Terrestrial nutrient loads and fluxes to the Southern California Bight, USA

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ABSTRACT

This study presents the first comprehensive regional estimates of terrestrial total nitrogen (TN) and total phosphorus (TP) loads and fluxes, from point sources (PS), non-point sources (NPS), and natural sources to the Southern California Bight (SCB), based on an extensive dataset collected across SCB watersheds in 2008-2009. The study estimated the net increase in anthropogenic nutrient inputs for 2008-2009 compared to loads prior to urbanization (c. 1850) by modeling the contribution of natural undeveloped land-use. Anthropogenic activities have increased terrestrial nutrient loads to the SCB by 47.32 Gg TN yr^{-1} and 2.88 Gg TP yr^{-1}, representing a 52-fold TN increase and a 30-fold TP increase from the pre-urbanization scenario. The average annual nutrient fluxes from SCB watersheds are amongst the highest fluxes observed in an urbanized coastal setting (3,157 kg TN km^{-2} and 210 kg TP km^{-2}). At a sub-regional scale, fluxes range from 15,988 kg TN km^{-2} and 1,038 kg TP km^{-2} in the highly urbanized and PS-dominated Santa Monica Bay to 44 kg TN km^{-2} and 19 kg TP km^{-2} in the relatively undeveloped Santa Barbara sub-region. Point sources contribute 92% of TN and 76% of TP loads to the SCB, with less than 1% of the loads attributed to the natural background sources. PS is a chronic source of nutrient loads to the SCB at a magnitude and timing atypical in Mediterranean ecosystems.

INTRODUCTION

Eutrophication is one of the major consequences of anthropogenically-induced global change on the world's coastal oceans (Vitousek *et al.* 1997, Boesch *et al.* 2000, Scavia *et al.* 2002). Increased nutrient fluxes from terrestrial runoff is considered one of the main causes of eutrophication (Howarth 2008), with a 20-fold increase in the coastal exports compared to pre-industrial times in some areas (Howarth *et al.* 1996). Globally, coastal eutrophication is greater where agricultural and urban land-uses are intense, but the distribution of loading and the effects on the coastal ecosystems are not uniform. Thus, there is a critical need to better document the quantitative links between anthropogenic activities in the watersheds, the nutrient inputs to coastal systems, and their ecosystem effects. Quantifying the relative magnitude and timing of nutrient flux to coastal waters is a key component in determining the appropriate coastal resource management strategy.

Over the past several decades, a great deal of progress has been made to estimate nutrient fluxes to coastal waters (Howarth *et al.* 1996, 2011; Schaefer *et al.* 2012), though data gaps remain, particularly in the SCB on the Pacific West Coast of the United States. Recently, Bergamaschi *et al.* (2012) estimated TN fluxes to the Pacific West Coast, including the SCB, using the SPAtially Referenced Regressions On Watershed attributes (SPARROW) model. However, SPARROW model output has a high level of uncertainty when based on limited flow and

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water quality constituent data sets, especially at this spatial scale. Ackerman and Schiff (2003) estimated stormwater dissolved inorganic nutrient fluxes to the SCB; however, the study did not estimate TN, TP, or contributions from baseflow during non-storm conditions. Under natural conditions, riverine fluxes would be expected to occur primarily during storm events, but urban subsidies of imported water from the Colorado River and Northern California have substantially changed regional water budgets. The riverine baseflow to the coast from urbanized watersheds has increased significantly through NPS runoff and inland PS discharges (Ackerman *et al.* 2005). Improved estimates of terrestrial TN and TP fluxes that include both storm and baseflow contributions are needed for SCB watersheds.

Quantifying the relative contribution of PS, NPS, and natural sources to coastal nutrient export can be challenging. Anthropogenic PSs, such as municipal effluents, are easier to quantify than NPSs, such as septic, stormwater and dry-weather urban runoff. Further, the majority of published literature on coastal nutrient exports are is based on regions with combined sewer and stormwater systems (Shields *et al.* 2008), making the identification of PS and NPS nutrients difficult. In these studies, the PS and NPS load estimates are often modeled using averaged values (for e.g., population density or categories of land-use) and may not reflect the effect of the level of treatment and control technologies or other site-specific factors. Similarly, there are few studies that quantify natural sources to coastal nutrient export, which can vary widely based on climate, land cover, geology, and watershed size (Yoon and Stein 2008).

The SCB is unique in that most of the municipalities and counties have completely separate sanitary and stomwater sewer collection systems (Tiefenthaler *et al.* 2008), and natural terrestrial nutrient sources are quantified for selected watersheds across the region (Yoon and Stein 2008). In most SCB watersheds, stormwater and urban runoff during non-storm conditions are discharged into rivers and storm channels, whereas treated effluents from the Public Owned Treatment Works (POTWs) in urbanized areas are discharged directly in to the ocean via separate outfalls (Lyon and Sutula 2011). In few cases, POTWs discharge into inland rivers. Thus, PS, NPS, and natural terrestrial sources of nutrients to the SCB can be characterized fairly accurately. To date, the available data has not been used to document the net increase in coastal nutrient exports from SCB watersheds relative to a pre-urbanization baseline. An extensive regional monitoring effort conducted in SCB watersheds during 2008-2009 provided an opportunity to fill several knowledge gaps related to sources, timing, and magnitude of terrestrial nutrient fluxes in this ecologically important and highly urbanized region of the California Current ecosystem.

The objectives of this study were to: 1) quantify the temporal and spatial variability in terrestrial TN and TP fluxes to the SCB and 2) quantify the relative contribution of natural, PS, and NPS of nutrients loads and fluxes to the SCB, relative to a pre-urbanization baseline.

METHODS

Study Area

The SCB includes the coastal ocean from Point Conception (34.45°N) to the US-Mexico border (32.53°N). The climate of this region is Mediterranean, with an average annual rainfall range of 10 to 100 cm, concentrated largely over the winter months of December-March, with an annual average of 15 rain events (Schiff *et al.* 2003). Most terrestrial runoff to the SCB occurs during wet-weather storm events. Baseflow during non-storm conditions is referred to as "dry weather" runoff. Precipitation in this region has a strong inter-annual variation; during the study year (2008-2009), total rainfall represents the 38th percentile of a comparative 13-year period (1997-2010).

