (88%) of the Santa Clara River watershed is native chaparral or woodland (oak and pine), while the remaining area is represented by agriculture (4.2%), urban (3.1%), barren (2.7%) and grassland (2.0%) (Warrick, 2002). The agricultural and urban areas are concentrated along the long, east–west running mainstem river channel (Fig. 1b) and near the river mouth.

Discharge from the Santa Clara River enters the eastern end of the Santa Barbara Channel. Initial dispersal of river water during stormwater events occurs in a well-defined jet, which is strongly influenced by river discharge inertia (Warrick et al., 2004b). This jet-like structure encourages rapid mixing with ambient coastal waters immediately upon discharge as suggested by Fischer et al. (1979) and observed by Warrick et al. (2004b). A conceptual model for water and sediment dispersal from the Santa Clara River was developed by Warrick et al. (2004a), which shows that sediment rapidly settles from the river plume, while fresh water mixes into surface waters and is advected by river discharge inertia, ocean currents and winds stresses. The effect of Coriolis on these plumes is generally negligible when compared to the strong forcing from the river, ocean and atmosphere.

Since the mouths of the Santa Clara and Ventura Rivers are only 7-km apart, these river waters can mix when discharged into the eastern Santa Barbara Channel (Warrick et al., 2004a). Unfortunately, no river nutrient sampling has been conducted on the Ventura River, which prevents calculations of nutrient fluxes from this river. However, since the two large rivers have similar runoff and land use patterns (Warrick, 2002), it is assumed that nutrient production rates in these landscapes are somewhat comparable. Although we focused our oceanographic observations on the Santa Clara River plume, we cannot assume that our observations were not influenced (if only slightly) by the Ventura River, as discussed below.

Table 1
Summary of USGS stream sampling for the Santa Clara River sites (see Fig. 1b for site locations)

Site	SCR	SP	Mouth
USGS station	11113300	11113500	11114000
USGS name	Santa Clara River near Santa Paula	Santa Paula Creek near Santa Paula	Santa Clara River at Saticoy
Watershed type	Mixed	Natural	Mixed
Percent of total runoff	~80%	~10%	~100%
Dates of Sampling	1966–1979	1966–1992	1969
H_4SiO_4			
Number of samples	0	16	4
Mean (µM)	n.a.	495	230
Range (µM)	n.a.	345–676	221–246
NO_3			
Number of samples	73	46	4
Mean (µM)	193	42	84
Range (µM)	1–386	1–177	55–132

Natural = chapparal and woodland. Mixed = mixed land use including natural, urban and agriculture.

2. Methods

Dissolved river nutrient fluxes were assessed with both river sampling data from the United States Geological Survey (USGS) and shipboard river plume observations in the Santa Barbara Channel. The USGS sampling is summarized from three sites within the Santa Clara River (Fig. 1b; Table 1). The site that best represents the discharge at the river mouth (labeled 'Mouth'; Fig. 1b) unfortunately had very little data (only four samples taken during very high discharge). Therefore, we included the two other monitoring sites, an upstream Santa Clara River mainstem site (SCR) and a small tributary, Santa Paula Creek (SP; Fig. 1b) to supplement the river mouth data. Below we show that the combination of SP and SCR represents a reasonable surrogate for nutrient concentrations at the river mouth.

Although nearly adjacent, the two sites (SP and SCR) have different land use and discharge patterns. On average the SP drainage produces ~10% of the total runoff volume measured at the mouth due to its small drainage basin area (Warrick, 2002). Further, the SP drainage is almost entirely chaparral and woodland, which is denoted with a "natural" watershed type in Table 1. In contrast, ~80% of the total discharge volume measured at the river mouth flows past the SCR site (the remaining ~10% of the total discharge is generated in the lowest portion of the watershed between SCR and the river mouth, which has mixed chaparral, agricultural and urban land uses; Warrick, 2002). Most of the water at SCR is derived from the relatively pristine Sespe Creek, although this water is mixed with runoff from the agricultural and urban areas along the Santa Clara River mainstem. Thus, the SCR basin is denoted with a "mixed" watershed type (Table 1).

River sampling and analyses were conducted by the USGS during both base-flow and storm-flow conditions between 1966 and 1992 (Table 1), with most (98%) of the sampling being conducted in the 1960s and 1970s. Although these data are somewhat dated, the land use conditions within the Santa Clara watershed (described above) have not changed significantly during this period (Warrick, 2002). Further, we show below that the historical river data compare well with our recent observations from the river plume, which suggests somewhat steady nutrient production rates. Methods and techniques of USGS river nutrient sampling and analysis are summarized in Ward and Harr (1990) and Fishman and Friedman (1989). In general, water grab samples are obtained from the center of flow (i.e., the thalweg) and processed by colorimetric techniques to determine reactive silicate and one or more of the following: total dissolved nitrate (rare), total dissolved nitrite (common), and/or total dissolved nitrate + nitrite (most common). Since dissolved nitrite was found to be very little of the total dissolved nitrate + nitrite (<5% for all samples), the nitrate and nitrate + nitrite results were combined for this work and are henceforth termed "nitrate". Ammonium–nitrogen was only measured twice at the SP site, and it was found to be 5–10% of the total dissolved inorganic nitrogen. Since inadequate data exist to quantify it, ammonium is not considered in this work. However, as we point out below ammonium cannot be ruled out as an important nitrogen source, especially during the summer. USGS sampling data were obtained from annual USGS water quality reports (e.g., USGS, 1971) and an online data source (USGS, 2001).

Shipboard sampling was conducted in the coastal waters off the river mouth during three separate multi-day cruises (1997 Plume, 1998 Plume and 1998 Low-Flow; Fig. 2). Total water discharge prior to the three cruises varied by many orders-of-magnitude (Table 2 and Fig. 3). The two plume cruises were conducted during and immediately after significant runoff events in the Santa Clara River. The 1997 Plume cruise was conducted following an event that was approximately an "annual event" (defined to be the 2.3-year recurrence interval flood) that peaked at 460 $m^3 s^{-1}$, whereas the 1998 Plume cruise followed a much larger, ~10-year recurrence interval event of ~3000 $m^3 s^{-1}$ that coincided with strong El Niño conditions. This high instantaneous flow rate was estimated from flow rates at other upstream and regional stream gauges (see Warrick et al., 2004a), since only the daily average flow rate was available for 1998. The 1998 Low-Flow cruise followed typical dry summer conditions with negligible river discharge of <1 $m^3 s^{-1}$.

Ocean water sampling was conducted with a Sea-Bird Electronics SBE32C compact carousel equipped with 12 electronically triggered 8-L Niskin bottles. Also included on the carousel were an SBE 911*plus* CTD, a Sea-Tech 660-nm beam transmissometer with a 25-cm path

