New insights into impacts of anthropogenic nutrients on urban ecosystem processes on the Southern California coastal shelf: Introduction and synthesis

Meredith D.A. Howard[1*], Raphael M. Kudela[2], Karen McLaughlin[1]

[1]Southern California Coastal Water Research Project, 3535 Harbor Blvd. Suite 110, Costa Mesa, CA 92626 USA

[2]University of California, Santa Cruz, Ocean Science Department, 1156 High Street, Santa Cruz, CA 95064 USA

[*]Corresponding Author: mhoward@sccwrp.org 714-755-3263

Abstract

Anthropogenic nutrient inputs are one of the most important factors contributing to eutrophication of coastal waters. Coastal upwelling regions are naturally highly variable, exhibiting faster flushing and lower retention times than estuarine systems. As such, these regions are considered more resilient to anthropogenic influences than other coastal waters. Recent studies have shown our perception of the sustainability of these systems may be flawed and that anthropogenic nutrients can have an impact at local and regional spatial scales within these larger upwelling ecosystems. Maintenance of an outfall pipe discharging wastewater effluent to the Southern California Bight (SCB) provided an opportunity to study effects of anthropogenic nutrient inputs on a near-shore coastal ecosystem. The diversion of wastewater effluent from a primary, offshore outfall to a secondary, near-shore outfall set up a large-scale, *in situ* experiment allowing researchers to track the fate of wastewater plumes as they were “turned off” in one area and “turned on” in another. In this introduction to a special issue, we synthesize results of one such wastewater diversion conducted by the Orange County Sanitation District (OCSD) during fall 2012. Anthropogenic nitrogen (N) from point-source discharges altered biogeochemical cycling and the community composition of bacteria and phytoplankton. Nitrification of ammonium to nitrate in wastewater effluent close to outfalls constituted a significant source of N utilized by the biological community that should be considered in quantifying “new” production. The microbial-loop component of the plankton community played a significant role, exemplified by a large response of heterotrophic bacteria to wastewater effluent that resulted in nutrient immobilization within the bacterial food web. This response, combined with the photosynthetic inhibition of phytoplankton due to disinfection byproducts, suppressed phytoplankton responses. Our findings have ramifications for future studies and regulatory monitoring, emphasizing the need to consider chemical and biological responses to wastewater effluent in assessing effects of anthropogenic nutrient inputs on urbanized coastal ecosystems.

Key words: wastewater; anthropogenic nutrients; microbial loop; phytoplankton; biogeochemical cycle; nitrogen

1. Introduction

Coastal upwelling regions along eastern boundary currents are among the most biologically productive ecosystems in the world's ocean, supplying a significant fraction of global "new" primary productivity, and representing ecologically and economically important habitats (Chavez and Toggweiler, 1995; Capone and Hutchins, 2013). These regions are highly variable in time and space, experiencing large ranges of nutrients, sea surface temperature (SST), dissolved oxygen (DO), carbon dioxide (CO_2), and pH (Chavez et al., 2003; Feely et al., 2008; Bograd et al., 2008; Booth et al., 2014; Bograd et al., 2015). Some upwelling regions face increased anthropogenic nutrient loading from publicly owned treatment works (POTWs), a potentially deleterious manifestation of human-accelerated global change (Howarth and Marino, 2006; Scavia and Bricker, 2006). Despite a perception that anthropogenic nutrient inputs to these regions are small compared to inputs from upwelling, recent evidence suggests such inputs may significantly affect near-shore waters adjacent to urban areas (Capone and Hutchins, 2013; Howard et al., 2014), with ramifications for the resilience of coastal ecosystems (Capone and Hutchins, 2013; Bograd et al., 2015).

The Southern California Bight (SCB) is one of the most densely populated areas in the United States, with four counties situated along the shoreline comprising nearly 25% of the nation's coastal population (Culliton et al., 1990; Schiff et al., 2000). Associated with this dense urban area are large point-source nutrient inputs from POTWs, combined with dynamic processes, such as upwelling, that impose natural variability characteristic of eastern boundary currents (Chavez et al., 2003, 2009). As such, the SCB presents a suitable environment to investigate responses to changes in point-source nutrient inputs. The SCB has a Mediterranean climate with rainfall and runoff limited to storms occurring primarily in winter (Lyon and Stein, 2009). Consequently, 92% of total terrestrial N loading to coastal waters of SCB is from wastewater effluent, most of which is discharged directly into coastal waters via outfall pipes (Sengupta et al., 2013). N contributions from outfall pipes are approximately equivalent to N inputs from upwelling at spatial scales of 10s of kilometers (km), effectively doubling N loading to the shelf, altering composition of the N pool (effluent N is primarily ammonium (NH_4^+); upwelled N is primarily nitrate (NO_3^-), and the N:P ratio, as relatively little phosphorus is discharged in wastewater effluent (Howard et al., 2014).

