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Baseline

A baseline of terrestrial freshwater and nitrogen fluxes to the Southern California Bight, USA

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ABSTRACT

Time series were compiled of terrestrial nitrogen, phosphorus, carbon, iron, and silica fluxes to the Southern California Bight (SCB), a U.S. West Coast embayment (Sutula et al., 2021). Monitoring data and model output were used to construct a baseline of inputs from direct point source (PS) discharges of wastewater treatment (WWT) effluent (via ocean outfalls) and PS, non-point and natural sources from coastal rivers. The baseline covers 1971—2017 for large WWT plants discharging >50 million gallons per day (MGD) and 1997–2017 for small WWT plants and rivers. PS are the dominant nitrogen source, with contributions of 70% of the total annual freshwater discharge and 95% of nitrogen loads. WWT upgrades have reduced organic nitrogen loads by 73% since 1971. Inorganic nitrogen loads have generally held constant (35–40 Gg y^{-1}) for the large WWT plants. This baseline represents a period prior to extensive wastewater and stormwater recycling that is increasing in the region.

Ocean discharges of wastewater and stormwater runoff are among the principle sources of pollution loading to our coasts, impacting receiving water quality and marine life (Lyon and Stein, 2009). One area of particular concern is the Southern California Bight (SCB), a large marine open embayment 94,000 km^2 in size that receives the urban and agricultural non-point source runoff from coastal rivers and ocean discharges from primary or secondary treated wastewater from a coastal population of 22.7 million (United States Census Bureau, 2008). Since the late 1990s, plants upgrades to "secondary" wastewater treatment (WWT) have substantially reduced the organic carbon loading that consumes oxygen and suspended matter associated with particulate contaminants such as heavy and trace metals that occurred prior to the Clean Water Act (1972; Setty et al. (2012)). However, these upgrades would not be expected to substantially affect nutrient loading (National Research Council, 2000). Even when WWT has reduced per capital nutrient loads, reductions can be overridden by population growth, which has roughly doubled since the 1970s in the SCB.

Documenting the baseline of anthropogenic discharges of freshwater and nitrogen to the coastal ocean has become a priority, for two reasons. First, climate change is driving acidification and deoxygenation (OAD) in the southern California Current Large Marine Ecosystem (CCS; Feely et al. (2008)) at rates roughly twice the global average (Osborne et al., 2020). Concern exists that these global trends may be intensified by local anthropogenic inputs of nitrogen and carbon (Howard et al., 2014; Bednaršek et al., 2020). Increased flux of nitrogen from terrestrial runoff is considered one of the main causes of coastal eutrophication (Howarth, 2008). In the SCB, observations of chronic algal blooms (Nezlin et al., 2018), declining oxygen (Booth et al., 2014) and undersaturated waters on the SCB (McLaughlin et al., 2018) suggest that coastal eutrophication could be a factor (Howard et al., 2014). Numerical ocean modeling studies estimated that local anthropogenic inputs have doubled available nitrogen from upwelling at subregional scales within 20 km of the coast (Howard et al., 2014). California's climate actions strategies and policies place at high priority the investigation of the degree to which anthropogenic inputs are currently influencing coastal acidification and deoxygenation (CAD) in the CCS, how their relative effect will change over time, and their influence on regional marine ecosystem vulnerability (Ocean Protection Council, 2018).

Second, this baseline of river runoff and ocean discharges would be expected to change with increased water recycling, which has been

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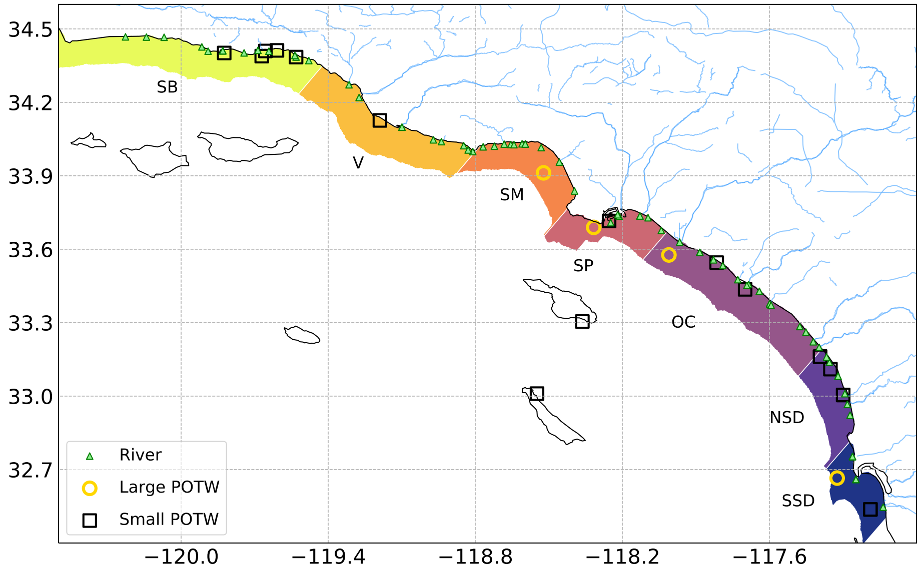

Fig. 1. Map of all inputs in the Southern California Bight categorized by type of input. There are four large POTWs, nineteen small POTWs, and 75 rivers. Colored sub-regions are used to summarize nutrient loading. SB = Santa Barbara, V = Ventura, SM = Santa Monica Bay, SP = San Pedro Bay, OC = Orange County, NSD = North San Diego, SSD = South San Diego.

accelerating in the region as a means to provide a sustainable and drought-proof source of water for this urbanized Mediterranean coast (Miller, 2006; Tran et al., 2016). In Southern California, recycling of wastewater for non-potable uses (e.g., irrigation) is already widespread (Markus and Deshmukh, 2010). This represents a diversion of freshwater and nutrient loads from the coast through land application, though the volume and associated loads diverted is low relative to what is still currently discharged via ocean outfalls and inland to coastal rivers. Water recycling for the purpose of indirect or direct potable use has the promise of reclaiming a much larger proportion of wastewater (Grant et al., 2012). However, treatment for potable reuses has resulted in ocean discharge of return brine from water treatment reverse osmosis, in which nitrogen and other constituents are concentrated (Pradhan et al., 2015). In addition, at some plants, provision of effluent of suitable quality for water recycling has caused some POTWs to reduce inorganic nitrogen from the typical concentrations (~35 mg L^{-1} N) found in conventional secondary effluent concentrations. Thus, as water recycling accelerates in the SCB, freshwater volume and concentration and loads of nitrogen may change in the future, which could greatly affect the transport, fate and effects of the wastewater plumes.