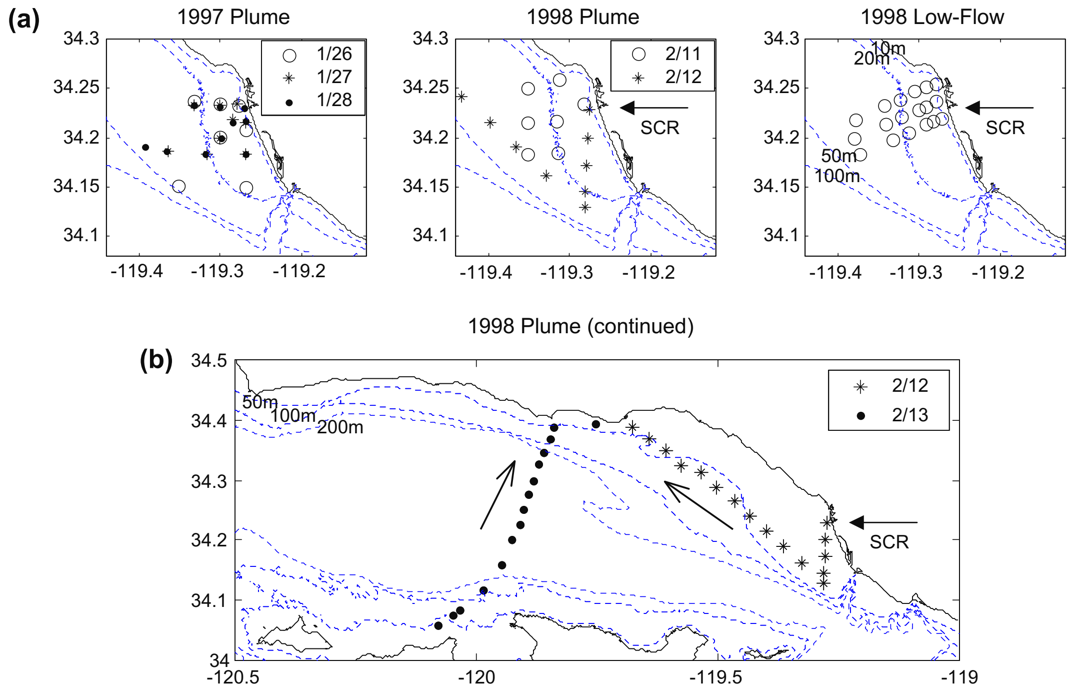

Fig. 2. Shipboard sampling stations in the Santa Barbara Channel. In each figure the Santa Clara River mouth (SCR) is identified with a large arrow. (a) Sampling stations near the river mouth during the three cruises: 1997 Plume, 1998 Plume, and 1998 Low-Flow. (b) Mid-channel stations from the 1998 Plume cruise during days 2 and 3. Large arrows indicate the direction of sampling on each day.

length, and a Sea-Tech chlorophyll fluorometer. Water samples were taken at the surface (0.5–1.5 m depth) and at 2–10 m increments depending on total water depth and the thickness of the surface and bottom plumes at each site. Nutrient samples (20 mL) were obtained and frozen immediately at sea for laboratory analysis using flow injection techniques at the UCSB Marine Science Institute Analytical Lab (see http://www.msi.ucsb.edu/ANALAB/ANALABtexts/Services/Nutrient). Here we present results for nitrate + nitrite (nitrite was always <5% of total), silicate, and phosphate. Chlorophyll analyses were conducted in duplicate by filtering 200-mL (per sample) of seawater on 25-mm Millipore GF/F filters at sea. Filters were immediately frozen in liquid nitrogen and analyzed on land using standard fluorometric procedures using a Turner Designs 10AU Digital Fluorometer. Chlorophyll measurements were only obtained during the 1998 Plume cruise and the 1998 Low-Flow cruise. Lastly, particulate silica (PSi) was analyzed by filtering 630 mL of seawater through a 0.6-μm polycarbonate membrane filter and using the NaOH/HF digestion methods of Brzezinski and Nelson (1989). PSi concentrations in the river plume were dominantly lithogenic material (>95%), which can be converted into sediment concentrations using an average clay mineralogy for the Santa Barbara Channel (110 $g\,mol^{-1}$ Si; Warrick et al., 2004a). PSi results are discussed thoroughly in Warrick et al. (2004a) and are shown here to compare with chlorophyll results.

Unfortunately, at the end of the first day of the 1998 Plume cruise (February 11, 1998) the ship's winch malfunctioned. For the following two days (February 12–13), sampling was conducted only in the water surface by lowering a single 8-L Niskin bottle into the water and manually triggering it closed. Instruments on the carousel (CTD, transmissometer, fluorometer) were not used. Sampling on these two days was conducted throughout the Santa Barbara Channel (Fig. 2b) to characterize the wide spread plume conditions following the large 1998 flooding event.

Table 2
Characteristics of Santa Clara River discharge for shipboard observation events

	Cruise		
	1997 Plume	1998 Plume	1998 Low-Flow
Shipboard sampling dates	Jan. 26–28	Feb. 11–13	Oct. 13
Number of samples			
Surface	25	37	12
Total	105	59	44
Peak river flow rate	460 $m^3\,s^{-1}$ (1/26/97)	~3000 $m^3\,s^{-1}$[a] (2/8/98)	0.5 $m^3\,s^{-1}$ (10/11/98)
Approximate event recurrence interval	2.2 years	~10 years	NA
Total water discharge[b]	$25 \times 10^6\,m^3$	$130 \times 10^6\,m^3$	$0.1 \times 10^6\,m^3$

[a] Peak discharge rate estimated from daily average runoff (see text).
[b] For the event periods defined by January 25–27, 1997, February 6–11, 1998, and October 8–13, 1998.

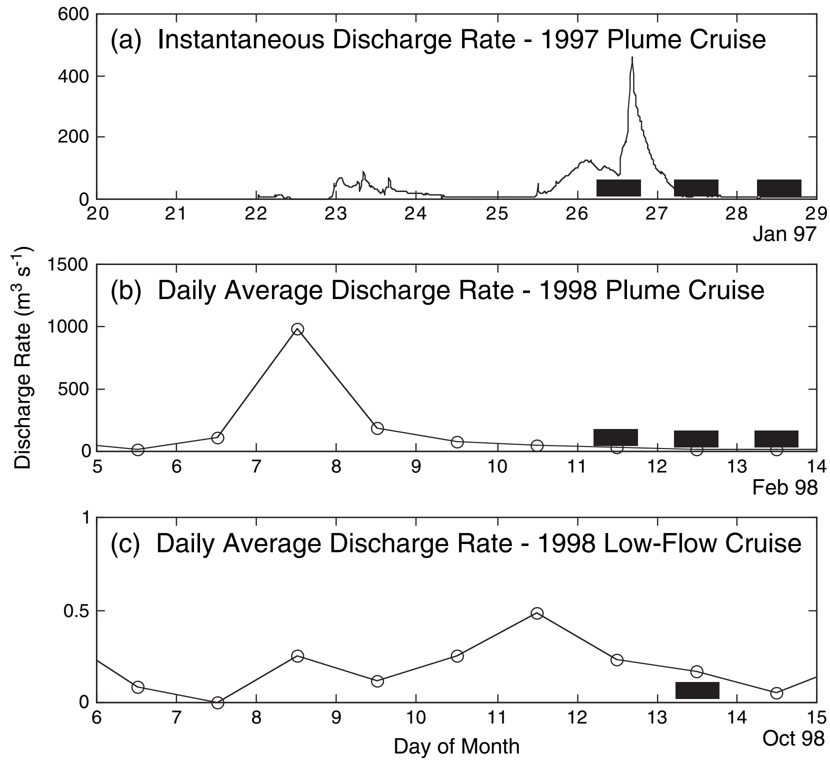

Fig. 3. Discharge from the Santa Clara River prior to and during the three cruises. Cruise times are shown with black bars. Note that discharge scales are different and flow variability over a day can be high. (a) 1997 Plume Cruise; (b) 1998 Plume Cruise; (c) 1998 Low-Flow Cruise.

3. Results

3.1. River discharge

The relationships between nutrient concentrations and river discharge for the USGS sampling sites are shown in Fig. 4. Nitrate concentrations are highly variable among the three sites. During low discharge rates ($<10\ m^3\ s^{-1}$) the "mixed" land use SCR station consistently had higher nitrate concentrations than the "natural" SP station (Fig. 4a). This pattern can also be observed in the average measured nitrate concentrations, which were over four times greater at SCR (193 μM) than at SP (42 μM; Table 1). However, the nitrate concentrations at SCR were inversely related to river discharge, whereas nitrate at SP increased somewhat with discharge. Best-fit logarithmic relationships for the SCR and SP data had moderate to poor correlation ($r^2 = 0.49$ and 0.26, respectively). At higher flow rates ($>10\ m^3\ s^{-1}$) the SCR and SP nitrate concentrations converge somewhat in the 0–200 μM range. Nitrate concentrations at the river mouth (Mouth) during very high river discharge rates ($>100\ m^3\ s^{-1}$) range over 50–150 μM with an apparent decreasing trend with discharge.