Emerging evidence suggests that anthropogenic nutrient inputs significantly affect coastal waters of SCB. The spatial extent and duration of phytoplankton blooms has increased during the past decade, with chronic outbreaks in areas of SCB that receive anthropogenic nutrient inputs (Schnetzer et al., 2007; Nezlin et al., 2012; Schnetzer et al., 2013; Seubert et al., 2013). Furthermore, observed distributions of chlorophyll *a* and phytoplankton in the near-shore cannot be accounted for by upwelling alone (Kim et al., 2009; Corcoran et al., 2010; Nezlin et al., 2012; Reifel et al., 2013). Accordingly, anthropogenic nutrient inputs represent an important water-quality consideration because stimulation of phytoplankton biomass and productivity may signal the occurrence of harmful algal blooms (HAB) and increased biomass to support respiration of organic matter that contributes to reduced DO (Booth et al., 2014).

The Orange County Sanitation District (OCSD) is one of three large POTWs discharging secondarily treated wastewater effluent into the coastal ocean adjacent to the greater Los Angeles basin. OCSD serves a population of more than 2.6 million, treating, collecting, and disposing of sewage from two plants, with effluent delivered off Huntington Beach, California. Maintenance of the primary ocean outfall pipes provided an uncommon opportunity to study effects of wastewater effluent on near-shore coastal waters. During maintenance events, wastewater effluent is diverted from a primary offshore outfall to a secondary near-shore outfall while the principal outfall is inspected and repaired. Consequently, such diversions set up large-scale, *in situ* experiments that allow researchers to track the fate of wastewater plumes as they are "turned off" in one area and "turned on" in another.

In this special issue, a series of papers presents the results of monitoring and research associated with the OCSD diversion during fall 2012. OCSD diverted approximately 528 x 10^6 L d^{-1} of secondarily treated wastewater effluent for three weeks. While previous diversions were conducted in SCB, OCSD had not conducted a diversion of this magnitude since 1972. The Environmental Impact Report (EIR) summarized anticipated biological responses to nutrient inputs, estimating the wastewater-effluent plume would contain up to 42 μM NH_4^+, potentially generating a phytoplankton bloom of 40-50 mg m^{-3} chlorophyll *a* (OCSD, 2011), based on observed impacts of a diversion in Santa Monica Bay in 2006 (Reifel et al., 2013). To mitigate the potential impacts of fecal indicator bacteria and other pathogens (Noble and Xu, 2004), OCSD used enhanced chlorination followed by dechlorination of the discharge, so the effect of the plume would primarily be due to nutrient additions rather than intact microbial populations.

A substantial field program was coordinated to track the fate of the wastewater plume and to ascertain effects of the diversion on nutrient inputs and biological responses. This multidisciplinary program combined monitoring by a robotics and sensor network coupled to predictive ocean modeling, field observations and experiments to assess effects of nutrient inputs on biogeochemical cycling and ecosystem dynamics, and *in situ* and satellite observations to identify and track plume location, transport, and mixing. This special issue summarizes our findings and discusses implications for N cycling and rate processes, and microbial responses to inputs of wastewater effluent in an urbanized coastal region of the SCB.

2. Materials and Methods

2.1 Study site and design

Ocean outfalls for OCSD are located off the coast of Huntington Beach, California (Fig. 1). From 11 September 2012 to 3 October 2012, OCSD diverted wastewater effluent from the primary 120-inch-diameter outfall pipe located 5 miles offshore at a depth of 56 m, to a near-shore 78-inch diameter outfall pipe located 1 mile offshore at a depth of 16 m. Ship surveys, experiments, and modeling were combined to monitor effects of the diversion, and a variety of instruments were deployed to track the plume and determine ecological effects in near-shore and offshore environments. A robotics and sensor network included four autonomous underwater vehicles, with three Teledyne Webb Slocum gliders and one REMUS, a buoyancy glider, a Liquid Robotics Surface Wave Glider, two water-quality buoys, an Environmental Sample Processor (ESP), three autonomous wave-powered profiling moorings (Wirewalkers), and four Acoustic Doppler Current Profilers (Fig. 1).