The effect of local anthropogenic inputs on CAD would be expected to vary spatially and temporally along the 450 km coastline of the SCB due to variability in magnitude and seasonality of terrestrial inputs and coastal oceanographic processes. Quantifying the relative magnitude and the inter-annual and seasonal variability in coastal nitrogen exports is a key step in establishing the quantitative links between local anthropogenic activities in watersheds and their coastal ecosystem effects. A spatially explicit, three-dimensional numerical ocean model of the southern CCS was developed and is being applied to disentangle the relative effects of climate change, natural climate cycles, and local terrestrial and atmospheric carbon and nutrient inputs, comprising of submesoscale circulation, biogeochemical cycles, and lower-trophic ecosystem (Deutsch et al., 2021; Renault et al., 2021). In the SCB, the investigation of the impact of local anthropogenic inputs on coastal biogeochemistry and CAD has proceeded through the compilation of observations and model output which describe a spatially explicit time series of terrestrial inputs to the SCB coastal ocean. These inputs are then being used as boundary conditions to force the SCB numerical model simulations to represent the effects of local terrestrial and atmospheric inputs, relative to natural climate cycles and climate change (Kessouri et al., 2021). The combined effects of local terrestrial and atmospheric inputs estimated on net primary productivity, coastal biogeochemistry and lower trophic ecosystem, including CAD, are described in a companion study (Kessouri et al., 2021).

The goal of this work is to present the detailed compilation and synthesis of the SCB time series of terrestrial nitrogen fluxes to the SCB as a companion to the available dataset (Sutula et al., 2021). Compilation included total and dissolved inorganic and organic nitrogen (N), phosphorus (P), silicate (Si), alkalinity, organic carbon (C) and iron (Fe) fluxes representing natural and anthropogenic sources from the coastal watersheds of the SCB that discharge to US coastal waters. The dataset represents the most comprehensive regional terrestrial nutrient and carbon coastal export estimates available for the SCB. It includes 1) WWT effluent discharged through ocean outfalls by county and municipal publicly owned treatment works (POTW, point source; PS) from 1971 to 2017 for large POTWs ≥50 million gallons per day (MGD), or 2.19 $m^3\ s^{-1}$, and 2000–2017 for small POTWs <50 MGD and 2) riverine surface water runoff (which contains both natural, PS and non-point source; NPS) for the period of 1997–2017. The dataset was analyzed to provide a synthesis of N coastal exports, specifically to: 1) quantify the temporal and spatial variability in riverine and ocean outfall fluxes to the SCB and 2) quantify the relative contribution of terrestrial natural sources, PS and NPS of N and P loads and fluxes to the SCB and how this varies spatially along the coast, and 3) provide a case study of how potable use water recycling has impacted the effluent quality and coastal nitrogen export of one POTW in the region.

The SCB is defined as an area from Point Conception (34.45°N) to the US - Mexico border (32.53°N). The climate of this region is Mediterranean, with rainfall concentrated largely over the winter months of December–March. The majority of runoff to the SCB occurs during wet weather storm events, with an average of 15 rain events per year (Schiff and Bay, 2003). Base-flow during non-storm conditions is hereto referred to as "dry weather" runoff. Precipitation in this region has strong inter-annual variability; over the study period of 1997–2017, total median annual rainfall was 9.9 cm, with ranges of 6.3–11.8 cm representing the 25th and 75th percentile and an annual maximum of 157 cm.

The methodology to approach developing the baseline reflects the fact that terrestrial nutrient sources are a combination of natural and anthropogenic sources (Yoon and Stein, 2008). In the United States, most of the monitored coastal watershed nutrient load estimates are from areas with combined sewer and stormwater systems (Shields et al., 2008) making the separation of PS and NPS difficult. The SCB is unique in that most of its municipalities and counties have completely separate sanitary and storm water sewer collection systems (Tiefenthaler et al., 2008). The nutrient fluxes flowing through the storm water collection systems are discharged into the rivers, whereas the treated effluents from POTWs are largely discharged for the majority of urbanized areas directly into the ocean via separate outfalls (Lyon and Sutula, 2011). For these reasons, the relative contribution of PS, NPS and natural terrestrial sources of nutrients can be characterized fairly accurately in the SCB.

We attempted uniformity across the sources in the targeted suite of compiled freshwater flow and constituent concentrations, including conductivity, dissolved inorganic nitrogen (DIN; ammonium, nitrate, nitrate), organic nitrogen (ON), phosphate and organic and particulate phosphorus, silica, total and dissolved iron, total organic carbon (TOC), and carbonate system parameters (alkalinity and pH or dissolved inorganic carbon (DIC)). SCB watersheds and the twenty-three large and small POTWs were grouped into 7 nearshore subregions for the purpose of synthesis (Fig. 1): Santa Barbara, Ventura, Santa Monica Bay, San Pedro Bay, Orange County, North San Diego, and South San Diego.