Since the runoff from SCR and SP will mix prior to discharging into the ocean, the effect of this mixing on nitrate concentrations was estimated by using the average

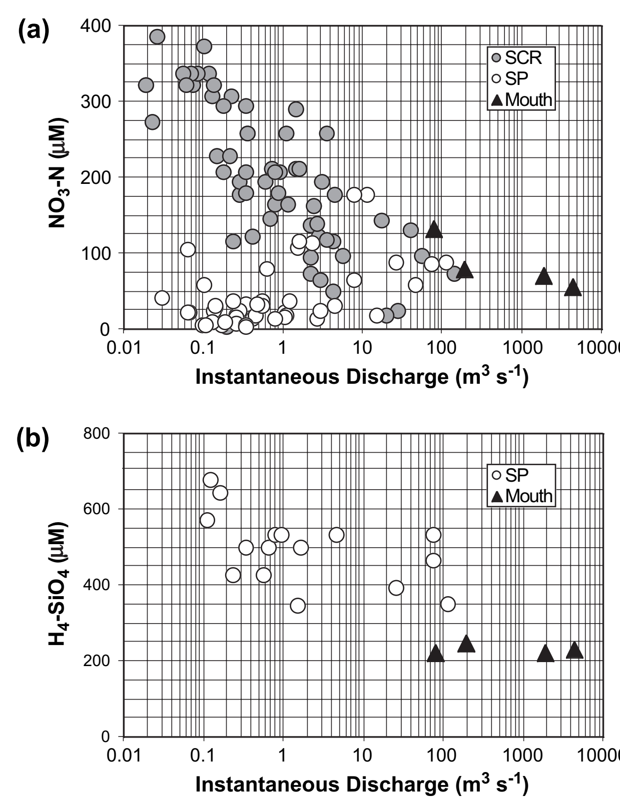

Fig. 4. Santa Clara River nutrient–discharge relationships from the USGS gauging stations (see Fig. 1 for station locations). (a) Nitrate. (b) Silicic Acid.

runoff rates from each tributary (80% and 10% of total river runoff, discussed above). Thus, if the mouth was discharging at 100 $m^3 s^{-1}$, then on average $\sim$80 $m^3 s^{-1}$ was produced from SCR and $\sim$10 $m^3 s^{-1}$ was produced from SP assuming negligible flood wave attenuation and similar flow response timing. Using this framework, the SCR and SP nitrate observations were binned into four orders-of-magnitude discharge rates for the river mouth (0.01–0.1 through 10–100 $m^3 s^{-1}$) and averaged using mean flow-weighting. These estimates of the mixed nitrate concentrations are plotted along with actual Mouth measurements in Fig. 5. Flow-weighted mixing of SCR and SP (labeled 'SCR + SP' in Fig. 5) produces nitrate concentrations that are inversely related to discharge. Further, the measurements at the Mouth station are within a standard deviation of the mixing results for the highest SCR + SP discharge rates, which suggests that the combination of SCR and SP is a reasonable surrogate for the discharge conditions at the river mouth. If the lowest portion of the watershed, which is not included in the SCR + SP results, is assumed to produce nutrients responses like SCR, the total SCR + SP flow-weighted nitrate concentrations would increase by 11–12%.

Much less data exist for river silicate concentrations (Fig. 4b). Data from the "natural" SP site show that silicate concentrations drop slightly with increasing discharge ($r^2 = 0.26$, logarithmic relationship). The Mouth station concentrations are approximately 200–250 μM during very high river runoff (> 100 $m^3 s^{-1}$). Thus, if the limited silicate data can be assumed to represent nutrient contributions from the remaining Santa Clara River watershed, somewhat decreasing concentrations with discharge are predicted, as found for nitrate.

3.2. Ocean plume observations

Fresh water and nutrients from the Santa Clara River altered the physical and chemical structure of the coastal surface waters, especially in the upper water column and near the river mouth. A summary of the water quality conditions with respect to depth shows that most of the freshened plume water is limited to the upper 8 m of the water column during the two plume cruises (Fig. 6a and c). These surface water plumes consistently had sharp ($\sim$1-m thick) salinity interfaces at 2–8 m depth, and plumes were thickest immediately off the river mouth and thinned with distance from the mouth (raw CTD data shown in Warrick, 2002). Below 8-m depth, salinity was much more uniform, although slight salinity increases were observed with depth during both 1997 and 1998 Plume cruises. The range in reduced salinities (i.e., the reduction of salinity from the ambient seawater salinity) during both plume cruises (0–4 pss) represent approximately 0–12% freshening of the seawater. Hence, the freshest coastal plumes represent a mixture of 1 part river water and 8 parts seawater. It is not unusual for a small, mountainous river like the Santa Clara to mix quickly within 1–3 km of the mouth, especially since the dynamics of the plume are initially dominated by river inertia, which will encourage

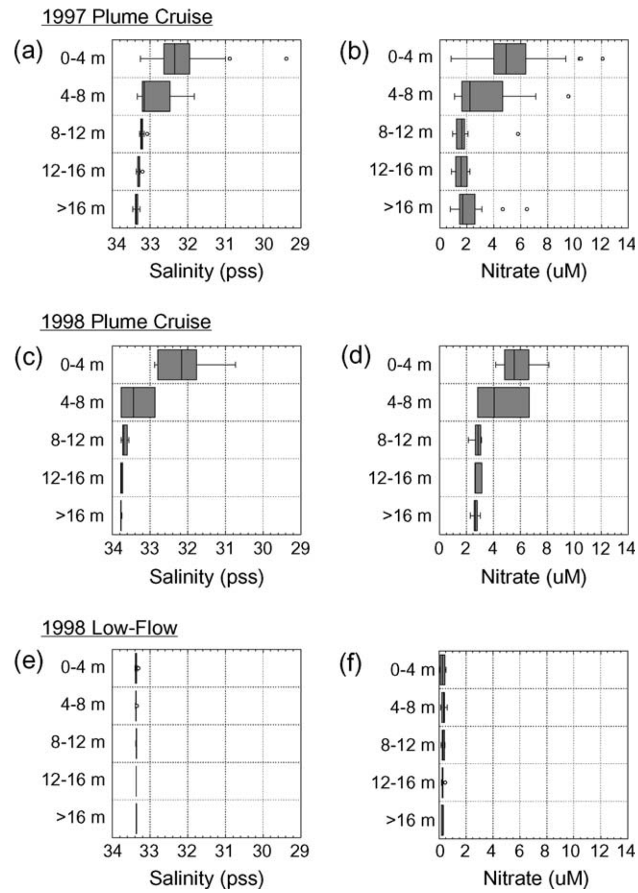

Fig. 6. Box plot summaries of the ocean salinity and nitrate observations with depth for the three cruises. Water quality samples are binned into 4-m depth bins. Note that the salinity axes have been reversed to mimic patterns in the nitrate data.

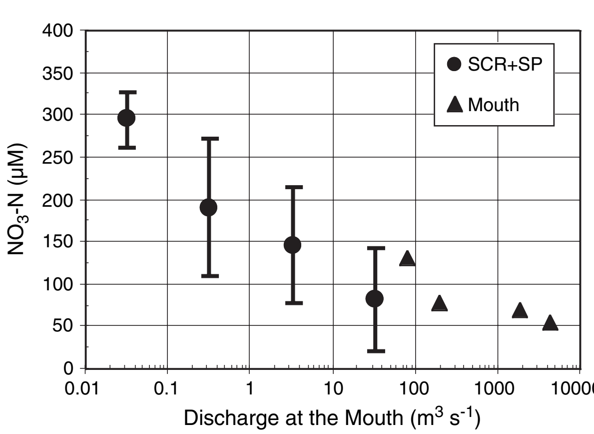

Fig. 5. Estimated nutrient concentrations at the Santa Clara River mouth by combining results from USGS sites SP and SCR for order-of-magnitude discharge ranges. Error bars are ±S.D.

vigorous mixing with the ambient seawater (Fischer et al., 1979; Warrick et al., 2004b).