The Regional Ocean Modeling System (ROMS) used a multi-scale, three-dimensional variational data assimilation method with a mesoscale atmospheric model to produce now-casts every six hours and daily 72-h forecasts during the diversion (Rogowski et al., 2014). Model outputs guided monitoring resources and ship surveys. ROMS incorporated real-time data streams, including both 2 km and 6 km HF radar surface current data, vertical profiles of temperature and salinity from gliders and the MBARI M1 mooring, and SST from Advanced Very High Resolution Radiometer (AVHRR), and Moderate Resolution Infrared Spectroradiometer (MODIS) (Rogowski et al., 2014). Observational data were not assimilated into now-casts and forecasts because they were not available in real time. Rogowski et al. (2014) provides a detailed description of modeling efforts during and after the diversion study.

2.2 Shipboard Surveys

Shipboard surveys covered pre-, during, and post-diversion intervals, as described by Caron et al. (this issue) and summarized here. Weekly "plume-tracking" cruises aboard the *M/V Nerissa* (OCSD) focused on water quality and enumeration of bacteria and phytoplankton for stations in the vicinity of the discharge and at the long outfall pipe. An adaptive sampling design was used to position stations up-coast and down-coast, depending on daily current predictions from ROMS, assuring sampling at a subset of stations in close proximity to the discharge. The sampling zones occupied on these regulatory-based surveys were defined in the California Ocean Plan.

Corresponding "event" cruises were conducted weekly aboard the *R/V Yellowfin* (Southern California Marine Institute) or the *M/V Nerissa*, occupying five stations on an onshore - offshore transect to document near-shore effects of wastewater effluent at the short outfall, and changes at the long outfall resulting from cessation of discharge. A "regional" cruise evaluated phytoplankton responses over a larger geographical area (Caron et al., this issue). Discrete sampling and experiments included characterization of spatial and temporal changes in nutrient concentrations, shifts in community composition of bacteria and phytoplankton, N cycling, and isotopic-source tracking to determine the extent of wastewater effluent effects. A number of experiments focused on phytoplankton responses to wastewater effluent and other nutrients, including N-preference and NH_4^+-inhibition. A retrospective analysis relied on satellite data from multiple sensors to distinguish biophysical responses from the diverted effluent (Gierach et al., this issue).

3. Results summary

3.1. Plume tracking

Multiple approaches were used during the 2012 OCSD diversion to overcome technical challenges associated with plume tracking, such as locating and monitoring the plume in near real-time. Technologies included wave-powered profiling moorings (Wirewalkers) (Lucas and Kudela, this issue; Kudela et al., this issue), buoys and moorings including bottom-mounted Acoustic Doppler Current Profilers (ADCP), two ocean buoys and an Environmental Sample Processor (Caron et al., this issue; Lucas and Kudela, this issue), autonomous underwater vehicles (AUVs) such as Teledyne Slocum gliders and a Liquid Robotics Waveglider (Seegers et al., this issue), and remote sensing (Gierach et al., this issue). From these observations, a consistent plume signature was identified, which allowed for plume tracking and estimation of plume dilution and dispersion.

Prior to the wastewater-effluent diversion, we expected the OCSD plume would be surface-trapped, given the volume of discharge and shallow release depth. Consistent with this expectation, visual observations confirmed the presence of a surface signature (Fig. 2). Vertical profiles, however, revealed a complex mixing pattern, with plume water interacting with both surface and bottom layers (Lucas and Kudela, this issue). This led to the presence of plume water in both near-field (mixing between the effluent and ambient waters) and far-field (mixing where dilution occurs primarily with waters of the same density), and a significant component in the subsurface (Lucas and Kudela, this issue).

Plume tracking by Lagrangian drifters showed plume waters mainly traveled in onshore and alongshore directions (Rogowski et al., 2014). Satellite imagery also proved useful to track the plume and biological responses (Gierach et al., this issue), revealing patterns consistent with

Lagrangian drifters. Gierach et al. (this issue) estimated that chlorophyll *a* and SST must vary by 1 mg m^{-3} and 0.5 °C, respectively in order to successfully identify and track the plume using satellite imagery, while synthetic aperture radar (SAR) was useful when wind speeds were 3 to 8 m s^{-1}. Glider profiles (Seegers et al., this issue) suggested most of the plume was entrained in the upper 20 m, but with a significant plume signature extending as deep as 40 m. Together, these observations provide a consistent view of plume dynamics, with waters in the plume characterized by low SST, low salinity, and elevated chromophoric dissolved organic matter (CDOM). The plume was predominantly surface-trapped and maintained in the upper ~20 m for significant periods (days) in the vicinity of the outfall. *In situ* observations confirmed elevated CDOM in the plume as detected by satellites (Seegers et al., this issue; Gierach et al. this issue). The distribution of the plume also agreed well with modeling outputs for plume dispersal (Uchiyama et al., 2014).