Among NPDES-permitted facilities, POTWs comprised the majority of discharges that occur via outfalls to the SCB; industrial point sources contributed a negligible amount of total nitrogen (TN) and total phosphorus (TP) to the SCB (Lyon and Stein, 2009) and were therefore excluded from data compilation. The four largest facilities each discharge over 100 MGD, and account for 86% of the total POTW effluent volume. These facilities are the Hyperion Treatment Plant (HTP) operated by the City of Los Angeles in the Santa Monica region, the Joint Water Pollution Control Plant (JWPCP) operated by the Los Angeles County Sanitation Districts in the San Pedro region, Orange County Sanitation District (OC San) Reclamation and Treatment Plants in Orange County, and the City of San Diego's Point Loma Wastewater Treatment Plant (PLWTP) in South San Diego (Fig. 1). HTP, JWPCP, and OC San currently treat to secondary or advanced secondary levels, while PLWTP treats to primary level. The small POTWs constitute a combination of secondary or tertiary treated effluents. One large and several small POTWs have partial or full nitrification-denitrification, which impacts DIN concentrations and loads. The historical record captures the changes in effluent volume and constituent concentrations with progressive WWT upgrades. The large POTW ocean outfalls discharge 2.5 to 8 km offshore at depths of 60 to 90 m, while the small POTW outfalls discharge approximately 1 km offshore between 5 and 20 m depth (Fig. 1).

Monthly discharge volume and constituent concentration data were compiled from each facility's discharge monitoring reports over the 1971–2017 for the four large POTWs and 2000–2017 for the small POTWs. Monitored constituents have changed over time according to permit requirements. Where constituent concentrations were incomplete or missing from permit monitoring, they were addressed with three approaches: 1) in the case of TOC, organic P or organic N, interpolation was done from the more routinely monitored biological oxygen demand in order to reconstruct the historical record pre-2008, and 2) for missing phosphate, nitrate, TN, TP, alkalinity, silicate and conductivity data, which most frequently occurred with small POTWs, characteristic concentrations were assigned based on the treatment level and unit processes in place for each POTW per Carey and Migliaccio (2009).

Riverine runoff from 75 SCB coastal confluences is derived from a combination of monitoring data and, for unmonitored watersheds, from predictive models. Surface water river runoff combines natural sources, point and non-point sources. In the SCB, several challenges exist to compiling a spatially explicit time series of riverine runoff: 1) 75 rivers and streams at the scale of the National Hydrography Dataset Plus (NHD+) flow to the SCB, 2) lack of continuous routine flow monitoring for many watersheds, 3) relative to the desired list of constituents, significant gaps in monitored constituents, particularly in constituents like alkalinity and silica. To force the numerical ocean model, the objective was a daily time series, with the intent to capture the seasonal and interannual magnitude and frequency of wet weather (storm events), through which the majority of flux occurs, compared to dry weather (base flow). Our approach to addressing these challenges involved three strategies, targeted at the terminus of the watershed where it entered the SCB estuarine or marine coastal waters:

1. Compile all existing monitoring data for wet and dry weather flow and constituents of interest;
2. Modeling to predict wet weather flow based on land use, where flow data were lacking
3. Modeling to predict dry weather constituent concentrations based on empirical observations, where monitored constituents were lacking.

For 40 watersheds, we largely relied on existing observations acquired from electronic databases or directly from responsible agencies during 1997–2017. Major data sources included US Geological Survey, the California Environmental Data Exchange Network, direct acquisitions from county stormwater agencies and public works and the California Department of Water Resources.

The other 35 rivers found in less developed coastal watersheds had significant data gaps for which we relied more heavily on the second and third approaches. To address gaps in discharge, we utilized the previous modeling approach of Ackerman and Schiff (2003), a land-use based rainfall-runoff model, which predicts wet weather flows Q (m^3 day^{-1}) based on land uses in the SCB. This modeling approach utilizes 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 is described in detail by Ackerman and Schiff (2003).

Modeling of dry weather constituents addressed two data gaps: 1) lack of monitoring in undeveloped watersheds and 2) lack of routine data on certain constituent types (e.g. silica, alkalinity) that was more pervasive among both developed and undeveloped watersheds across the SCB coastal watersheds. To address these gaps, we employed the modeling approach of Olson and Hawkins (2012) to use catchment summaries of geologic properties (geology, climate, atmospheric deposition, soils, vegetation, topography) and other environmental factors (SI Tables 1.1 and 1.2) to develop random forest (RF) models to predict dry weather constituents for the coastal watersheds of Southern California, Central Coast, and Northern California. Models were derived from observations at 1989 stream sites in California coastal watersheds. RF models explained 71%–24% of the variation in the calibration data, with normalized RMSEs that were all $<$10%. Model performance varied across constituent (SI Table 1.3). Alkalinity and silicate models performed best with good model fit (0.54 to 0.71) and an intercept and slope that indicated minimal prediction bias of median scores (SI Fig. 1.1). Performance was somewhat lower with the validation dataset. In contrast, the ammonium model had the poorest performance, with model fit of 0.24, with an intercept and slope that indicated an underprediction of high values and an over-prediction of low values (SI Fig. 1.1). We note that stream nitrogen is generally dominated by nitrate and organic nitrogen, except under circumstances of heavy agricultural influence. Therefore a poor ammonium result has little impact on prediction of riverine nitrogen loads, particularly in underdeveloped catchments where monitoring data gaps are the norm.

POTW and riverine wet, dry weather, or total nutrient loads (L), given as daily loads (kg day^{-1}) or annual mass loads (kg) were estimated from constituent concentrations (c, mg L^{-1}) and flow Q (m^3 day^{-1}), with appropriate conversion factors. For flux, defined as watershed area-specific load and expressed as kg km^{-2} day^{-1}, was calculated from dividing L by watershed area (A_w). Using continuous flow data, days representing wet weather events versus dry weather base flow were categorized by any daily precipitation event exceeding 0.5 cm per day,