Conceptual Approach to Estimating Nutrient Loads and Fluxes

In this study, terrestrial nutrient loads were defined as the combination of riverine nutrient loads and direct PS discharges to the SCB from National Pollution Discharge Elimination System (NPDES) permitted facilities via ocean outfalls. Riverine TN and TP loads were the summed loads from inland PS, NPS, and natural sources. The PS discharges was estimated from NPDES monitoring data summarized annually for major and minor NPDES permit holders. In Southern California, the municipal stormwater programs are required to collect data on stormwater discharge and contaminant loads at the base of selected SCB watersheds (Ackerman and Schiff 2003). The present study used monitoring data collected through the SCB Regional Monitoring Program to estimate wet- and dry-weather loads and fluxes in monitored watersheds, supplemented with modeled estimates for wet weather in unmonitored watersheds. The model was used to estimate nutrient loads and fluxes from developed (NPS) versus undeveloped (natural) land-uses. Finally, the model used to hindcast the nutrient fluxes to the SCB in a natural landscape setting (no development scenario) and estimate fluxes from natural land-uses allowed for separation of anthropogenic NPS and natural contributions to riverine nutrient fluxes. Atmospheric deposition was not estimated separately, but included as an unquantified source to riverine fluxes from NPS runoff and natural areas.

Among NPDES-permitted facilities, POTWs contributed most of PS nutrient loads to the SCB, with negligible industrial PS contributions (Lyon and Stein 2009). Therefore, industrial PS contributions were not included in total PS load estimates. Nutrient loads for the 23 POTWs that discharge directly to the SCB and the five that discharge inland to rivers were estimated from the quarterly NPDES monitoring reports using measured effluent discharge and concentration data (Lyon and Stein 2009; Supplemental Information (SI) Table SI-1; ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2013AnnualReport/ar13_245_258SI.pdf). For NPDES discharges to inland rivers, the nutrient load attributed to PS was subtracted from the total loads estimated for that river, parsing out loads attributable to NPS and natural sources.

Field Sampling and Laboratory Methods

Discharge and water quality samples were collected at 34 wet-weather and 57 dry-weather mass emission stations by Ventura, Los Angeles, Orange and San Diego Counties under their NPDES permits or by SCB Regional Monitoring Program partners from November 2007 to October 2009 (Table 1). County NPDES reports were also reviewed for data on wet- and dry-weather runoff nutrient concentrations to supplement these data. Flow data available to calculate riverine loads and fluxes included: 1) continuous flow data from USGS or County-maintained gauges and 2) wet-weather event monitoring, in which flow data was available only for the duration of the storm event. Event based flow monitoring, and water level elevation data were used to generate a continuous record of discharge.

Water quality samples of contaminants during storm events were collected as time-weighted (Orange County) or flow-weighted (all other counties) composites and reported as event mean concentrations. Dry-weather water quality was determined from single grab samples. The stormwater agencies analyze nitrite + nitrate (NO_x), ammonium (NH_4), and soluble reactive phosphorus (PO_4) using automated colorimetry via an autoanalyzer (APHA 1992). Constituents of interest not routinely analyzed included particulate nitrogen (PN) and particulate phosphorus (PP), TN and TP, and urea. PP and PN was subtracted from total nutrients to yield dissolved organic P (DOP) and N (DON). These additional constituents were analyzed on a split sample for all wet-weather samples and on selected dry-weather samples. Silicate was measured by automated colorimetry (APHA 1992). TP and TN were digested using the persulfate method (Valderrama 1981), then analyzed as PO_4 and nitrite (NO_2) by autoanalyzer (APHA 1992). Suspended matter particulate collected on a 0.7 µm glass fiber filter samples analyzed for PN and PP. PP samples were digested by combustion and hydrolysis as in Solorzano and Sharp (1980) then analyzed as PO_4 by autoanalyzer (APHA 1992). Total suspended solids (TSS) were measured using a gravimetric technique (Banse *et al.* 1963).

Table 1. Number of monitored wet- and dry-weather sites and number of wet- and dry-weather site-events monitored by Ventura, Los Angeles, Orange, and San Diego Counties (under their NPDES permits) and SCB Regional Monitoring Program (Bight'08) partners from November 2007 to October 2009.

	No. of Wet Weather Sites	No. of Site-Events Monitored	No. of Dry Weather Sites	No. of Site-Events Monitored
Ventura County	4	8	3	9
Los Angeles County	7	14	7	49
Orange County	12	22	11	44
San Diego County	11	22	11	11
Bight '08 Partners	--	--	25	150
Total	**34**	**66**	**57**	**263**

Estimation of Nutrient Loads and Fluxes from Monitoring Data

POTW and riverine wet-weather, dry-weather, or total nutrient loads (L), given as daily loads (kg day^{-1}) or annual mass loads (kg), were estimated using nutrient concentrations (c, mg L^{-1}), flow (Q, $\mathrm{m}^3\ \mathrm{day}^{-1}$), and a unit conversion constant k :

$$L = kcQ \qquad \textbf{Eq. 1}$$

For flux, defined as watershed area-specific load and expressed as kg $\mathrm{km}^{-2}\ \mathrm{day}^{-1}$, was calculated using L and watershed area (A_w)

$$F = LA_w^{-1} \qquad \textbf{Eq. 2}$$

Using continuous flow data, days representing wet-weather events versus dry-weather baseflow were categorized by plotting a hydrograph for November 2008-March 2009. Cumulative density frequency plots (CDFs) were produced to compare observed flow among the streams and to calculate the percent of time flow was above baseflow conditions (i.e., wet-weather events).

Modeling to Estimate Riverine Fluxes in Unmonitored Watersheds and Natural Source Contributions

A modified version of the land use based rainfall runoff model previously developed by Ackerman and Schiff (2003) for the SCB was used to estimate freshwater runoff Q ($\mathrm{m}^3\ \mathrm{day}^{-1}$) and TN and TP loads associated with wet-weather events. This modeling approach uses a paradigm in which rainfall produces runoff that varies in volume and water quality as a function of the type of land cover (for e.g., natural versus commercial, agricultural, residential and other land-uses). The general model set up, derivation of runoff coefficients for stormwater discharge volumes, and land-use specific runoff concentrations is described in detail by Ackerman and Schiff (2003).