Dilution of the plume was more difficult to estimate. We expected the plume would be diluted 30:1 in the near-field, primarily due to the design of diffusers. Data from Lagrangian drifters showed dilution > 100:1 within 1 km of the outfall pipe (Rogowski et al., 2014). Nutrient distributions were consistent with at least 100:1 dilution within the region (Caron et al., this issue), but surface mapping showed water of low salinity, and low variable fluorescence occurred several km from the outfall (Kudela et al., this issue). These observations can be reconciled by taking into account the subsurface lensing observed by Lucas and Kudela (this issue). While the bulk of the plume was surface-trapped and rapidly diluted, a significant fraction of wastewater effluent was likely entrained in intermediate layers, persisting until dissipated by intermediate- and far-field processes, such as wind-driven mixing and internal waves. Weak transport and rapid mixing resulted in a plume-influenced region extending several km around the outfall pipe, and remaining in the general vicinity of the outfall pipe for several days (Lucas and Kudela, this issue). This was sufficiently long for biological responses to develop, exemplified by heterotrophic bacteria (Caron et al., this issue), and phytoplankton growth and photosynthesis (Kudela et al., this issue).

The OCSD diversion was studied with intensive observations and modeling. It is unlikely that a comparable study could be maintained by most management entities, highlighting the need for a cooperative use of advanced technologies. Notably, results from gliders, drifters, shipboard observations, and satellite retrievals converged on similar estimates of dilution, while high-resolution vertical observations from Wirewalkers and spatial transects of properties such as variable fluorescence identified more concentrated layers and lensing effects. This suggests that routine monitoring at the meso-scale using multiple observational approaches would capture the bulk oceanographic responses to nutrient inputs, but could miss small-scale effects.

3.2. Biological responses

Biological responses during the OCSD diversion in 2012 differed from those in previous studies. Prior to the OCSD diversion, a much smaller diversion was conducted from the Hyperion Wastewater Treatment Plant in Santa Monica Bay, California for three days in 2006. Also, there was a major breach in San Diego, California in 1992, resulting in discharge of untreated effluent for several months. Although information in the published literature about the San Diego event is sparse, dinoflagellate blooms were reported around the periphery of an effluent plume that was visible from airborne platforms (Casey et al., 1992; Tegner et al., 1995; Lange et al., unpublished data). The March 1993 issue of the journal, *Photogrammetric Engineering and Remote Sensing* featured the San Diego breach on the cover, as reproduced here (Fig. 3). The 2006 diversion in Santa Monica Bay produced dramatic biological responses, including increases of potentially harmful dinoflagellates, *Lingulodinium polyedrum* and *Cochlodinium* sp., subsequently identified as *C. fulvescens* (Howard et al., 2012) and *Akashiwo sanguinea* (Reifel et al., 2013).

Given this historical context and anticipated impacts of the OCSD diversion described in the EIR (OCSD, 2011), we anticipated a large phytoplankton response to nutrient inputs during the 2012 diversion. The EIR predicted a persistent phytoplankton bloom with chlorophyll *a* of 40-50 mg m^{-3} in response to NH_4^+ in the discharge effluent (OCSD, 2011). But contrary to expectations, chlorophyll *a* remained low throughout the diversion (Caron et al., this issue; Kudela and Lucas, this issue; Kudela et al., this issue; Seegers et al., this issue). So what actually happened following the diversion? Caron et al. (this issue) showed responses by various fractions of the planktonic community, including counts of phytoplankton, microzooplankton, picoeukaryotes, cyanobacteria, and heterotrophic bacteria. Overall, phytoplankton composition shifted slightly during the diversion, with increased cyanobacteria and phototrophic, picoplanktonic eukaryotes. In contrast to the Hyperion diversion in Santa Monica Bay, there was little to no increase of potentially harmful dinoflagellates, despite the longer diversion (three weeks vs. three days). While background concentrations of the toxic diatom, *Pseudo-nitzschia* spp. were detected, Caron et al. (this issue) measured relatively low concentrations of domoic acid (≤ 0.05 μg L^{-1}) associated with this genus. Total phytoplankton biomass as chlorophyll *a* remained low throughout the diversion (< 5 mg m^{-3}), while bacterial biomass and microbial grazers showed strong responses, with heterotrophic bacteria increasing by an order-of-magnitude at mid-diversion (Caron et al., this issue). There was some evidence of increased chlorophyll *a* toward the end of the diversion (Lucas and Kudela, this issue), and subsurface observations from gliders (Seegers et al., this issue) corroborated a moderate increase of phytoplankton biomass at depth, although stimulation of a bloom did not occur.