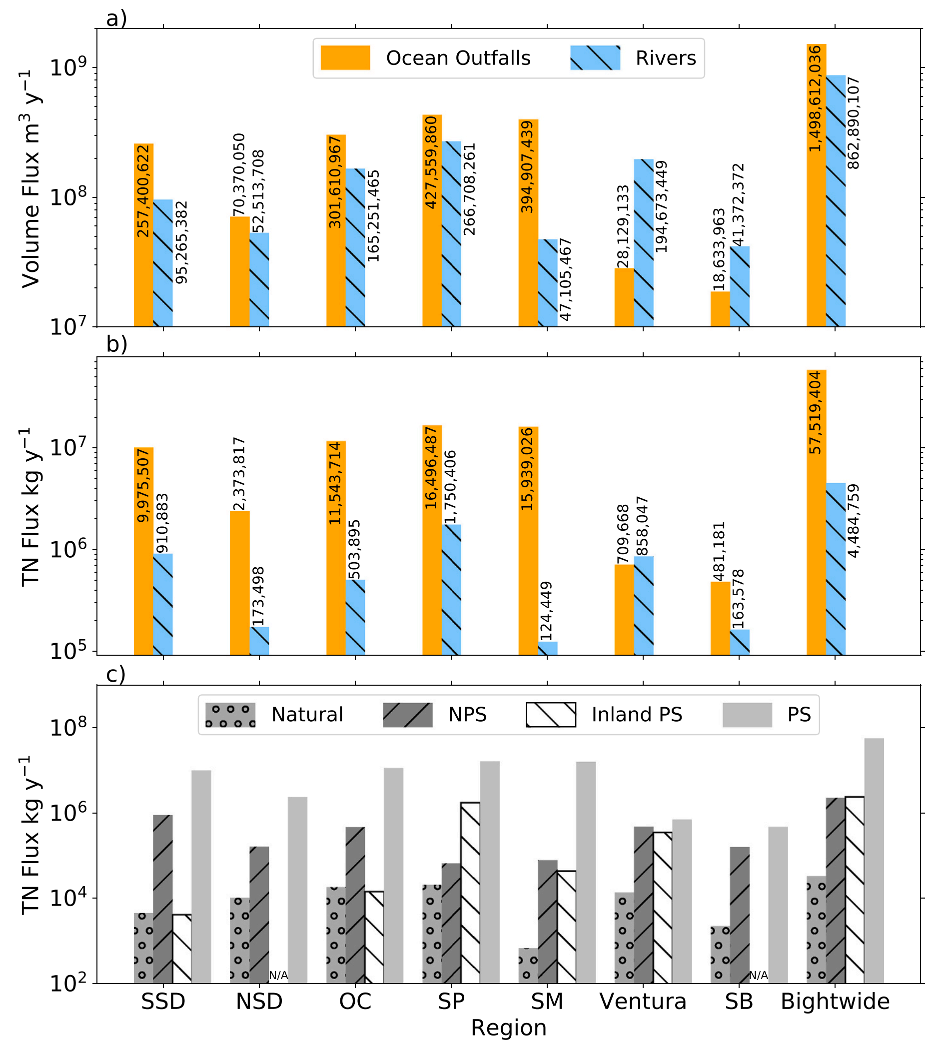

Fig. 2. Comparison of terrestrial total nitrogen (TN) from ocean outfalls and rivers to the SCB from ocean outfalls and rivers as a yearly average of 1997–2017.

Table 1
Average constituent concentrations of all large POTWs and all rivers for 1997–2017.

Constituent (mg L^{-1} unless otherwise noted)	Large POTWs	Rivers
Total nitrogen	40.9	4.13
$NO_3^-+NO_2$	2.40	1.91
NH_4^+	32.8	0.47
Organic nitrogen	5.75	1.71
Total phosphorus	2.85	0.72
PO_4^{3-}	2.09	0.27
Organic phosphorus	0.75	0.31
Dissolved oxygen	6.59	24.2
Total organic carbon	32.3	1.20
Total iron	1.30	0.09
SiO_4	37.9	19.1
Alkalinity	391.9	253.7
pH (pH units)	7.23	7.50
Temperature (°C)	25.4	18.9
Salinity (PSU)	1.46	0.53

on days of storm, plus 72 h (defined by SCB stormwater managers as the typical time to return to base flow conditions).

Total riverine nutrient loads are the sum of PS, NPS and natural background source contributions. Inland points sources were estimated from POTW National Pollutant Discharge Elimination System (NPDES) monitoring data for eighteen inland POTWs discharged treated effluent

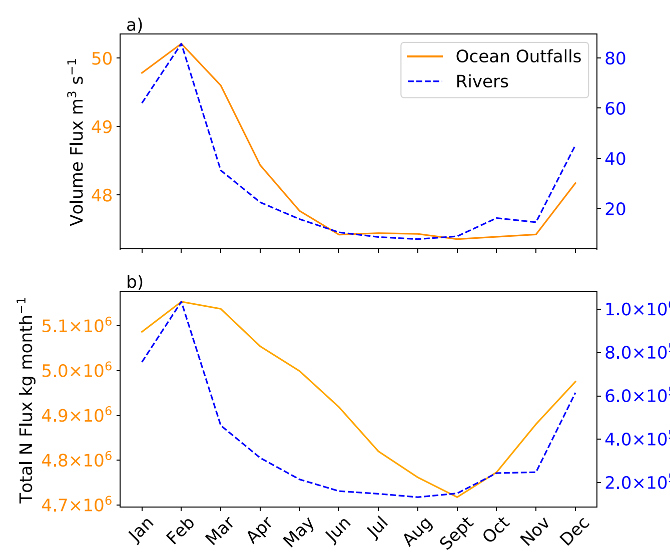

Fig. 3. Average by month for 1997–2017 of all ocean outfall and riverine a) volume flux and b) TN flux.

Table 2
Average baseline trends for inputs in each region for 1997–2000 and 2013–2017.

Region	All outfall DIN loads (kg day^{-1})			River DIN loads (kg day^{-1})		
	1997–2000	2013–2017	% Change	1997–2000	2013–2017	% Change
South San Diego	23,435	22,393	−4.4%	928	1319	+42.1%
North San Diego	6849	6382	−6.8%	189	118	−37.7%
Orange County	33,440	19,156	−42.7%	933	627	−32.7%
San Pedro	39,124	42,324	+8.2%	11,098	1845	−83.3%
Santa Monica Bay	37,210	38,264	+2.8%	149	135	−9.3%
Ventura	1725	2206	+27.8%	1620	1755	+8.4%
Santa Barbara	1157	1214	+4.9%	203	114	−43.9%
US SCB Total (inc. islands)	143,037	131,987	−7.7%	15,119	5914	−60.9%

Table 3
Comparison of riverine and ocean outfall nutrient fluxes from SCB watersheds to estimates cited in similar studies. All estimates are normalized per watershed area in kg km^{-2} yr^{-1}.