Nutrient distributions with depth resemble the salinity patterns described above and suggest significant inputs from the river (Fig. 6b and d). Although only nitrate concentrations are shown in Fig. 6, silicate and phosphate patterns closely resemble those of nitrate with different amplitudes. The greatest concentrations of nitrate were found in the most freshened surface waters. Nitrate concentrations in the surface waters (0–4 m) ranged from 1 to 12 μM during the 1997 Plume cruise (Fig. 6b) and 4 to 8 μM during the 1998 Plume cruise (Fig. 6d). One of the 1997 Plume cruise surface samples was obtained outside of the region of the turbid river plume and had a nitrate concentration (1 μM) that was lower than the underlying ambient coastal waters. The ambient water nitrate concentrations were 1–3 μM during both plume cruises. Two of the deepest (>16-m) samples during the 1997 Plume Cruise had elevated nitrate concentrations (4.5 and 6.5 μM), although these samples were obtained along the thermocline (at 37 and 36 m, respectively) and should thus be expected to have elevated nutrient concentrations. Again, the other dissolved nutrients had very similar distributions with depth, although silicate concentrations (5–40 μM; ambient ~5 μM) were higher than nitrate, while phosphate (0.25–3.5 μM; ambient ~0.25 μM) were lower.

Water column properties were very different during the 1998 Low-Flow cruise (Fig. 6e and f). Salinity varied by only ~0.2-psu with depth, and the lowest observed salinities (<33.35-psu) were in surface waters (0–4 m) located immediately off the river mouth. Nutrient concentrations were somewhat uniform with depth and significantly lower than during the two plume cruises. Nitrate concentrations (0.05–0.6 μM; Fig. 6f) were somewhat higher, however, in waters with low salinity, suggesting that some river influence on the nutrients existed. These highest concentrations were at the stations nearest the river mouth.

The spatial patterns of the surface water observations (uppermost sample in the water column, 0.5–1.5 m depth) during plume conditions are shown in Figs. 7 and 8. These samples represent the portion of the water column with the most significant and concentrated influence from the river plume. During each plume sampling date, the lowest salinities and highest nutrient concentrations occurred near the Santa Clara River mouth. The mixing dynamics of the river plume over three days can also be observed in the 1997 Plume data (Fig. 7). On January 26 the plume water is largely nearshore and highly concentrated with nutrients (note that some influence of the Ventura River may have occurred along the northern edge of our sampling grid). The plume advects offshore and somewhat southward on January 27, which is consistent with currents measured in the Santa Barbara Channel during that day (Warrick et al., 2004a). By January 28 the offshore plume waters have become much less concentrated than January 27, suggesting further mixing and advection. Note that suspended sediment (as measured by beam transmissometer; BAT) did not advect as far from the river mouth as the nutrients did (Fig. 7). This is due to sediment flocculation and settling, which produces non-conservative mixing processes for sediment in the surface plume waters (discussed by Warrick et al., 2004a). The river plume on February 11 of the 1998 Plume cruise appears to have advected slightly to the west-northwest, which is also consistent with temporal variations in regional current measurements, although this pattern may also be due to influences from the Ventura River as the plume boundaries were difficult to identify during this large flood.

The surface water observations of the offshore portions of the 1998 Plume cruise (Fig. 8) show that river water (as shown by salinity) and nutrients were most concentrated near the river mouth region (the eastern channel). Strong inverse relationships between salinity and all nutrients were observed. These inverse relationships suggest a strong river contribution to the elevated offshore nutrient concentrations. Thus, the data in Fig. 8 suggest that flood waters reached at least 20-km into the channel, which is consistent with SeaWiFS remote sensing observations following this large flood showing turbid plume waters 30–40 km off the Santa Clara River mouth (Mertes and Warrick, 2001).

3.3. Biological response to river nutrients

Chlorophyll concentrations are used to evaluate biological responses to the discharged river nutrients (sampled only during the 1998 Plume and Low-Flow cruises). The chlorophyll results can be compared to semi-monthly monitoring during 1996–2001 at seven stations within the Santa Barbara Channel by the UCSB Plumes-and-Blooms Research Group (data available at: http://www.icess.ucsb.edu/PnB/PnB.html). These mid-channel surface water observations ($n = 593$) suggest that chlorophyll is generally highest during the summer upwelling and bloom periods, when it can exceed >5 $\mu g\,L^{-1}$, and somewhat lower (generally 0.5–2.0 $\mu g\,L^{-1}$) during the remainder of the year. This produces a skewed distribution of concentrations with a mean of 2.1 $\mu g\,L^{-1}$ (standard deviation = 2.4 $\mu g\,L^{-1}$) and a median of 1.3 $\mu g\,L^{-1}$ (pers. comm., O. Polyakov, UCSB).

Chlorophyll concentrations during the 1998 Plume Cruise were generally low near the Santa Clara River mouth and somewhat elevated in the offshore plume (Fig. 8). During the first day of the 1998 Plume Cruise (February 11) when sampling occurred only in the river mouth region, chlorophyll concentrations were <1 $\mu g\,L^{-1}$ (mean = 0.70, standard deviation = 0.27). During the subsequent day (February 12), sampling