Modeled storm discharge Q was calculated as a function of drainage area (A, km^2), mean rainfall intensity (I, mm day^{-1}), hydraulic runoff coefficient (C), and a unit conversion constant (k):

$$Q = AICk \qquad \textbf{Eq. 3}$$

Hydraulic runoff coefficient (C) values and land-use specific runoff coefficients vary as a function of land-use/cover type (Table SI-2). Within each watershed, discharge Q was calculated as the sum of land-use specific discharges from each of six categories -- agriculture, commercial, industrial, open space (natural), residential, and other urban -- for all catchments (Table SI-3). The hydraulic runoff coefficients were derived specifically for Southern California using bounded iterative optimization from local runoff data.

Daily nutrient loads (L) and fluxes (F) were estimated for each catchment and summed to determine the total loads for a given watershed, using Equations 1 and 2. The model domain included all Southern California coastal watersheds with an initial total watershed area of 27,380 km^2 (Figure 1). Daily precipitation data for approximately 200 rain gauge stations was obtained from the National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite, Data and Information Service (NESDIS), National Climatic Data Center (NCDC), and Climate Data Online (CDO) databases. Rainfall data were aggregated to daily precipitation totals (cm day^{-1}) for the watersheds and interpolated within each watershed on a regular grid using a biharmonic spline interpolation method (Sandwell 1987).

Modeled nutrient loads were validated with measured loads from 23 watersheds that had a complete suite of measured discharge and nutrient concentration data for the 2008-2009 wet season. Model error in predicting wet-weather concentrations and fluxes was quantified through a least squares regression between observed and modeled nutrient concentrations and fluxes using a linear regression model with no-intercept. The model was used to estimate daily discharge and nutrient loads in unmonitored watersheds (7% of total SCB coastal watershed area). Based on the 29 storm site events during 2008-2009, a good correspondence was observed between modeled ($562 \times 10^6\ \mathrm{m}^3$) versus measured stormwater volume ($461 \times 10^6\ \mathrm{m}^3$) with a $R^2 = 0.78$ and slope of 1.17. A time-series of modeled versus measured discharge showed that the model captures the timing and magnitude of peak flows to the SCB, but does not capture dry-weather flows (Figure SI-1). At a watershed scale, the model predicted 50 to 60% of the variation in watershed TN and TP loads and 14 to 63% of the variation in dissolved inorganic nutrient load. The model under-predicts nutrient loads, with slopes from 0.14 to 0.63 (Table SI-4). When aggregated across watersheds, the relative error in total regional predicted versus measured load ranges from 4 to

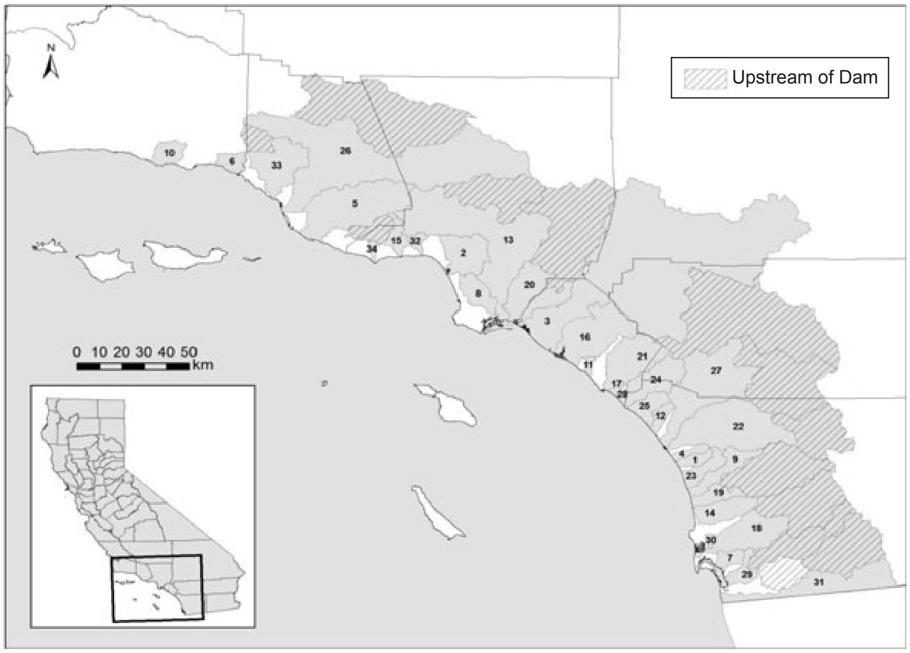

Figure 1. Map of the coastal watersheds draining to the Southern California Bight; hashed lines indicate areas behind major dams that were excluded from the model domain (see Methods section).

38% for TP and TN, respectively, and 18 to 78% for dissolved inorganic forms.

To estimate the contribution of NPSs and natural sources to riverine loads and fluxes, modeled wet-weather estimates were aggregated into categories of loads and fluxes from open (natural) versus developed land-uses (NPS, agriculture, other urban, commercial, residential). These estimates were compared to PS estimates from inland and ocean POTW PS discharges Bight-wide and for six SCB sub-regions: South San Diego, North San Diego/South Orange County, North Orange County/San Pedro Bay, Santa Monica Bay, Ventura and Santa Barbara. To estimate anthropogenic influence on nutrient loads to the SCB, the model was run with a scenario of 100% natural landscape (open land-use/no development) for the entire Bight as a representation of a "pre-urbanization" baseline. Because there were no dams withholding potential runoff in the modeled pre-urbanized state, the model domain was expanded to include areas above existing dams. Pre- and post- urbanization modeling scenarios compare changes in loads due to anthropogenic sources, i.e., change in land-use, and the addition of dams to withhold runoff and ignores potential climatic variation, i.e., rainfall; therefore, precipitation data from 2008-2009 was used for both types of scenario.