Source	Region	TN
Howarth et al. (1996)	North Canadian River	76
	Northeast Coast (US)	1070
	North Sea	1450
	Northwest European Coast	1300
	Amazon & Tocatins	505
Ludwig et al. (2009)	Mediterranean Sea	707
	Black Sea	422
This study	Southern California Bight	4050
	South San Diego	6921
	North San Diego	816
	Orange County	6683
	San Pedro	8389
	Santa Monica	20,385
	Ventura	306
	Santa Barbara	783

into 8 watersheds, half of which are located in Los Angeles and San Gabriel River watersheds (SI Table 2.1). Modern natural source contributions were estimated from modeled wet weather discharges of natural lands in the coastal watersheds (per methods of Sengupta et al. (2013)) and natural background concentrations of nutrients (Yoon and Stein, 2008). PS and natural sources were removed from monitored loads to yield an estimate of NPS contributions.

Summarizing over the entire SCB, median total annual terrestrial inputs over the 20-year time series (1997–2017) were estimated as 2889 $\times$ 10^6 m^3 of fresh water discharge and 73 Gg TN. Bight-wide, point sources represented 74% of the total annual terrestrial freshwater discharge, but 97% of the TN loads (SI Table 2.2), the majority of which was discharged directly to ocean outfalls (1498 $\times$ 10^6 m^3 of freshwater, 58.5 Gg TN; Fig. 2). Of the direct ocean outfalls, small POTW outfalls account for 11.1% of the TN load. Annual median riverine discharge from coastal watersheds contributed 881 $\times$ 10^6 m^3 of freshwater and 4.75 Gg TN to the SCB (SI Table 2.2). Approximately 51% of TN riverine loads are from inland PS discharges (Fig. 2, SI Table 2.2), while 48% of TN are from NPS sources (SI Table 2.2). These estimates represent a 80-fold increase in TN from a pre-urbanization scenario of 100% open land use (0.91 Gg TN estimated by Sengupta et al. (2013)).

Bight-wide, the area-normalized annual nitrogen fluxes (4050 kg TN km^{-2}) are among the highest published compared to the US Atlantic Coast and Northern Europe watersheds (Table 3). At a subregional scale, the TN fluxes peak at 20,385 kg km^{-2} in the PS-dominated subregion of Santa Monica Bay. The densely populated Orange County, San Pedro Bay and Santa Monica Bay coastal watersheds, of which 53% are are developed land uses, contributed 75% of the total terrestrial TN loads to the SCB (Fig. 2). Collectively within these regions, PS contributes the majority of the TN loads (4% inland PS, 95% ocean PS of TN loads), while NPS contributes an additional 1% (Fig. 2). South San Diego is also dominated by PS (92%), but contributes an order of magnitude less TN than LA and northern Orange County. Of the remaining sub-regions, outfall PS contribute most of Ventura TN loads (44%) with NPS contributing second most (30%), while ocean outfall PS dominate Santa Barbara and North San Diego TN exports (74% and 93%, respectively).

The effect of anthropogenic land use changes is disproportionate on nutrient forms. Large POTW effluents discharges to outfalls are

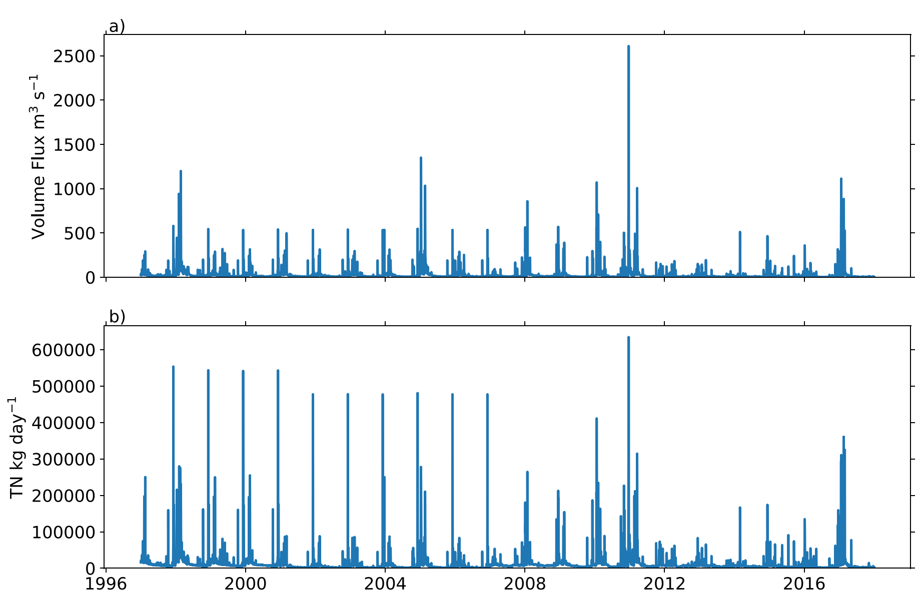

Fig. 4. Daily time series of 1997–2017 of all rivers summed for a) riverine discharge and b) TN load.