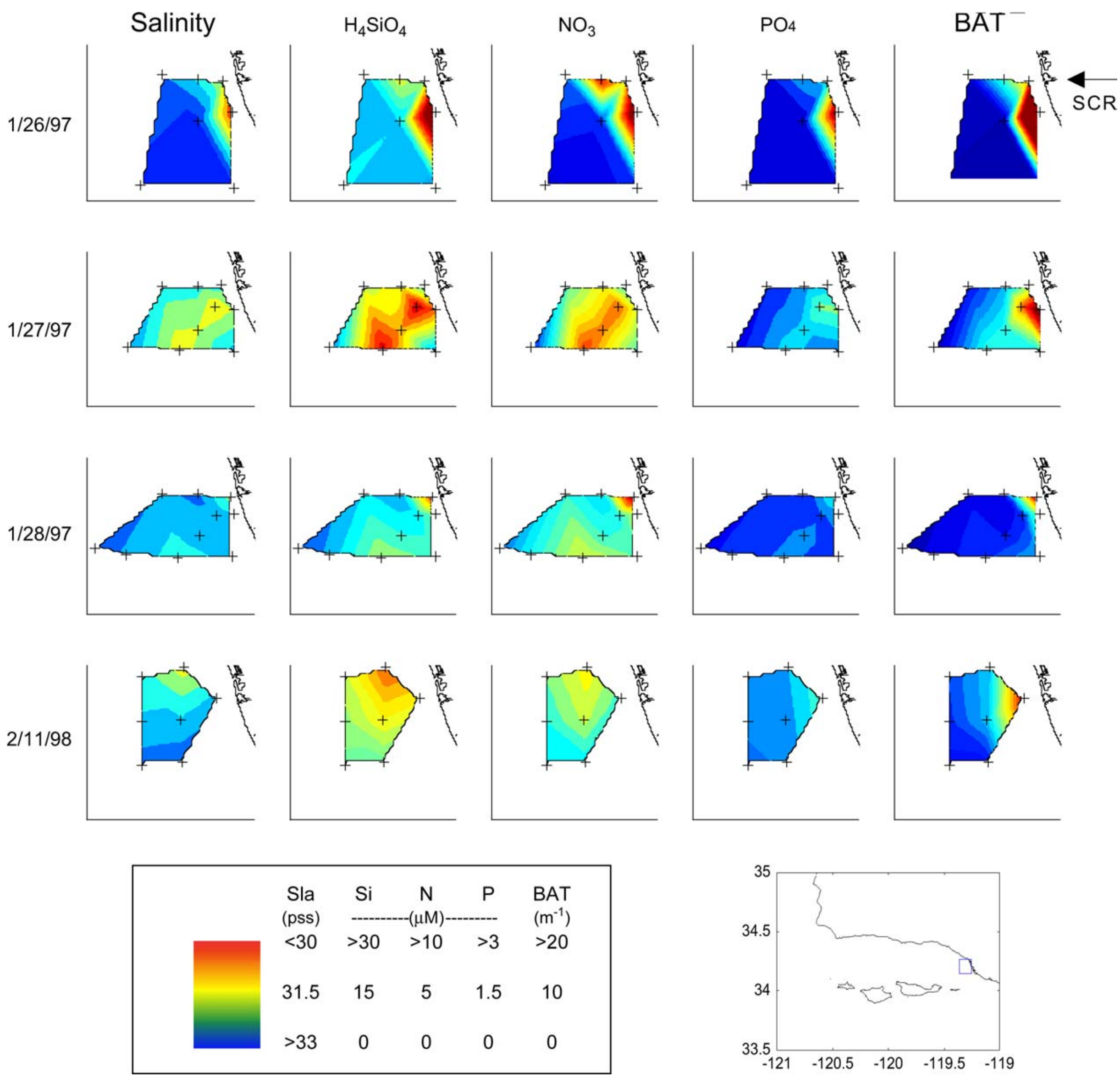

Fig. 7. Surface water observations near the Santa Clara River mouth of the Santa Clara River plume during the 1997 Plume and the 1998 Plume cruises.

focused both on the river mouth region and a cross-section of the eastern channel. On this second day chlorophyll concentrations in the immediate river mouth region were 0.5–1.5 $\mu g\ L^{-1}$ (suggesting negligible to slight increases from the previous day), while the concentrations offshore of this region were considerably higher at 1.5–4.5 $\mu g\ L^{-1}$ (Fig. 8). During the final day of sampling (February 13), mid-channel chlorophyll concentrations were observed to be consistently near 1 $\mu g\ L^{-1}$ (mean = 0.99, standard deviation = 0.27) with no apparent spatial patterns.

Chlorophyll during the 1998 Low-Flow Cruise (data not shown) was consistently low with a mean concentration of 0.45 $\mu g\ L^{-1}$ (standard deviation = 0.16 $\mu g\ L^{-1}$). The Low-Flow chlorophyll distributions did not show coherent spatial patterns with respect to the river mouth. These low chlorophyll observations were consistent with SeaWiFS ocean color measurements obtained on the same date (SeaWiFS data available at: http://www.ices-s.ucsb.edu/chlorophyll/chlor_image.html), which ranged between 0 and 0.5 $\mu g\ L^{-1}$ in the region sampled off the river mouth.

Thus, low algal biomass concentrations were observed near the river mouth region during both plume and low-flow conditions. However, following the 1998 flood discharges elevated levels of chlorophyll were observed offshore of the river mouth region in waters with both reduced salinities and elevated nutrient concentrations, which suggests river influences to these waters (Fig. 8).

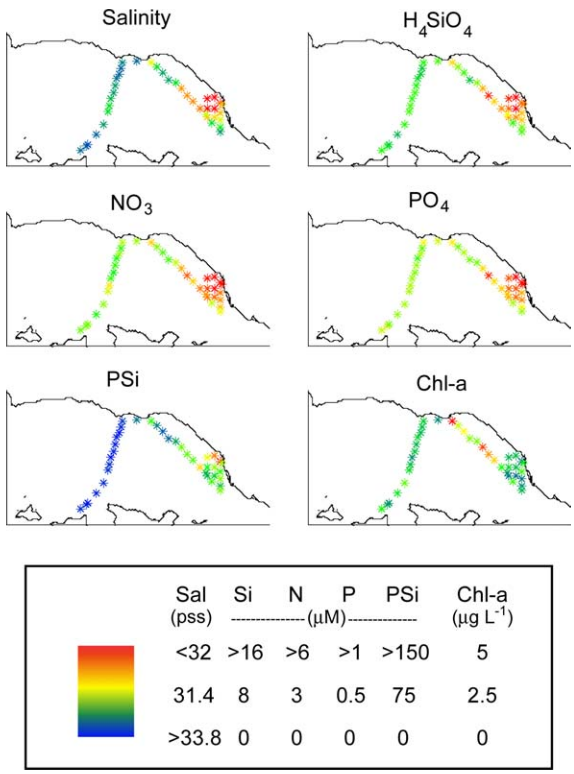

Fig. 8. River mouth and mid-channel surface water observations of salinity, nutrients, particulate silica (PSi), and chlorophyll-*a* during the 1998 Plume cruise (February 11–13, 1998).

4. Discussion

Here we evaluate the nutrient loading implications of the observations and compare these findings to the current understanding of nutrient cycles and primary production in the Santa Barbara Channel and other Eastern Pacific systems. We begin with an evaluation of the nutrient mixing relationships and use this information to compute total event and annual nutrient fluxes from the Santa Clara River.

4.1. Nutrient mixing relationships

The strong inverse relationships between water salinity and nutrient concentrations were evaluated to determine whether conservative or non-conservative (i.e., linear or non-linear) mixing was observed in the river plumes. Data used for this analysis consisted only of the ocean surface samples, since they were sampled within the well-mixed plume waters. We suggest that conservative mixing processes were observed in our data since: (1) linear regressions fit the data well; (2) mixing of river plume waters was rapid; and (3) biological effects on nutrient concentrations were not significant.

For the two plume cruises, linear regressions explain between 74% and 91% of the variance in the salinity–nutrient concentration relationships and are highly significant ($p < 0.01$; Fig. 9). Correlation was consistently highest for silicate ($r^2 = 0.87$–0.91) and lowest for phosphate ($r^2 = 0.74$–0.81). Correlations between nutrients and salinity during the 1998 Low-Flow cruise ($r^2 = 0.12$–0.76; Fig. 9) were weaker than the plume cruises. However, the Low-Flow correlations for silicate and phosphate are highly significant ($p < 0.01$), while the nitrate correlation is not significant ($p > 0.05$).

Non-conservative mixing would be expected in our observations if significant nutrient removal occurred from phytoplankton uptake. This uptake would result in either draw-down (i.e., downward curved) patterns in the nutrient–salinity data or day-by-day decreases in nutrient concentrations with respect to salinity. Nutrient–salinity relationships for the two plume cruises do not show either pattern (Fig. 9). Nutrient uptake could have already occurred between the river mouth and our ocean observations, although the low algal biomass (chlorophyll $< 1\ \mu g\ L^{-1}$) and high turbidity (BAT $> 10\ m^{-1}$, equivalent to a euphotic zone < 0.5-m deep; Kirk, 1994) of this region suggest that phytoplankton growth was negligible. Negligible phytoplankton growth is also supported by the simple model of Wofsy (1983), which predicts severe limitation of algal growth within mixed layers of 2–8 m and suspended sediment concentrations of 20–100 mg L^{-1}, such as seen in the Santa Clara River plume (e.g., see fig. 5a of Wofsy, 1983).

Lastly, if nutrient draw-down was observed in our data, it should be greatest in the regions of high algal biomass. This can be evaluated with statistics of the linear regression results (Table 3). In this table, the slope (m) and offset (b) represents the best-fit variables in the following relationship:

$$C = mS + b \tag{1}$$

where C is the nutrient concentration (μM) and S is water salinity (pss). If the mixing is conservative, then b represents the best-estimate of the nutrient concentration of the river water endmember (i.e., $S = 0$ pss). Residuals of the linear nutrient regression relationships (i.e., the difference between the observed nutrient concentration and estimated concentration from regression) were not correlated with any measured water property (including chlorophyll concentrations). Thus, the presence of high concentrations of phytoplankton did not explain the variability of the data about the linear regression relationships, supporting the observation that significant nutrient draw-down did not occur within the spatial and temporal distribution of our observations.