RESULTS

Spatial Variability in N and P Loads, Fluxes, and Sources to the SCB

The total annual terrestrial inputs to the SCB during the 2008-2009 water year were estimated as 1800 x 10^6 m^3 of fresh water discharge, 47.80 Gg TN and 2.86 Gg TP. Normalizing these annual loads by contributing watershed areas yields 3517 kg TN km^{-2} and 210 kg TP km^{-2} fluxes to the SCB (Table 2). These estimates represented a 52-fold increase in TN and a 30-fold increase in TP from a pre-urbanization scenario of 100% open land-use predicted by the

Table 2. Total annual loads (Gg) and fluxes (kg km^{-2}) for total nitrogen (TN) and total phosphorus (TP) in the Southern California Bight and six sub-regions.

	TN		TP	
	Load (Gg)	Flux (kg km^{-2})	Load (Gg)	Flux (kg km^{-2})
Southern California Bight	47.8	3517	2.83	210
Santa Barbara	0.036	44	0.0153	19
Ventura	0.604	100	0.16	27
Santa Monica Bay	15.6	15988	1.01	1038
SanPedro/Orange County	23.2	2434	0.77	81
North San Diego	0.52	64	0.113	14
South San Diego	7.81	2132	0.756	206

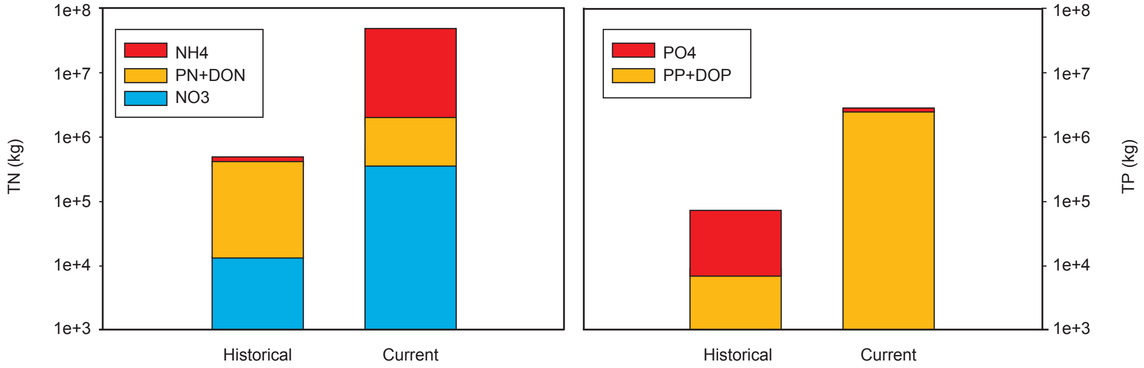

Figure 2. Comparison of terrestrial nutrient loads to the SCB pre-urbanization (historical) and current for total nitrogen as a sum of ammonium (NH4) + particulate nitrogen (PN) + dissolved organic nitrogen (DON) + nitrates (NO3), and total phosphorus as a sum of phosphates (PO4) + particulate phosphorus. The left panel represents the pre-development scenario, and the right panel shows the sum of natural, point, and nonpoint sources for 2008-2009.

land-use rainfall runoff model (0.91 Gg TN and 0.096 Gg TP; 31 kg TN km^{-2} and 3.3 kg TP km^{-2}, Figure 2). The effect of anthropogenic land-use changes was disproportionate on nutrient forms. Dissolved organic and particulate N and P were the dominant forms of nutrient in the runoff in the pre-urbanization scenario. Relative to this time period, DIN and PO_4 loads increased 580-fold and 409-fold respectively, compared to 4 fold increase in PN + DON and an 8-fold increase in PP + DOP.

Bight-wide, PS represented 58% of the total annual terrestrial freshwater discharge, 92% of the TN loads, and 76% of the TP loads to the SCB (Figure 2; Table 2), most of which was discharged directly via ocean outfalls (1060 x 10^6 m^3 of freshwater, 43.70 Gg TN and 2.16 Gg TP). Riverine discharge from coastal watersheds during the 2008-2009 water year contributed 750x10^6 m^3 of freshwater, 4.10 Gg TN and 0.70 Gg TP to the SCB. Approximately, 41% of TN and 30% of TP riverine loads were from inland PS discharges, while the remaining loads were from NPSs and natural sources.

Densely populated Los Angeles (LA) and northern Orange County (OC) metropolitan areas (46% developed land-use; Table SI-5), contributed 79% of the total TN loads and 62% of the total TP loads to the SCB (Table 2; Figure 3). LA and OC are a part of the Santa Monica Bay (SMB) and San Pedro/Orange County (SPOC) sub-regions, respectively, that collectively contributed 3,600 kg TN km^{-2} and 170 kg TP km^{-2} fluxes to the SCB. SPOC contributed the highest loads, but had lower fluxes than SMB (Table 2), since the drainage area for San Pedro is an order of magnitude higher than for Santa Monica Bay (Table SI-5). PS contributed most of the TN loads (4% inland PS, 91% ocean PS), while NPS contributed an additional 5% in the SMB and SPOC sub-regions.

South San Diego (SSD), another major metropolitan area within the region (21% developed land-use), contributed loads that were an order of magnitude less than loads from LA and OC metropolitan areas (16% TN loads and 27% TP loads to the SCB), although the fluxes were comparable (Table 2). Most of TN loads (86%) in SSD were from PSs.

For the remaining sub-regions, NPSs contributed the greatest nutrient loads to the SCB; ocean and inland PS discharges and natural sources to the ocean contributed less than 2% of TN and TP loads. The TN and TP loads from Ventura were comparable to those from North San Diego (NSD), but fluxes for Ventura were two times greater than those for NSD (Table 2). The Santa Barbara (SB) sub-region, with low development and low agricultural land-use, contributed the lowest TN and TP loads and fluxes to the SCB, approximately two orders of magnitude less than the LA, OC, and SD metropolitan area contributions.