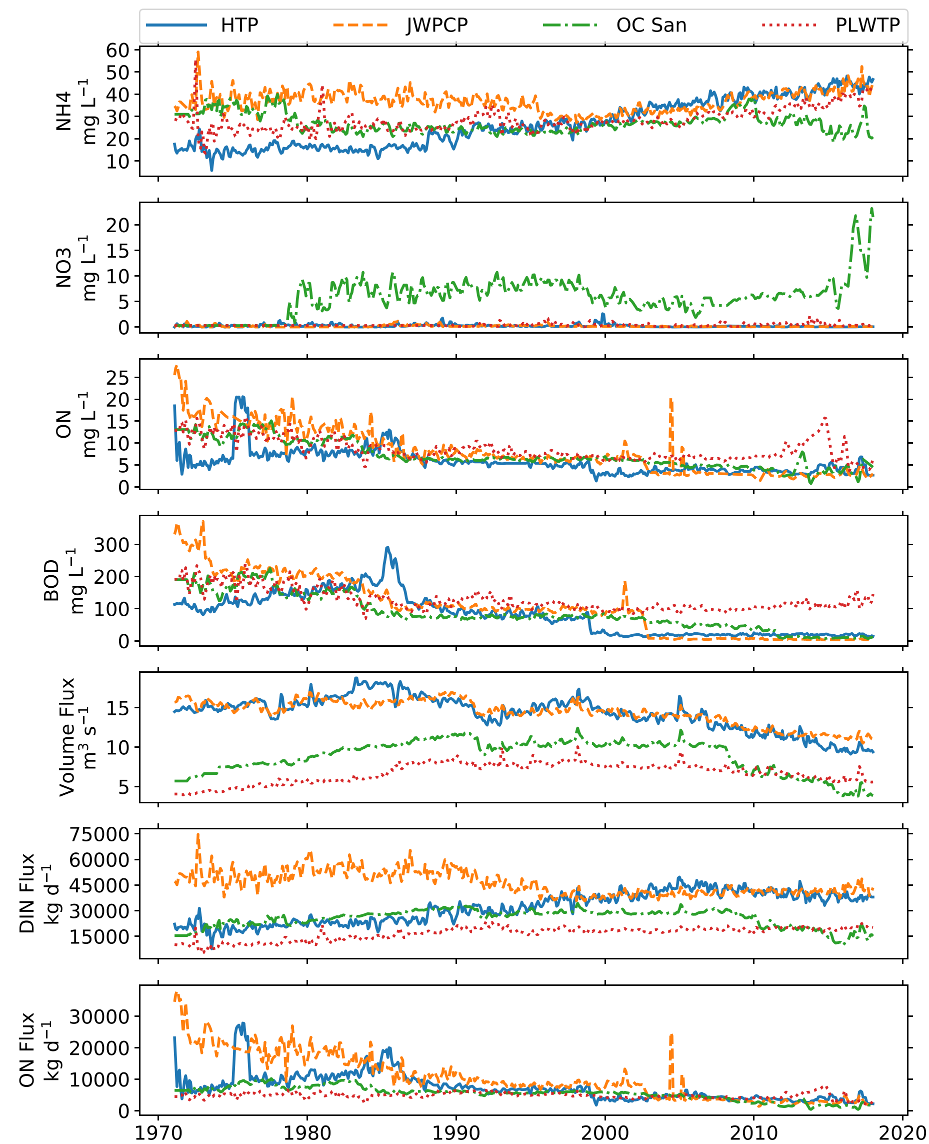

Fig. 5. Long-term monthly time series of 1971–2017 of large POTWs volume flux and concentrations of ON, BOD, NH4, NO3, and DIN flux. HTP = Hyperion Treatment Plant (City of Los Angeles), JWPCP = Joint Water Pollution Control Plant (Los Angeles Sanitation District), OC San = Orange County Sanitation District, PLWTP = City of San Diego Point Loma.

dominated by ammonium, representing 80% of TN. For river runoff, nitrate and organic nitrogen are comparable in concentration (Table 1), in contrast, to runoff from undeveloped landscapes, in which dissolved organic and particulate N are the dominant forms (Sengupta et al., 2013).

Freshwater volume flux and constituents varied on distinct seasonal and interannual timescales. Fig. 3 shows the 1997–2017 average by month of volume flux and TN. Because ocean outfalls and inland PS discharges are relatively seasonally constant and dominate the total TN and TP loads to the SCB, monthly effluent volume to the SCB were only slightly higher during the winter than the summer, relative strong seasonality observable in riverine discharge (Fig. 3).

Over the 50-year time series, the large POTW outfall discharge volumes and nitrogen loads have responded to a combination of population increase, improved wastewater treatment, water conservation and, for one large POTW, nutrient management and wastewater recycling. Overall, outfall volume from these large POTWs declined from its peak range in 1980–1998 by approximately 45%, reflecting trends in water conservation and non-potable use recycling. Organic nitrogen loads in these outfalls declined by 73% from peaks in the 1970–1990 due to wastewater treatment upgrades targeting BOD and organic solids reduction, particularly for those that have moved to secondary treatment (HTP, JWPCP, OC San). In contrast, relative to current day 2013 to 2017 time period, mean DIN loads from these outfalls either roughly doubled from the 1970s baseline for the Cities of San Diego and Los Angeles outfalls due to rapid population increase in those regions, while DIN loads slightly declined on the order of 16–18% for LA County Sanitation District and OC San outfalls (Fig. 5).

Since 1997–2000 however, the largest change in both DIN form as well as decline in DIN loads occurred in Orange County subregion due to operations at OC San (Table 2, Fig. 7), where a indirect potable water recycling and reuse program has reduced volumes discharged to their outfall by 60% since its inception in 2007. In the 1980s, progressive plant upgrades began to partially nitrify ammonium, resulting in elevated nitrate concentration (Fig. 5), while partial nitrification-denitrification (NDN) upgrades in 2010 dropped DIN loads to 46% of their 1997–2000 baseline (Fig. 7). Notable increases in both nitrate and ammonium concentration after 2010 in outfall effluent are due to the return of water treatment reverse osmosis brine to the outfall. In contrast, over this same period, DIN loads at the two large POTW outfalls