4.2. Estimates of event loading

Assuming conservative mixing, the estimates of river nutrient concentrations from the cruise data (b; Table 3)

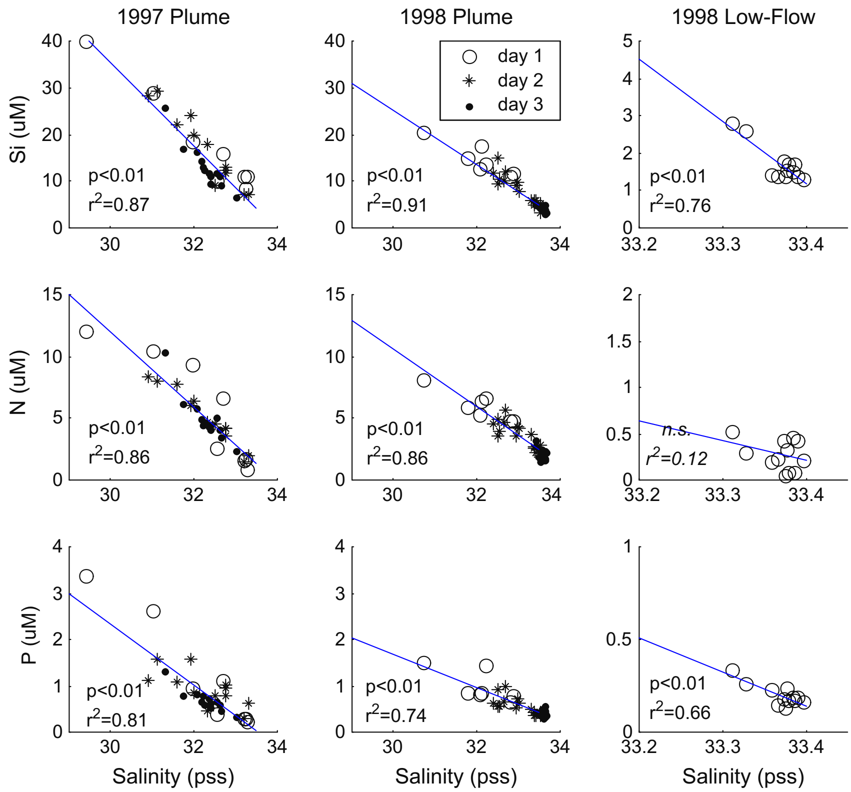

Fig. 9. Salinity and nutrient concentrations for the surface water samples of the three ocean cruises (1997 Plume, 1998 Plume, and 1998 Low-Flow). Linear regression lines and correlation coefficients (r^2) are shown, which assume conservative mixing processes between ocean and river waters. 1998 Low-Flow data are plotted on different scales than the 1997 and 1998 Plume data.

compare well with the USGS river nutrient sampling data (Fig. 10), where *b* values are plotted against the flow-weighted average discharge during each event sampled (0.3, 125 and 770 $m^3 s^{-1}$ for 1998 Low-Flow, 1997 Plume and 1998 Plume, respectively). The nitrate concentration estimate for 1998 Low-Flow was not included, since this linear regression was not significant. These estimates of river nutrient concentrations suggest decreases with increasing discharge, which is consistent with the river observations. Further, the plume data provide the first estimate of the phosphate loading from the Santa Clara River, since it was not included in USGS sampling.

Nutrient loads during the three sampled events were calculated by multiplying mean event nutrient concentrations and event river discharge. These estimates of loads (Table 4) reveal that significantly more nutrients were discharged during the 1998 flooding event than the 1997 event or 1998 low-flow. For example, the 1998 Plume event discharged over three-times more silicate, nitrate and phosphate than the 1997 event. These six-day 1998 Plume event loads were 300–600 times greater

Table 3
Linear regression statistics for surface water nutrient concentrations against Salinity ($C = mS + b$, see text)

Sampling date		Si			N			P		
	n	*m*	*b*	r^2	*m*	*b*	r^2	*m*	*b*	r^2
1997 Plume	**25**	**−8.9 ± 0.7**	**303 ± 23**	**0.87**	**−3.1 ± 0.3**	**105 ± 9**	**0.86**	**−0.67 ± 0.07**	**26 ± 2**	**0.81**
1/26/97	6	−7.8	269	0.96	−2.9	99	0.84	−0.81	27	0.97
1/27/97	9	−10	341	0.89	−2.9	98	0.94	−0.39	14	0.46
1/28/97	10	−11	374	0.94	−4.8	149	0.91	−0.54	18	0.88
1998 Plume	**37**	**−6.5 ± 0.3**	**224 ± 11**	**0.91**	**−2.3 ± 0.2**	**80 ± 5**	**0.86**	**−0.36 ± 0.04**	**13 ± 1**	**0.74**
2/11/98	7	−4.2	149	0.80	−1.5	53	0.78	−0.32	11	0.45
2/12/98	15	−7.1	243	0.83	−2.2	75	0.66	−0.33	12	0.53
2/13/98	15	−6.4	219	0.51	−2.6	90	0.19	−0.02	1	0.00
1998 Low-Flow	**12**	**−17 ± 3**	**550 ± 100**	**0.76**	**−2.1 ± 2**[a]	**72 ± 62**[a]	**0.12**[a]	**−1.8 ± 0.4**	**62 ± 14**	**0.66**

95% confidence intervals are also given for the compiled data from the three cruises.
[a] Not significant ($p > 0.05$).

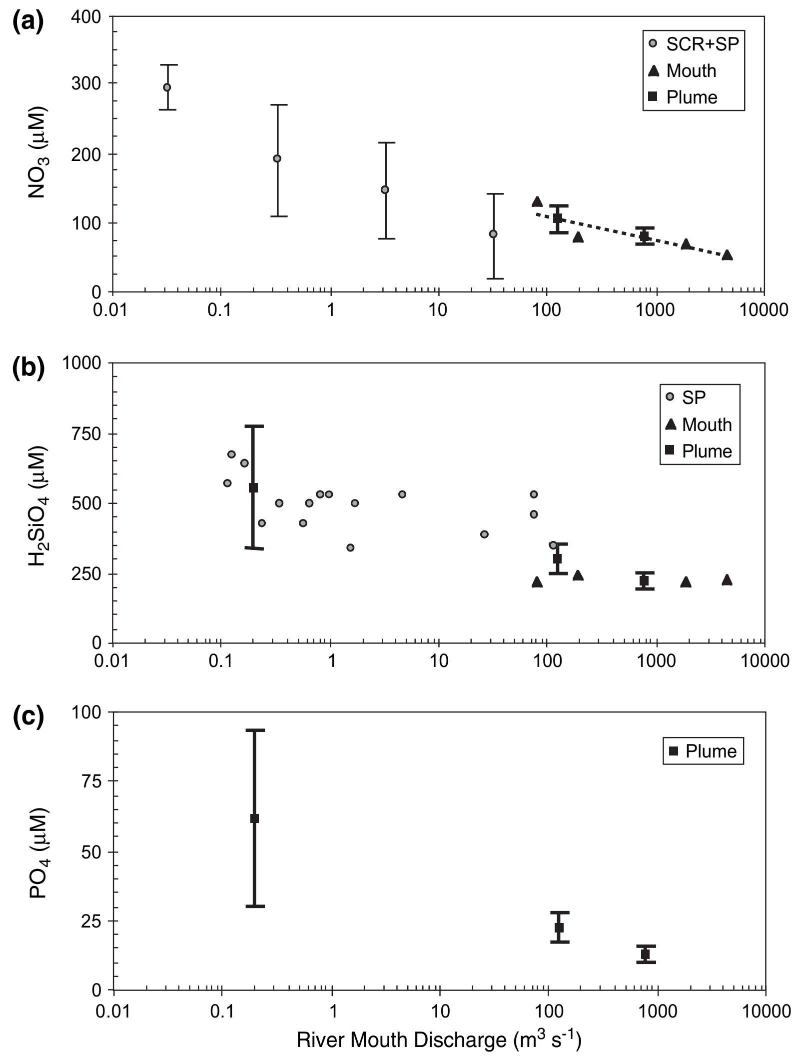

Fig. 10. Nutrient concentration–river discharge relationships for the ocean observations ('Plume') along with the river data from Fig. 5. Nutrient concentrations from ocean observations were estimated from linear regression intercepts (b; Table 3) and are plotted with 95% confidence intervals. River discharge values for cruise data calculated from flow-weighted average discharge rate during the discharge event. Dashed line in (a) is the regression through the combined 'Mouth' and 'Plume' observations as noted in text.

than the estimated loads discharged during the six days prior to the 1998 Low-Flow sampling.