Temporal Variability in N and P Loads, Fluxes, and Sources to the SCB

There were no strong seasonal effects on nutrient loads from sub-regions and watersheds with dominant PS sources, (e.g., Los Angeles and San Gabriel Rivers; Table 3), possibly because the PS contributions remain relatively constant throughout the year. The San Gabriel River, Los Angeles River, San Diego Creek, Santa Clara River and Calleguas Creek watersheds represented the dry weather “hot

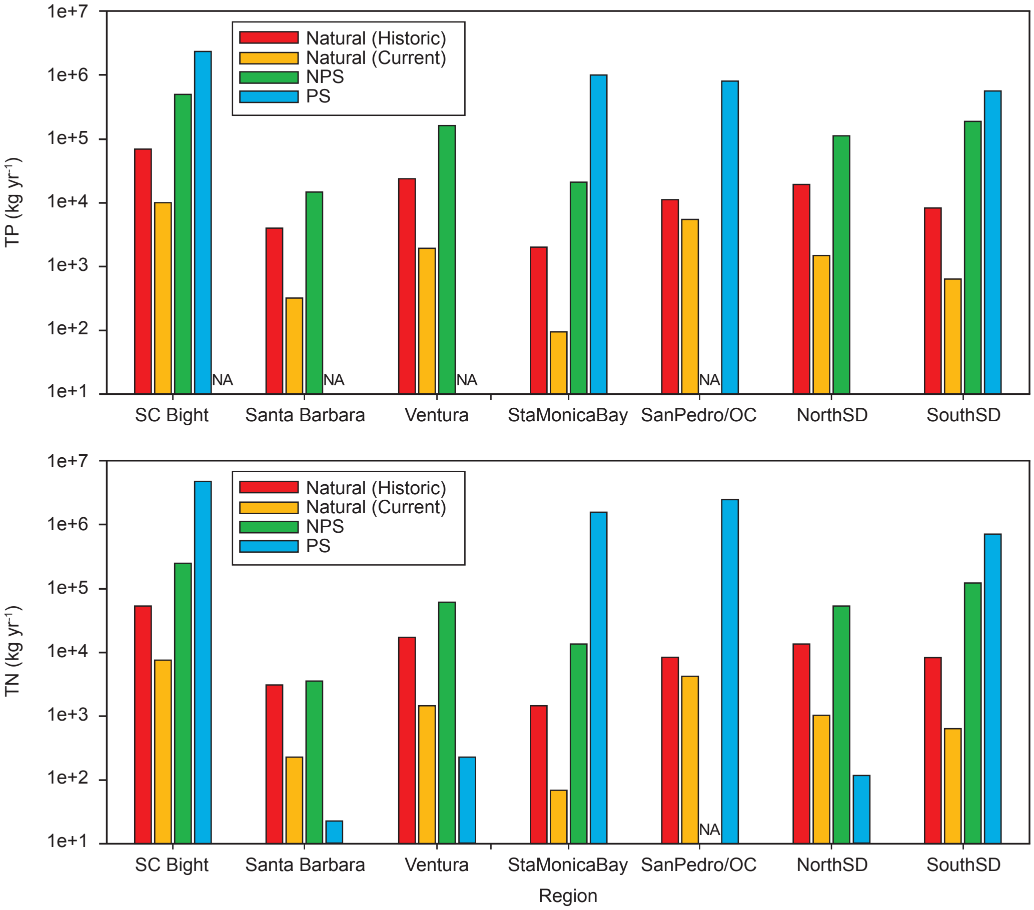

Figure 3. Comparison of natural, non-point, and point sources of terrestrial nutrient loads to the SCB for TP (top) and TN (bottom) for southern California Bight and the six sub-regions. The leftmost bar in each cluster represents the pre-development scenario, and the rest show the division of loads into natural, point, and nonpoint sources for 2008-2009. Inland PS discharge has been added to the total PS column

spots" for nutrient loading to the SCB, possibly due to inland PS discharges and irrigated agricultural discharges in Calleguas Creek (Figure 4).

Across watersheds, riverine TN loads were 46% higher and TP loads were 71% higher during wet weather compared to dry weather (Table 4). The discharge from 10 watersheds (Los Angeles River, San Gabriel River, Santa Ana Channel, Calleguas Creek, Ballona Creek, Newport Bay, Tijuana River, Santa Margarita River, Santa Clara River, Chollas Creek) represented 84% of the total riverine TN and 80% of TP loads to the SCB (Table 3). The ranges in temporal variability were extreme; in some watersheds where dams occur in the upper watershed (for e.g., Santa Ana River), wet-weather flows were captured behind the dam and either not released, or released slowly during dry weather. In contrast, in watersheds, such as Santa Margarita River, more than 95% of the TN and TP loads occurred during wet weather. The dominance of wet weather over dry-weather loads was driven by discharge rather than concentration. Averaging across watersheds, mean TN and TP concentrations in wet-weather riverine runoff to the SCB was not significantly different than the dry-weather concentrations (Table 5). Differences in nutrient form were more noticeable; DON was higher and PN lower during dry weather than during wet weather, while PO4 was lower and PP higher during wet than during dry weather. Urea was a minor component of total DON (10%), with average concentrations of 0.17 to 0.1 mg urea-N L^{-1} for wet and dry weather, respectively.

DISCUSSION

This study presents the first comprehensive regional estimates of terrestrial TN and TP loads and fluxes to the SCB. Bight-wide, the annual nutrient flux estimates, 3,157 kg TN km^{-2} and 210 kg TP km^{-2} are comparable or higher than the estimates for the US Atlantic Coast and Northern Europe watersheds,

Table 3. Watershed area (m^2), total nitrogen (TN) and total phosphorus (TP) loads ($kg\ km^{-2}\ yr^{-1}$) for annual, wet weather (WW), and dry weather (DW); and total wet- and dry-weather discharge (m^3) derived from monitoring data. Watersheds are listed in descending order of annual TN load; numbers in parentheses indicates location on Figure 1 map. * Los Angeles River and San Gabriel Rivers contribute 1.27E+06 kg of TN and 1.54E05 kg of TP based on river monitoring data; however, loads estimated using POTW effluent data for these systems were higher (Table SI-1).