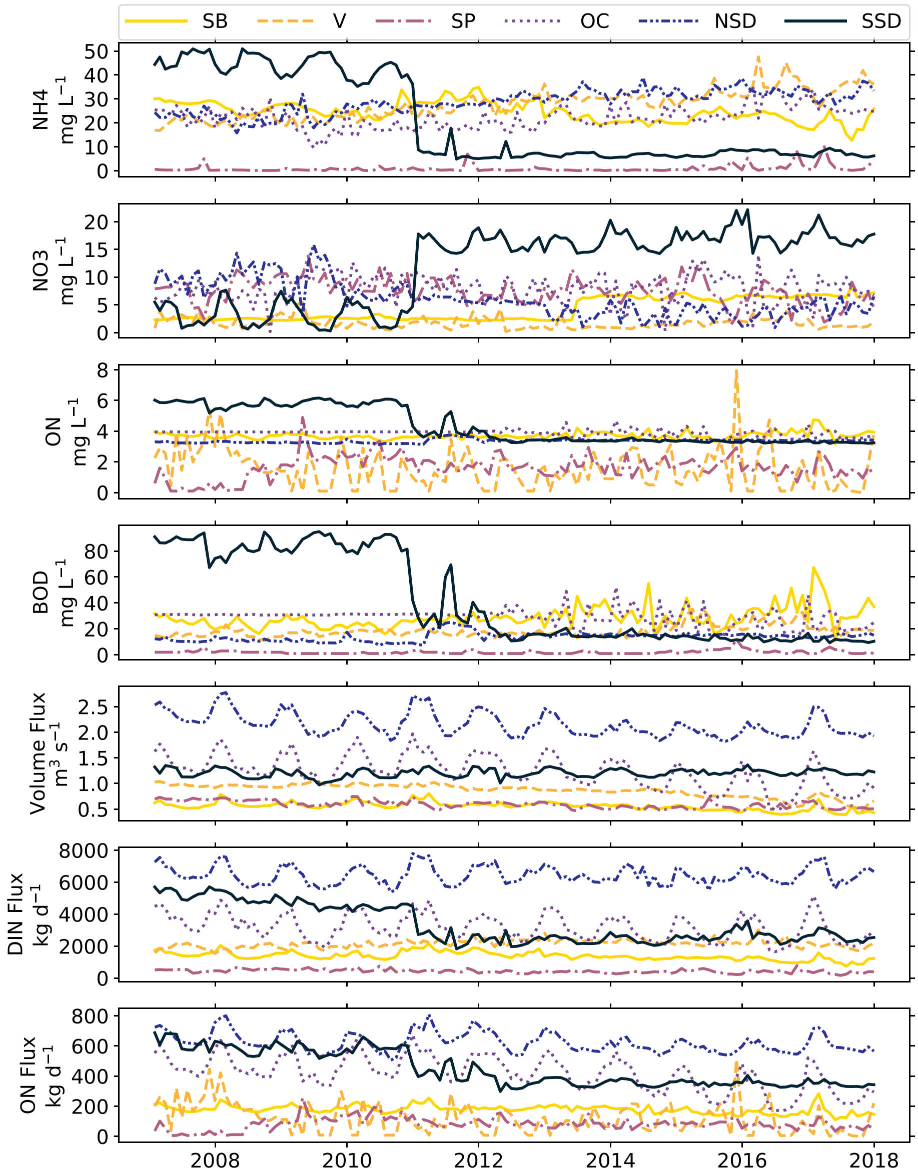

Fig. 6. Monthly time series of 2007–2017 small POTWs summed volume flux, flow-weighted concentration means of ON, BOD, NH4, NO3, and summed DIN and ON flux for each of the regions defined in Fig. 1. Santa Monica is excluded because the region does not have a small POTW.

in Los Angeles slightly increased 3 to 8% (Table 2).

Publicly available electronic records of small POTW discharge and loads are reliable after 2006 and for this reason, we focus on the last decade to investigate trends. From these records, grouped by subregion for where the outfall occur, some subregional patterns and trends are notable (Fig. 6). First, distinct winter-summer seasonality is observable, though not consistently across all seasons. DIN loads are the lowest, which is not only due to lower population but because most POTWs in that region are already at tertiary treatment with advanced nutrient removal strategies in place. In contrast, volumes and DIN loads from small POTW outfalls are the highest in North and South San Diego due to population increases and inland water nutrient criteria that have restricted effluent discharges to coastal rivers.

Over the past decade, Ventura was the only subregion that saw an increase in small POTW DIN loads (10%). In other subregions, DIN loads reduction are notable due to increased water recycling. Small POTW DIN loads declined by 23–27% in Orange County, San Pedro and Santa Barbara. In North San Diego, DIN loads throughout the decade have stayed relatively constant, while in South San Diego, partial NDN upgrades in 2012 at the South Bay International WWTP significantly decreased small POTW DIN loads by 50% in that region. Loads to this POTW are diverted from the Tijuana River at the US-Mexican border, representing transboundary nutrient loads from Mexico that enter U.S waters. Transboundary sewage spills that occur from infrastructure breakdowns or extreme wet weather events are discharged through the Tijuana River. Mexican transboundary inputs to US waters via the South Bay International WWTP and the Tijuana River represent 35% of total DIN loads to the South San Diego subregion. Additional Mexican WWTP loads are discharged to ocean waters south of the US Mexican border, but not included in our estimates here.