Experimental manipulations using enclosures showed the phytoplankton community was physiologically capable of using nutrients in the wastewater effluent (Seubert et al., this issue; Kudela et al., this issue). A "worst-case scenario" of 1:10 dilution resulted in substantial growth (Seubert et al., this issue), while lower additions of effluent (such as 1:100 or 1:1000) or various combinations of nutrients supported robust growth rates, often exceeding 1 division day^{-1} (Kudela et al., this issue). NH_4^+ inhibition has been suggested to affect growth and productivity of some phytoplankton taxa (Dugdale et al., 2006), particularly diatoms, but high NH_4^+ concentrations sufficient to be inhibitory were not detected (Seubert et al., this issue; Kudela et al., this issue). The results from N uptake kinetics experiments showed no obvious physiological impairment attributed solely to N concentrations; NH_4^+ suppression of NO_3^- uptake was not sufficient to account for the lack of biological response, and there was physiological capacity to respond to ambient N substrates (Kudela et al., this issue).

To explain the lack of phytoplankton stimulation despite an apparent physiological capacity for a bloom to develop, Kudela et al. (this issue) considered effects of chlorination and subsequent dechlorination, and the production of inhibitory disinfection by-products (DBP). Wastewater effluent contained hypochlorite residuals above regulatory requirements, thereby documenting over-chlorination. Kudela et al. (this issue) found that effluent treated with hypochlorite that was incompletely neutralized with bisulfite led to a significant inhibition of phytoplankton photosynthesis lasting ~24 h, with suppressed growth continuing for at least 72 h. Analogous inhibition of heterotrophic bacteria was not observed, consistent with the findings of Caron et al. (this issue) and Seubert et al. (this issue). These results suggest DBP may have precluded development of a phytoplankton bloom while allowing a strong response by the bacterial assemblage. Caron et al. (this issue) propose that the presence of DBP on the continental shelf for several days (Kudela et al., this issue; Lucas et al., this issue) was sufficient to depress phytoplankton and stimulate bacteria, resulting in nutrient immobilization in the bacterial food web, and thereby suppressing stimulation of a phytoplankton bloom that had been anticipated prior to the diversion.

3.3. Biogeochemical cycling

Wastewater effluent in ocean outfalls represents a large point source of NH_4^+; therefore, high rates of NH_4^+-oxidation were expected to occur near the outfall with ramifications for N cycling. McLaughlin et al. (this issue) hypothesized NH_4^+ in effluent would sustain high nitrification rates, i.e., the sequential oxidation of NH_4^+ to NO_3^- via nitrite (NO_2^-) near the long-outfall pipe during normal operations, and would be reduced to background rates when the pipe was out of operation. The authors also expected effluent N to be incorporated into biomass of bacteria and phytoplankton around outfall pipes. The expected decrease of nitrification at the long-outfall pipe, measured in bottle incubations as accumulation of ^{15}N in the dissolved NO_3^- pool following addition of isotopically enriched $^{15}NH_4^+$, was observed following the diversion to the short outfall, and "background" nitrification rates were consistent with those previously reported for SCB (Ward, 1987). Furthermore, decreased nitrification at the long outfall was consistent with decreased NH_4^+ emission during the diversion.

The importance of nitrification to biogeochemical cycling of N around the OCSD outfall was substantiated by nutrient concentrations revealing a "hot spot" of NH_4^+ and NO_2^- over the ocean outfall pipe under normal operations. The dual isotopic composition of dissolved NO_3^- ($\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$) indicated N-assimilation and denitrification rates were low relative to nitrification, consistent with low phytoplankton biomass observed during the study period (Caron et al., this issue; Seegers et al., this issue), possibly caused by DBP in wastewater effluent (Kudela et al., this issue). The isotopic composition of suspended particulate matter indicated low $\delta^{15}N_{PN}$ and $\delta^{13}C_{PN}$ values around the outfall under normal operations, suggesting incorporation of "nitrified" (low ^{15}N NO_3^-) and wastewater dissolved organic carbon into biomass. These results suggest that effluent altered N cycling in close proximity to the outfall (McLaughlin et al., this issue). An implication of these findings is that rapid oxidation of effluent NH_4^+ around outfalls contributes significantly to the pool of NO_3^- in urban coastal areas. This unconventional source of NO_3^- in the context of "new" production (*sensu* Dugdale and Goering, 1967) should be considered in distinguishing upwelled and regenerated NO_3^- to support primary productivity. Thus, both NH_4^+ and transformed NO_3^- represent new sources of N. Resulting changes in the proportions of N forms have implications for the community composition of phytoplankton, as preferences for specific N forms differ among taxonomic groups (Dortch and Conway, 1984; Dortch, 1990; Kudela and Cochlan, 2000; Dugdale et al., 2007; Kudela et al., 2008; Collos and Harrison, 2014).