Watershed	Area	Annual Load		WW Discharge	Annual WW Load		DW Discharge	Annual DW Load	
		TN	TP		TN	TP		TN	TP
*San Gabriel River (20)	3.00E+08	7.31E+05	7.35E+04	8.10E+07	2.39E+05	4.19E+04	7.20E+07	4.91E+05	3.16E+04
*Los Angeles River (13)	1.40E+09	5.36E+05	8.08E+04	8.70E+07	3.30E+05	4.34E+04	9.70E+07	2.07E+05	3.74E+04
Calleguas Creek (5)	8.70E+08	3.60E+05	1.01E+05	2.40E+07	2.17E+05	7.83E+04	1.30E+07	1.43E+05	2.24E+04
Tijuana River (31)	5.70E+08	3.45E+05	8.83E+04	2.60E+07	3.22E+05	8.24E+04	1.30E+06	2.32E+04	5.93E+03
Newport Bay (16)	3.70E+08	2.74E+05	6.98E+04	2.20E+07	2.48E+05	6.89E+04	5.30E+06	2.59E+04	9.62E+02
Santa Clara River (26)	3.10E+09	2.37E+05	5.83E+04	1.80E+07	5.98E+04	2.23E+04	5.60E+05	1.77E+05	3.60E+04
Santa Margarita River (27)	9.80E+08	1.37E+05	2.02E+04	1.70E+07	1.35E+05	1.91E+04	7.60E+06	2.65E+03	1.08E+03
Santa Ana Channel (3)	5.80E+08	1.10E+05	1.83E+04	4.10E+07	1.09E+05	1.82E+04	2.80E+05	8.12E+02	0.00E+00
Chollas Creek (7)	8.70E+07	1.08E+05	1.34E+04	8.10E+06	1.06E+05	1.31E+04	4.10E+05	1.99E+03	3.22E+02
Ballona Creek (2)	3.20E+08	9.39E+04	1.67E+04	2.70E+07	7.68E+04	1.38E+04	9.30E+06	1.71E+04	2.91E+03
Agua Hedionda Creek (1)	7.90E+07	7.57E+04	4.16E+03	8.70E+06	5.57E+04	3.30E+03	1.20E+07	2.00E+04	8.53E+02
Escondido Creek (9)	2.20E+08	6.36E+04	2.51E+03	9.50E+06	4.75E+04	2.09E+03	4.10E+06	1.61E+04	4.18E+02
San Marcos Creek (23)	1.50E+08	5.99E+04	4.67E+04	1.10E+07	5.87E+04	4.65E+04	1.70E+06	1.16E+03	1.95E+02
San Diego River (18)	4.50E+08	5.45E+04	5.18E+03	1.90E+07	5.14E+04	4.68E+03	4.90E+06	3.06E+03	4.95E+02
San Dieguito River (19)	1.40E+08	4.34E+04	1.43E+04	4.20E+06	2.34E+04	1.30E+04	6.60E+06	2.01E+04	1.25E+03
San Luis Rey River (22)	9.20E+08	4.34E+04	8.19E+03	5.90E+06	2.22E+04	3.86E+03	8.40E+06	2.13E+04	4.23E+03
Malibu Creek (15)	1.20E+08	3.89E+04	4.36E+03	5.40E+06	2.28E+04	3.44E+03	6.60E+06	1.61E+04	9.12E+02
Dominguez Channel (8)	1.70E+08	3.34E+04	1.26E+04	1.80E+07	2.17E+04	1.08E+04	4.10E+06	1.17E+04	1.73E+03
San Juan Creek (21)	4.50E+08	2.98E+04	7.70E+03	1.10E+07	2.80E+04	7.65E+03	2.90E+06	1.85E+03	9.00E+01
Los Penasquitos Creek (14)	3.40E+07	2.88E+04	5.89E+03	9.70E+06	2.76E+04	5.67E+03	2.10E+06	1.15E+03	2.14E+02
Goleta Slough (10)	1.30E+08	2.88E+04	1.24E+04	3.90E+06	2.77E+04	1.22E+04	6.20E+05	1.16E+03	1.69E+02
Tecolote Creek (30)	2.50E+07	1.53E+04	1.73E+03	3.80E+06	1.53E+04	1.72E+03	1.20E+05	3.25E+01	5.00E+00
Secunda Deschecha (28)	2.80E+07	1.39E+04	1.29E+03	2.60E+06	5.48E+03	1.07E+03	5.80E+05	8.39E+03	2.21E+02
Sweetwater Creek (29)	1.20E+08	9.17E+03	9.36E+02	1.10E+06	2.80E+03	2.16E+02	2.30E+06	6.37E+03	7.20E+02
Buena Vista Creek (4)	5.80E+07	9.15E+03	1.26E+03	4.40E+06	8.38E+03	1.23E+03	4.30E+05	7.66E+02	3.48E+01
San Mateo Creek (24)	3.40E+08	8.94E+03	7.48E+02	2.50E+06	4.56E+03	7.14E+02	9.50E+05	4.39E+03	3.40E+01
Carpenteria Creek (6)	9.40E+07	7.67E+03	2.90E+03	2.60E+06	7.67E+03	2.90E+03	3.40E+03	NA	NA
Prima Deschecha (17)	2.10E+07	5.94E+03	2.06E+02	4.70E+05	4.88E+03	9.45E+01	3.30E+05	1.05E+03	1.11E+02
Ventura River (33)	7.80E+08	3.90E+03	3.12E+02	1.40E+06	6.24E+02	7.80E+01	5.40E+06	3.28E+03	2.34E+02
Zuma Creek (34)	2.60E+07	5.85E+02	1.56E+02	1.00E+05	5.69E+02	1.56E+02	2.00E+04	1.56E+01	0.00E+00
Laguna Creek (11)	2.70E+07	4.27E+02	3.24E+01	6.70E+04	2.78E+02	2.97E+01	1.80E+04	1.49E+02	2.70E+00
Topanga Creek (32)	5.10E+07	1.89E+02	4.08E+01	6.20E+05	3.06E+01	2.55E+01	4.70E+05	1.53E+02	1.53E+01
San Onofre Creek (25)	1.50E+08	1.35E+02	3.00E+01	9.30E+04	1.35E+02	3.00E+01	NA	NA	NA
Las Flores Creek (12)	7.80E+07	7.80E+01	5.46E+01	2.00E+04	7.80E+01	5.46E+01	3.70E+03	NA	NA