In contrast to outfall discharges, collective riverine discharge and loads show strong winter wet and summer dry seasonality but show less distinct long term trends. Upgrades to full NDN in several inland POTWs in the Los Angeles and San Gabriel River, two of the largest rivers in the region, resulted in a decline in DIN concentrations and loads by 84% and 66% respectively from the 1997–2000 baseline (Fig. 4b). These declines are notable after 2010. Within year seasonality in TN loads exceeded that of interannual varability. Across watersheds, riverine TN loads increased by 10% during 1997–1998 El Niño relative to the 2010–2011 La Niña. In contrast, riverine TN loads were 46% higher during storm

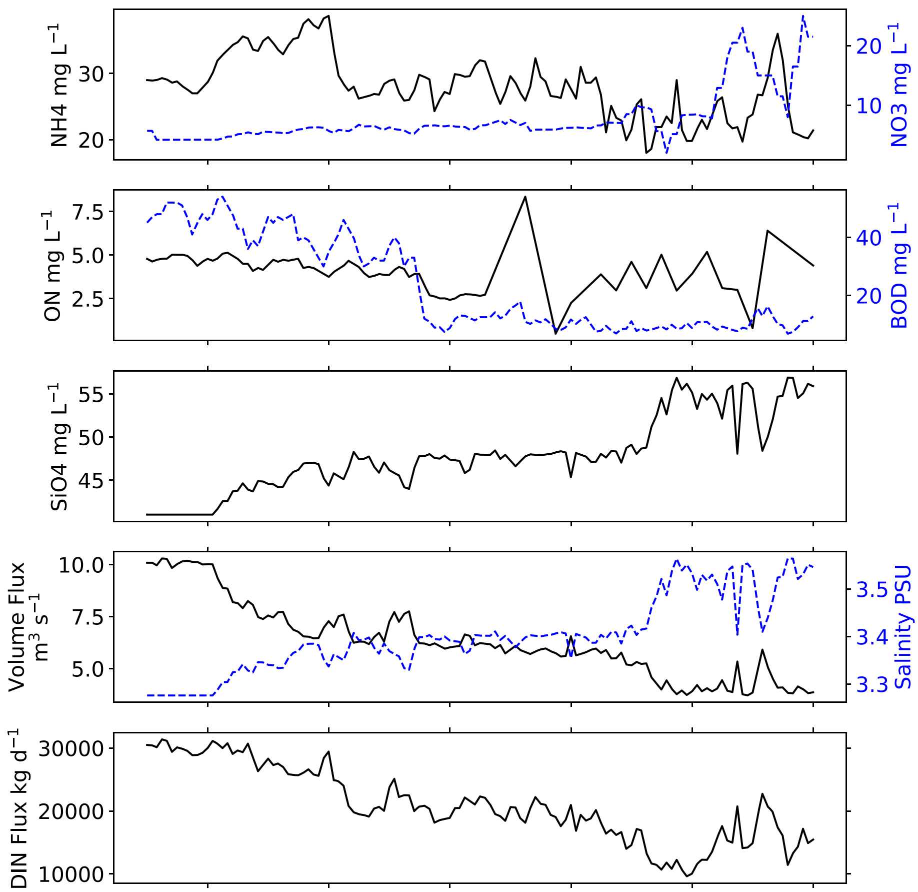

Fig. 7. Monthly time series of various OC San constituents for 2007–2017. OC San began its wastewater recycling program in 2008.

conditions than dry weather baseflow conditions. The ranges in this temporal variability can be extreme; in some watersheds where dams occur in the upper watershed (e.g., Santa Ana River), wet weather flows were nearly completely captured behind the dam and were either not released or released slowly over dry weather. In contrast, in watersheds where river flow is intermittent or ephemeral, greater than 95% of the TN loads can occur during storm conditions. The San Gabriel River, Los Angeles River, San Diego Creek, Santa Clara River, Tijuana River, Chollas Creek, Santa Ana Channel, Ballona Creek, Santa Margarita River and Calleguas Creek watersheds represent the chronic, dry weather "hot spots" for nutrient loading to the SCB due to either inland PS discharges or irrigated agricultural discharges. The discharge from these 10 watersheds represents 57% of total riverine freshwater flows and 60% of the total riverine TN to the SCB. Over the 1997–2017 time series, climate-driven interannual variability in riverine discharge and nitrogen loads is notable (Fig. 4), driven by the peak winter storm flows.

Generally, confidence in the POTW ocean outfall load estimates for the present study are high (within ±5% error) because the data are submitted monthly with strict regulatory requirements for quality assurance procedures. Riverine fluxes are likely reliable generally within an order of magnitude. However, these riverine runoff estimates do not adequately capture temporal variability in wet or dry weather concentrations over wet and dry weather events, seasonally and inter-annually, particularly with respect to well-studied watershed processes, such as first-flush phenomenon, that inherently provide tremendous variability (Bertrand-Krajewski et al., 1998). Constituent concentrations from a given land use will vary from site to site and storm to storm. This variability is magnified when the area of interest is expanded from single land use areas to watersheds because of runoff behavior and complexity. Our approach was based on the need to investigate seasonal to interannual loading to the SCB at sub-regional scales, but understanding inter-storm and intra-site variability is critical to estimate loads on a shorter time scales and at fine spatial resolutions. To overcome these uncertainties, more complex models dynamic watershed loading models are required to incorporate time varying riverine hydraulic, hydrodynamic, and water quality processes.

Coastal eutrophication is one of the major consequences of anthropogenically-induced global change on the world's coastal oceans, intensifying global processes linked to anthropogenic CO_2, warming, acidification, deoxygenation, and harmful algal blooms (Doney, 2010; Wallace et al., 2014). While nutrient pollution in coastal waters is generally greatest where agricultural activity and urbanization are intense, neither the distribution of loading nor the effects on the coastal ecosystems are uniform. Cost-effective solutions to accelerate ecosystem recovery from eutrophication and response to climate change stress on water resources are best founded on quantitative understanding of the linkage between anthropogenic activities in watersheds, nutrient inputs to coastal systems, and their ecosystem effects (Duarte and Krause-Jensen, 2018). This study presents a baseline of point, non-point source and natural sources of freshwater discharge and nitrogen loads to the SCB, representing an urbanized coastal zone, prior to the widespread implementation of potable reuse water recycling in the region.

CRediT authorship contribution statement

Martha Sutula: Conceptualization, Methodology, Data curation, Funding acquisition, Project administration, Writing – original draft. **Minna Ho:** Data curation, Formal analysis, Visualization, Writing – original draft. **Ashmita Sengupta:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Fayçcal**

Kessouri: Formal analysis, Validation, Writing – review & editing. **Karen McLaughlin:** Data curation, Formal analysis, Writing – review & editing. **Kenny McCune:** Writing – review & editing. **Daniele Bianchi:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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