The molar nutrient ratio (Si:N:P) within the Santa Clara River flood discharge was calculated to be 18:6:1 during the 1998 event and 14:5:1 during 1997 event. These ratios suggest that the discharged river water quality is different than upwelled waters, which typically have a molar ratio of 13:10:1. The river and upwelled waters have somewhat similar Si:P ratios, but very different Si:N and N:P ratios (by a factor of approximately two). This suggests that the Santa Clara River water contains ~50% the amount of nitrate (with respect to silicate and phosphate) as upwelled water. Estimates of new primary production from the river nitrate and phosphate varied by over two orders-of-magnitude between the low-flow event and the large 1998 flood event (Table 4).

4.3. Annual variability of river loads

A first-order estimate of nitrate fluxes from the Santa Clara River during three contrasting years was produced using the combined river and ocean observations (Fig. 10) and daily flow rate records obtained at the 'Mouth' station (Fig. 1). (Silicate and phosphate loads were not estimated due to data limitations.) River nitrate concentrations for discharges less than 100 m^3 s^{-1} were assumed to be equivalent to the SCR + SP results over the four orders-of-magnitude discharge groupings (discharges less than 0.01 m^3 s^{-1} were assumed to be 500 ± 100 μM, a conservatively high estimate discussed below). Nitrate concentrations for flow rates greater than 100 m^3 s^{-1} were evaluated by combining the four observations at the 'Mouth' station with the results from the two plume cruises. A best-fit power relationship

Table 4
Comparison of macronutrient load estimates from the Santa Clara River during the three sampled events

Cruise	1998 Low-Flow	1997 Plume	1998 Plume
Event type	Summer Low-Flow	Annual Event	~10-year Flood
Event duration	6 days	6 days	6 days
Nutrient loads ($10^6 \times$ mol)[a]			
Si	0.05 ± 0.02	7.6 ± 1.2	29 ± 3
N	n.s.[b]	2.6 ± 0.4	10 ± 1
P	0.006 ± 0.003	0.6 ± 0.1	1.6 ± 0.3
River discharge nutrient ratio (Si:N:P)	9:(n.s.)[b]:1	14:5:1	18:6:1
Total primary production C-fixed (t C)[c]			
From nitrate	~0[d]	210 ± 40	820 ± 110
From phosphate	8 ± 4	720 ± 140	2100 ± 400

[a] Loads estimated by the product of water discharge (Table 2) and the estimates of average nutrient concentrations (Table 3).
[b] n.s. = not significant.
[c] Estimated from a C:N molar ratio of 6.6:1 and a C:P molar ratio of 106:1.
[d] Primary production assumed to be negligible since nitrate loads were assumed to be low.

through these data (Nitrate = $250 \times (\text{Discharge})^{-0.178}$; $r^2 = 0.85$; $p < 0.01$), was used to estimate river nitrate concentrations. The slope of this power function (-0.178) had a standard error of 0.038 or approximately 21%, thus, an error of $\pm 21\%$ was assumed for nitrate fluxes estimated within this upper discharge range.

Nitrate loads were estimated for three contrasting years: 1997 ("average" runoff), 1998 ("wet", El Niño), and 1999 ("dry", La Niña). Years were defined by the hydrological "water year" that runs from October to September. Total runoff from the Santa Clara River differed by well over two orders-of-magnitude during these three years (Fig. 11). Although discharge amounts differed significantly, runoff rates were consistently flashy during both wet and dry years, with most runoff events occurring between late fall and early spring.

Estimated nitrate export also varied by approximately two orders-of-magnitude during the three years. Cumulative export was greatest during the wet El Niño ($72 \pm 4 \times 10^6$ mol) and least during the dry La Niña ($2.2 \pm 0.2 \times 10^6$ mol). The majority of the nitrate flux occurs during brief runoff events, which results in rapid rises in the cumulative nitrate flux curves (Fig. 11). Nitrate contributions during low flow are negligible, especially during summer and late fall. Very low flows (<0.01 m^3 s^{-1}), for which concentrations were assumed to be 500 μM, are responsible for $<0.5\%$ of the total nitrate fluxes; increasing these assumed concentrations by a factor of two still results in $<1\%$ of the annual nitrate fluxes discharged by these very low flow rates. Errors in the nitrate fluxes are given both by assuming independent, random application of error (thick lines) and assuming dependent errors (thin lines, Fig. 11). Unfortunately, dependent errors in river nutrients cannot be ruled out with our limited data set. Regardless, even under the most extreme scenario, the wet, El Niño year still discharges over an order-of-magnitude

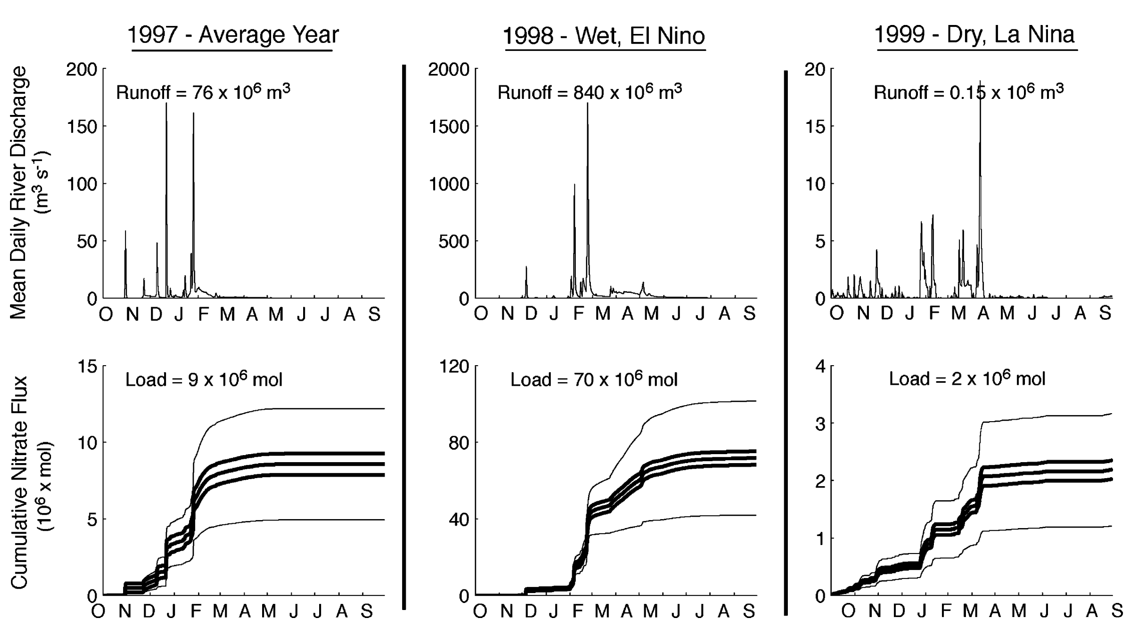

Fig. 11. Santa Clara River discharge of water and cumulative nitrate during three contrasting water years, 1997, 1998 and 1999. Mean daily river discharge from the 'Mouth' river gauge. Cumulative nitrate discharge calculated from daily loads as detailed in the text. Thick lines of cumulative nitrate load represent the mean $\pm$ S.D. assuming independent, random errors in daily nitrate concentrations. Thin lines represent maximum and minimum errors assuming dependent, non-random errors.

more nitrate than the dry La Niña (42×10^6 and 3.2×10^6 mol, respectively).