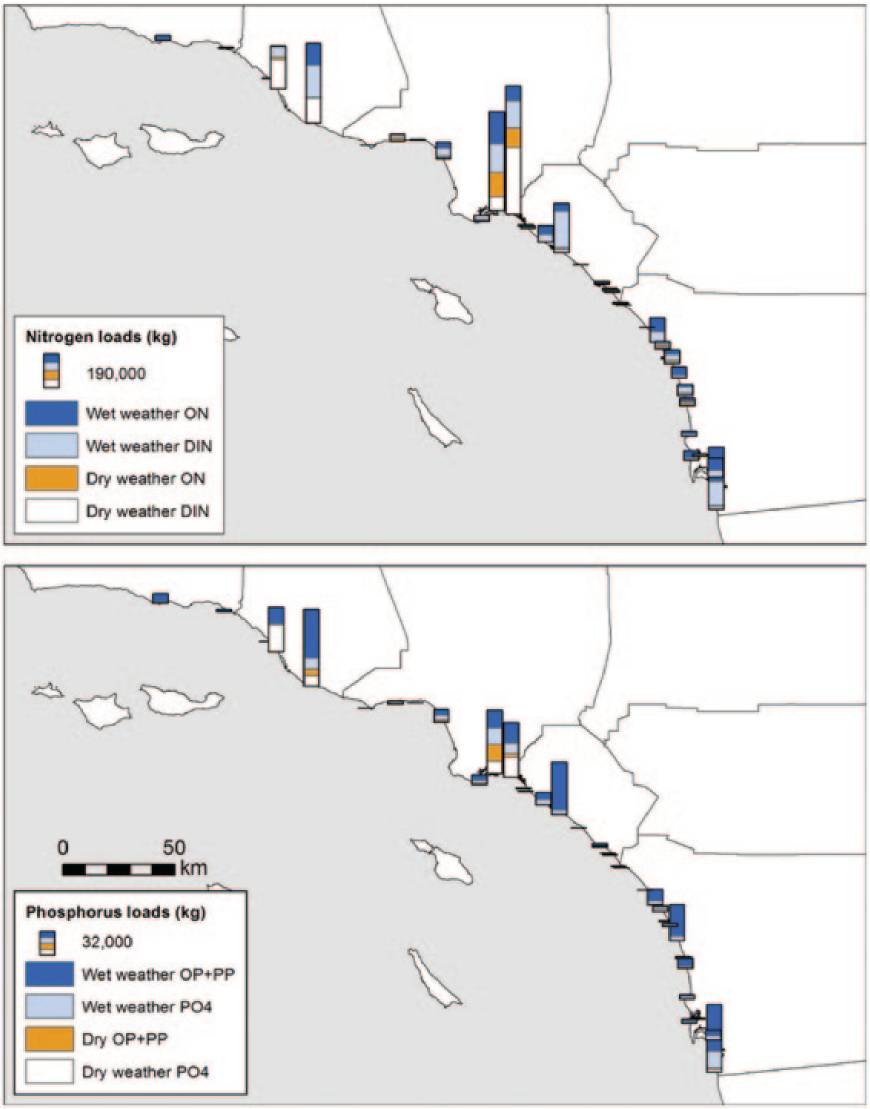

Figure 4. Relative magnitude of wet- and dry-weather Nitrogen and Phosphorus loading among SCB watersheds during 2008-2009.

Table 4. Total annual, wet- and dry-weather riverine loads (Gg yr^{-1}) and fluxes (kg km^{-2} yr^{-1}) to the Southern California Bight by nutrient form.

Nutrient Form	Wet Weather		Dry Weather		Total	
	Annual Load	Annual Flux	Annual Load	Annual Flux	Annual Load	Annual Flux
TN	2.67	171	1.23	78.8	3.9	249.8
NH_4	0.271	17.4	0.07	4.5	0.37	21.5
NO_3	1.15	73.8	0.802	51.4	1.95	125.2
DON+PN	1.26	80.5	0.354	22.7	1.62	103.2
TP	0.64	40.9	0.151	9.7	0.79	50.6
PO_4	0.166	10.6	0.107	6.9	0.273	17.5
DOP+PP	0.472	30.3	0.044	2.8	0.517	33.2

Table 5. Mean concentrations and standard deviations (Std Dev) of N and P forms (total nitrogen (TN), NO_2+NO_3 (NO_x), ammonium (NH_4), dissolved organic nitrogen (DON), urea, and particulate nitrogen (PN), total phosphorus (TP), phosphate (PO_4), dissolved organic phosphorus (DOP), and particulate phosphorus (PP)) in wet- and dry-weather discharge, and percentage of TN and TP where applicable; n = sample size (total number of wet or dry weather sampling events); and all concentrations are expressed in mg L^{-1}.

Constituent	Wet Weather (n = 66)		Dry Weather (n = 263)	
	Mean ±Std Dev	% of TN	Mean ±Std Dev	% of TN
TN	4.16±2.18	--	3.38±3.57	--
NO_x	1.61±1.17	39%	1.33±2.25	36%
NH_4	0.26±0.29	6%	0.11±0.12	3%
DON	1.18±0.82	28%	1.74±2.32	48%
- Urea	0.17±0.13	4%	0.10±0.11	3%
- Other DON	1.01±0.69	24%	1.64±2.21	45%
PN	1.10±1.26	27%	0.48±0.74	13%
	Mean ±Std Dev	% of TP	Mean ±Std Dev	% of TP
TP	1.52±1.93	--	0.60±1.02	--
PO_4	0.68±0.93	45%	0.43±0.86	68%
DOP	0.26±0.23	17%	0.15±0.32	23%
PP	0.58±0.93	38%	0.06±0.09	9%

which are among the highest published estimates (Table 6). Terrestrial TN loads from Southern California, defined in this study as inclusive of the SCB and the Central Coast to 37° latitude, estimated by SPARROW modeling for the base year 1992 (41 Gg TN yr^{-1}, Bergamaschi *et al.* 2012) were slightly less than those estimated for the SCB alone (47.8 Gg TN yr^{-1}). This may be due to differences between the base prediction year for SPARROW (1992) and the study year (2008), variation in precipitation, and population growth in SCB watersheds over this 15 year timeframe.