4. Conclusions

Eutrophication of coastal waters associated with anthropogenic nutrient inputs is well-documented (Howarth, 2008; Paerl and Piehler, 2008), but is often overlooked for coastal upwelling regions. Several insights emerged from the diversion described here with implications for coastal ocean management. First, results indicate anthropogenic N inputs from point-source ocean outfalls impact biogeochemical processes, community composition of phytoplankton and bacteria, phytoplankton physiology, and N cycling within the vicinity of the outfall. Decreased nitrification rates at the long outfall during the diversion indicate that wastewater effluent altered

N cycling in close proximity to the outfalls. The geographic extent of this effect needs to be characterized in future studies to assess if management actions to mitigate these effects are warranted. Second, rapid oxidation of effluent NH_4^+ to NO_3^- in close proximity to the outfalls represents a significant source of “new” N to the biological community that needs to be considered in quantifying biomass and productivity of phytoplankton in near-shore waters. Changes in the inventory, form, and biogeochemical cycling of N affect the phytoplankton community composition and competition among algal taxa (Dortch and Conway, 1984; Dortch, 1990, Dugdale et al., 2007; Collos and Harrison, 2014) and development of phytoplankton blooms (Kudela and Cochlan, 2000; Glibert et al., 2005; Beman et al., 2005; Glibert et al., 2006; Howard et al., 2007; Cochlan et al., 2008; Heisler et al., 2008; Kudela et al., 2008), as N is the primary macronutrient limiting phytoplankton in coastal waters (Dugdale, 1967; Ryther and Dunstan, 1971; Eppley et al., 1979; Howarth and Marino, 2006). Third, wastewater effluent elicited significant changes in microbial community composition, evident in a muted phytoplankton response and large increase in abundance of heterotrophic bacteria, suggesting the microbial loop plays a significant, perhaps under-appreciated role in urbanized coastal waters of SCB. Finally, a convergence of dilution estimates from multiple observational modes highlights the ability to track the bulk transport of effluent plumes, while observations of lensing and small patches of less-diluted effluent highlights the need for high-resolution sampling to quantify spatial and temporal variability.

Our findings indicate wastewater effluent alters N cycling and processes and microbial community composition in the nearshore urbanized coastal waters of the SCB. Studies from the Hyperion Wastewater Treatment Plant diversion in Santa Monica Bay in 2006 suggested regulatory implementation of nutrient reductions to avoid bloom development and minimize anthropogenic impacts (Reifel et al. 2013). However, our results do not support regulatory changes at this time, as too few studies have been completed and the spatial extent of the relative impact is currently unknown. Instead, we suggest additional studies that will determine the spatial extent of the anthropogenic impacts and use modeling and scenario analysis to determine if nutrient reductions will significantly reduce these impacts.

Routine regulatory requirements for monitoring point-source discharges through the National Pollutant Discharge Elimination System (NPDES) permits for ocean monitoring of large POTW discharges in SCB do not include measurements of nutrients, biological productivity, or chemical processes. Additionally, NPDES permit requirements for monitoring effluent differ amongst the four large POTW permits in SCB. Given that wastewater effluent may constitute nutrient inputs comparable to those from coastal upwelling (Howard et al., 2014), and that wastewater effluent influences N cycling in close proximity to outfalls (McLaughlin et al., this issue), a comprehensive record of the total N loading that includes different forms of N would be beneficial. Current NPDES requirements are not focused on nutrients; thus, regulatory monitoring programs do not provide comprehensive data to evaluate long-term ecological changes associated with point-source nutrient discharges. These parameters, however, are critical for identifying the impacts from point source discharges on coastal ocean ecosystems. Therefore, we suggest more nutrient focused regulatory monitoring requirements for both effluent and receiving waters that should be incorporated into NPDES monitoring requirement programs.

Mitigation of pathogens by OCSD’s enhanced chlorination and dechlorination of discharge proved successful (Rogowski et al., 2014), but had the unintended consequence of inhibiting phytoplankton biomass and productivity, and possibly preventing development of a harmful algal bloom, such as occurred in Santa Monica Bay following a shorter diversion. Future diversions and normal operations of POTWs should consider possible effects of DBP on the biota, as monitoring of residual chloride may not fully capture potential impacts on the biological community.