4.4. New production

New primary production in the Santa Barbara Channel will respond to the various nutrient inputs into the photic zone. We have shown that the Santa Clara River discharges significant loads of all macronutrients, now we examine how these loads compare to upwelling inputs. An order-of-magnitude estimate of upwelling along the western Santa Barbara Channel can be calculated by using an average upwelling rate of 1 Sv (i.e., $10^6\ m^3\ s^{-1}$) per 1000 km of coastline (pers. comm., F. Chavez, MBARI). This value is confirmed with annual mean wind stress of $0.12\ N\ m^{-2}$ (from the WNW) at the west Santa Barbara Channel buoy (NDBC buoy 46054), which results in approximately 1.4 Sv of Ekman transport (to the SES) per 1000 km of coastline. Assuming an open "coastline" of 50-km for the Santa Barbara Channel and that upwelled waters contain an average of nitrate concentration of 10 μM, the Santa Barbara Channel would receive approximately $15 \times 10^9\ mol\ yr^{-1}$ of nitrate. This rate of nutrient contribution is 2–3 orders-of-magnitude greater than the river contributions during the wet, El Nino year of 1998 (Fig. 11). Even if a small fraction (5%) of the upwelled water were to lead to local new production in the Santa Barbara Channel, this flux is still *much* larger than the inputs from the Santa Clara River.

However, the upwelling region near Point Conception is known to have relatively low new production, as the realization ratio (ratio of available nitrate to effective conversion into nitrogen biomass) for this region is approximately 0.2 (Dugdale et al., 1997). One explanation given for this is ecosystem grazing pressure, although recent insights on Fe-limitation in regions with narrow shelves would predict similar results (Bruland et al., 2001). Further, during the 1998 El Nino conditions, reduced upwelling rates and a deep thermocline resulted in ~70% decreases in total new production (compared to average) in the California Current (Chavez et al., 2002). Thus, assuming full conversion of river nitrate into nitrogen biomass (discussed below), the new production from river runoff would account for approximately 0.03–4% of the combined new production (river + upwelling) within the channel for the three years considered in Fig. 11. Since upwelling is generally reduced during El Niño (Chavez et al., 2002), river contributions are most significant during these years (~4% of new production in 1998).

Primary production from the river nutrient contributions, however, may be somewhat different than upwelling production. For example, the average macronutrient molar ratio (Si:N:P) of river event runoff was 16:5:1 (Table 4), which is considerably different from the average ratio of 13:10:1 in upwelled waters. This suggests that phosphate and silicate will be much more abundant in river plume waters (with respect to nitrate) than in upwelled waters. Further, although we did not measure Fe, we would assume that it is replete in river plume waters due to the abundance of terrestrial sediments. Thus, we hypothesize that the river water phytoplankton blooms will not be limited by Fe, which combined with the macronutrient ratios, may favor different algal assemblages than upwelling inputs. Unfortunately, neither phytoplankton assemblages nor nutrient uptake measurements in plume waters are available to test for nutrient limitation and community response effects.

Finally, river nutrient contributions are extremely pulsed (Fig. 11), with the majority of the loads occurring during brief runoff events (50% of the computed annual loads occurred during the top 7–16 days of runoff). Production following these events is also likely pulsed once sediments settle and light can penetrate the surface mixed layer. River nutrient contributions during the summer and fall low-flow are generally negligible. This suggests that new production during these periods from dissolved inorganic river nutrients is similarly low.

This contrasts with ocean color observations, which reveal that chlorophyll concentrations are high in the river mouth region throughout the year (Otero and Siegel, in press). Thus, although ocean color suggests that the eastern Santa Barbara Channel has similar chlorophyll concentrations as the western channel, this cannot be explained by new production from river inorganic nutrients especially during low-flow periods. The ocean color patterns must result from other nutrient sources or are false chlorophyll signals produced by other coastal water properties, such as suspended sediments and CDOM. Unfortunately, neither scenario can be tested with our data, in part because in situ and ocean color chlorophyll measurements during our Low-Flow cruise were uncharacteristically low.

We end this section with a brief comparison of our results to other eastern boundary upwelling systems that receive direct input from river systems. Unfortunately, river nutrient inputs in many of these regions have not been quantified, even though river plumes are generally of comparable size and duration to our observations here (Warrick and Fong, 2004). One exception is the Columbia River plume in the California Current system, which is known to influence coastal biologic and biogeochemical patterns for 100s of km from the river mouth (Stefansson and Richards, 1963; Hobson, 1966; Pruter and Alverson, 1972). Columbia River macronutrient inputs are especially important during the winter season, when they can dominate coastal macronutrient budgets (Conomos and Gross, 1972), somewhat similar to the Santa Clara River. Unlike the Santa Clara, the Columbia continues to discharge substantially during the summer, although this discharge is often depleted in nitrate due to photosynthesis in the river and estuary (Conomos and Gross, 1972). The Columbia River is an important source of silicate year-round, however, and future work by the newly funded, multi-year, multi-collaborator River Influences on Shelf Ecosystems project (RISE; lead investigator: Barbara Hickey, U. Washington) hypothesizes that the ecological implications of Columbia River silicate and iron discharge are great in the California Current system (background can be found at: http://www.ocean.washington.edu/rise/index.htm).

5. Conclusion

Upwelling is by far the largest source of macronutrients to the Santa Barbara Channel region of southern California, especially during the late spring and summer. River discharge, in comparison, contributes 2–4 orders-of-magnitude less Si, N and P on an annual basis, although these inputs occur dominantly following large winter storms and are discharged into the far eastern channel. River macronutrients may be especially important to algal growth during wet, El Niño years since runoff is enhanced and upwelling inputs are generally reduced. Also, we found that the molar ratios of river and upwelling macronutrient inputs are significantly different.

Our results do not suggest that river discharge is responsible for the year-round high chlorophyll patterns observed by ocean color satellites along the coast near the river mouth. This may suggest that along with river flood contributions, there is significant nutrient recycling within this shelf environment. Or, since the eastern channel is underlain by a broad, shallow shelf, there may be the presence of internal waves and mixing processes providing sub-thermocline waters (or organic river nutrient sources deposited in shelf sediments) into the photic zone. This broad, shallow shelf may also be a potential source of iron (e.g., Bruland et al., 2001), which may enhance primary production in waters advected into this region and already replete in macronutrients. Or, ammonium contributions from the river, which could not be evaluated here, may be important especially in the summer. Lastly, resuspension of sediments from the inner shelf may provide optical conditions that provide false chlorophyll positives from the ocean color techniques in the river mouth region. These topics are potentially ripe and important areas for future research.

Other questions are raised by our results that may provide important research topics. These include measurement of nutrient uptake timing and rates within river plume waters with emphasis on what, if any, nutrients may be limiting algal growth. Further, the phytoplankton species compositions (including harmful algal bloom species, if present) growing within plume waters should be measured and compared to results from upwelled waters. We showed here that river nutrient concentrations correlated with watershed land use characteristics. What is not known is whether these patterns are applicable to the greater southern California region, including the large urban centers. Quantifying these inputs is important to evaluating the influence of river discharge on the nutrient budget of the greater Southern California Bight. Lastly, future work should include data collection and analysis of ammonium due to its presence in treated municipal wastewater discharge and the use of ammonium-based fertilizers.

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