The anthropogenic nutrient export quantified in this study (47.32 Gg TN yr^{-1} and 2.88 Gg TP yr^{-1}) represents a 52-fold increase in N and a 30-fold increase in P from a pre-urbanization baseline (c. 1850s). These estimated increases are comparable to those observed in Sobota *et al.* (2013) for the continental United States, and higher than estimates from other studies of anthropogenic-enhanced fluxes in the continental United States (6-fold; Howarth *et al.* 2002, Howarth 2003) and the Yellow Sea of China (10- to 15-fold; 2003). Globally, dissolved inorganic nutrients have a disproportionate share in increases relative to the pre-urbanization estimates. For example, Yasin *et al.* (2010) report a disproportionate increase in DIN and DIN compared to DON and DOP in coastal watersheds of Africa. These increases can be generally attributed to fertilizer application, treated municipal and industrial wastewater releases, human-induced increases in atmospheric deposition of oxidized forms of nitrogen, and fixation by leguminous crops (Howarth *et al.* 1996).

The distribution of PS, NPS, and natural source contributions in the present study is comparable to that observed by Bergamaschi *et al.* (2012), who found that population-based sources, including PSs and NPSs, in urban areas contribute 97% of the TN exported to the SCB and central coast nearshore. Discharge from POTW PS is the predominant source of TN and TP loads to the SCB, primarily via four major ocean outfalls, while loads from natural sources are relatively small (<1%). This is consistent with Bergamaschi *et al.* (2012), who estimated that natural sources contribute approximately 1% of coastal TN coastal export. Further, despite differences in base year (1992 versus 2008) and geographic scope, the present study's monitored estimates of coastal export support the SPARROW modeled estimates of source distribution for the highly urbanized study region. These estimates are consistent with Bergamaschi *et al.* (2012), who observed that natural sources provide an increased contribution to terrestrial nutrient export with increasing latitude along the Pacific Coast, from

Table 6. Comparison of riverine nutrient fluxes from SCB watersheds to fluxes cited in similar studies. All estimates are in kg km^{-2} yr^{-1}.

Source	Region	TN	TP
Howarth *et al.* 1996	North Canadian River	76	4.5
	Northeast Coast (US)	1,070	139
	North Sea	1,450	117
	Northwest European Coast	1,300	82
	Amazon & Tocatins	505	236
Schaefer *et al.* 2012	Spokane River	117	N/A
	Yakima River	194	N/A
	Snake River	93	N/A
	Nehalem River	1670	N/A
	Deschutes River	71	N/A
	Willamette River	1065	N/A
	Suislaw River	1086	N/A
	Rogue River	114	N/A
	Klamath River	115	N/A
	Eel River	334	N/A
	Russian River	329	N/A
	Sacramento River	104	N/A
	Stanislaus River	106	N/A
	Tuolumne River	80	N/A
	Merced River	99	N/A
	Pajaro River	460	N/A
	Salinas River	88	N/A
	Santa Clara River	512	N/A
	Area-weighted mean of all watersheds	165	N/A
Ludwig *et al.* 2009	Mediterranean Sea	707	32
	Black Sea	422	21
This Study	Riverine Flux - Southern California Bight	249.8	50.6
	Riverine Flux - Southern California Bight (Top 10 Watersheds)	875	151
	Anthropogenic Nutrient Export (Riverine + Direct Discharges to SCB)	3157	210

25% (15 Gg TN) in northern California to roughly 50% (144 Gg TN) in Oregon and Washington. Notably, the present study's projected increases from a pre-urbanization baseline were two times (6- to 20-fold) higher than projections by Howarth *et al.* (1996) for temperate climates, as the natural source contribution in Mediterranean regions (1 Gg in the SCB) is much lower than that observed in temperate climates.

The relative importance of NPS versus PS is scale-driven, both spatially and temporally, with PS loads spatially significant only for urbanized settings at regional scales. At continental (Bouwman *et al.* 2005) or global scales (Seitzinger *et al.* 2005), the significance is placed on NPS loads. At a sub-regional scale, variations in the importance of PS versus NPS contributions are predictable as a function of primary land-use (Alvarez-Cobelas *et al.* 2008). PS loads are most significant in highly urbanized sub-regions with predominantly commercial, industrial, and residential land-uses (San Pedro, Santa Monica Bay, southern San Diego); whereas NPS loads are most significant in sub-regions dominated by agricultural land-uses (parts of Ventura and northern San Diego Counties). The range in flux estimates, from 44 kg TN km^{-2} in the relatively pristine Santa Barbara sub-region to 15,988 kg TN km^{-2} in the highly urbanized and PS-dominated sub-region of Santa Monica Bay, reflects this variation in land-use composition relative to significant source type. Comparable N fluxes were reported by Sobota *et al.* (2009) in central California watersheds (581 - 11,234 kg TN km^{-2}), though fluxes in that region are driven by agricultural NPS rather than PS as is the case in the SCB.

The temporal scale of PS, NPS, and natural discharges to the coast is important to understanding effects on the nearshore environment, particularly in Mediterranean climates with distinct wet-weather (high) and dry-weather (low) riverine fluxes of nutrients to the coastal ocean. In urbanized subregions, such as Santa Monica, San Pedro Bay and southern San Diego, PSs have the most influence on total terrestrial flux and provide a chronic source of nutrients throughout the year. In NPS-dominated watersheds, storms events provide a pulsed discharge during which the majority of nutrients are exported to the coast.

The effects of increased anthropogenic nutrient loads to the SCB are not well understood and require further study. Over the last decade, managers have become more focused on this issue because of increased awareness of harmful algal blooms (Trainer *et al.* 2000, Schnetzer *et al.* 2007, Caron *et al.* 2010) and decline in dissolved oxygen in the SCB (Booth *et al.* In press). In addition, the conventional paradigm that terrestrially-derived nutrients are overwhelmed by upwelling sources in California Current nearshore zone has been recently challenged. Howard *et al.* (In press) found that annually anthropogenic N sources equal that of upwelling for regions of the SCB dominated by urban and agriculture. Similarly, a recent study has observed that nearshore circulation models are needed to quantify the effects of anthropogenic nutrients on primary productivity and dissolved oxygen in the SCB (Booth *et al.* In press). The findings of the present study provide a quantitative linkage between anthropogenic activities in watersheds and nutrient inputs to coastal systems, establishing boundary conditions for terrestrial inputs to further understand the ecosystem effects of anthropogenic nutrients on the nearshore SCB.

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SUPPLEMENTAL INFORMATION

Supplemental Information is available at ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2013AnnualReport/ar13_245_258SI.pdf.