The multi-dimensional approach to monitoring developed for this study provided several important points for future diversions and/or management scenarios that require enhanced or extensive monitoring. First, now-casts and forecasts from ROMS combined with real-time observations provided a comprehensive overview of oceanic conditions independent of sporadic *in situ* and remote sensing data. Accordingly, ROMS outputs were critical to management decisions and to guide adaptive sampling. Second, satellite observations supported detection of the wastewater plume over a larger spatial scale than would have been possible with *in situ* observations alone, but with some limitations due to cloud cover that affected availability of imagery. We recommend the expenditure of effort to develop metrics to use satellite data for tracking plumes of wastewater effluent and quantifying phytoplankton responses, as this approach offers important advantages in spatial and temporal resolution. A more comprehensive assessment of point-source nutrient discharge for the SCB or other regions could also benefit from an Observing System Simulation Experiment (OSSE) framework, which would allow for a value-of-information approach to identify the most effective monitoring tools, and also assess new technologies as they become available. For the SCB, this approach is not warranted at this time given the infrequent timing of diversions (decades) and the current lack of a regulatory requirement for more sophisticated monitoring, but consideration should be given to this recommendation for other locales or for the SCB if agencies are required in the future to take a more holistic approach to wastewater management.

Acknowledgments

We thank OCSD for in-kind support, and the captains and crews of the *R/V Nerissa* and *R/V Yellowfin*. George Robertson (OCSD) was instrumental in making this project possible. This work was supported by the National Science Foundation (NSF) RAPID award OCE1251573 (RMK), National Oceanic and Atmospheric Administration (NOAA) ECOHAB award NA11NOS4780030 (RMK and MDH), and the Southern California Coastal Water Research Project Authority (SCCWRP). This is NOAA ECOHAB publication # 819. We thank Abel Santana (SCCWRP) for creation of the maps, Jeff Myers (NASA Ames Research Center) for the San Diego image, and Mike McCarthy and Michael Mengel (OCSD) for photographs of the surfacing effluent.

References

Beman, J.M., Arrigo, K.R., Matson, P.A., 2005. Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. Nature 434, 211-214.

Bograd, S.J., Castro, C.G., DiLorenzo, E., Palacios, D.M., Bailey, H., Gilly, W. Chavez, F.P., 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophys. Res. Lett. 35, L12607.

Bograd, S.J., Buil, M.P., DiLorenzo, E., Castro, C.G., Schroeder, I.D., Goericke, R., Anderson, C.R., Benitez-Nelson, C., Whitney, F.A., 2015. Changes in source waters to the Southern California Bight. Deep Sea Research Part II: Topical Studies in Oceanography 112, 42-52.

Booth, A.T., Sutula, M., Micheli, F., Weisberg, S.B., Bograd, S.J., Steele, A., Schoen, J., Crowder, L.B., 2014. Patterns and potential drivers of declining oxygen content along the southern California coast. Limnol. Oceanogr. 59, 1127-1138.

Capone, D.G., Hutchins, D.A., 2013. Microbial biogeochemistry of coastal upwelling regimes in a changing ocean. Nature Geosci. 6, 711-717.

Caron, D.A., Gellene, A.G., Smith, J., Seubert, E.L., Campbell, V. Sukhatme, G.S., Seegers, B., Jones, B.H., Howard, M.D.A., Kudela, R.M., Hayashi, K., Ryan, J., Birch, J., Demir-Hilton, E., Yamahara, K., Scholin, C., Mengel, M., Robertson, G., 2016. Response of the phytoplankton and bacterial communities during a wastewater effluent diversion into nearshore coastal waters. Estuar. Coast. Shelf Sci. (accepted).

Casey, R. Ciccateri, A., Dougherty, K., Gacek, L., Lane, S., Liponi, K., Leeds, R., Walsh, F., 1992. Oceanographic effects of the 1992 Point Loma sewage pipe spill. Proc., Annual Mtg. Geol. Soc. America 24, 26-29.

Chavez, F., Toggweiler, J.R.T., 1995. Physical estimates of global new production: The upwelling contribution. In: Summerhayes, C.P., Emeis, K.C., Angel, M.V., Smith, R.L., Zeitzschel, B. [Eds.], Upwelling in the oceans: Modern Processes and Ancient Records. Wiley, pp. 149–169.

Chavez, F., Smith, J., Lluch-Cota, S.E., Niquen, M.C., 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299, 217-221.

Chavez, F.P., Messie, M., 2009. A comparison of Eastern Boundary Upwelling Ecosystems. Prog. Oceanogr. 83, 80-96.

Collos, Y., Harrison, P.J., 2014. Acclimation and toxicity of high ammonium concentrations to unicellular algae. Mar. Poll. Bull. 80, 8-23.

Corcoran, A.A., Reifel, K.M., Jones, B.H., Shipe, R.F., 2010. Spatiotemporal development of physical, chemical, and biological characteristics of stormwater plumes in Santa Monica Bay, California (USA). J. Sea Res. 63, 129-142.

Culliton, T., Warren, M., Goodspeed, T., Remer, D., Blackwell, C., McDonough III, J., 1990. Fifty Years of Population Changes Along the Nation’s Coasts. Coastal Trends Series, Report No. 2, National Oceanic and Atmospheric Administration, Strategic Assessment Branch. Rockville, MD.

Dortch, Q., 1990. The interaction between ammonium and nitrate uptake in phytoplankton. Mar. Ecol. Prog. Ser. 61, 183-201.

Dortch, Q., Conway, H.L., 1984. Interactions between nitrate and ammonium uptake: variation with growth rate, nitrogen source and species. Mar. Biol. 79, 151-164.

Dugdale, R.C., 1967. Nutrient limitation in the sea: Dynamics, identification and significance. Limnol. Oceanogr. 12, 685-695.

Dugdale, R.C., Goering, J.J., 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnol. Oceanogr. 12, 196-206.

Dugdale, R.C., Wilkerson, F.P., Hogue, V.E., Marchi, A., 2006. Nutrient controls on new production in the Bodega Bay, California, coastal upwelling plume. Deep-Sea Research II 53, 3049-3062.

Dugdale, R., Wilkerson, F., Hogue, V., Marchi, A., 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuar. Coast. Shelf Sci. 73, 17-29.

Eppley, R., Renger, E., Harrison, W., 1979. Nitrate and phytoplankton production in California coastal waters. Limnol. Oceanogr. 24, 483-494.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., Hales, B., 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320, 1490.

Gierach, M.M., Holt, B., Trinh, R., Pan, B., Rains, C., 2016. Satellite detection of wastewater diversion plumes in Southern California. Estuar. Coast. Shelf Sci. (accepted).

Glibert, P., Seitzinger, S., Heil, C.A., Burkholder, J.M., Parrow, M.W., Codispoti, L.A., Kelly, V., 2005. The role of eutrophication in the global proliferation of harmful algal blooms. Oceanography 18, 198-209.

Howard, M.D.A., Jones, A.C., Schnetzer, A., Countway, P.D., Tomas, C.R., Kudela, R.M., Hayashi, K., Chia, P., Caron, D.A., 2012. Quantitative real-time PCR for *Cochlodinium fulvescens* (Dinophyceae), a potentially harmful dinoflagellate from California coastal waters. J. Phycol. 48, 384-393.

Howard, M.D.A., Sutula, M., Caron, D.A., Chao, Y., Farrara, J.D., Frenzel, H., Jones, B., Robertson, G., McLaughlin, K., Sengupta, A. 2014. Anthropogenic nutrient sources rival natural sources on small scales in the coastal waters of the Southern California Bight. Limnol. Oceanogr. 99, 285-297.

Howarth, R.W., Marino, R., 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnol. Oceanogr. 51, 364-376.

Howarth, R.W., 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. Harmful Algae 8, 14-20.

Kim, H. J., A. J. Miller, J. McGowan, and M. L. Carter. 2009. Coastal phytoplankton blooms in the Southern California Bight. Prog. Oceanogr. 82, 137-147, doi:10.1016/j.pocean.2009.05.002

Kudela, R.M., Howard, M.D.A., Hayashi, K., Beck, C., 2016. Evaluation of ammonium inhibition and nitrogen uptake kinetics during a wastewater diversion into nearshore coastal waters in Southern California. Estuar. Coast. Shelf Sci. (submitted).

Kudela, R.M., Lucas, A.J., Negrey, K.H., Howard, M., McLaughlin, K., 2016. Death from below: Investigation of inhibitory factors in bloom development during a wastewater effluent diversion. Estuar. Coast. Shelf Sci. (accepted).

Kudela, R.M., Cochlan, W.P., 2000. The kinetics of nitrogen and carbon uptake and the influence of irradiance for a natural population of *Lingulodinium polyedrum* (Pyrrophyta) off Southern California. Aquat. Microbial Ecol. 21, 31-47.

Kudela, R.M., Lane, J.Q., Cochlan, W.P., 2008. The potential role of anthropogenically derived nitrogen in the growth of harmful algae in California, USA. Harmful Algae 8, 103-110.

Lyon, G. S., Stein, E.D., 2009. How effective has the Clean Water Act been at reducing pollutant mass emissions to the Southern California Bight over the past 35 years? Environ. Mon. Assess. 154, 413-426.

Lucas, A.J., Kudela, R.M., 2016. The fine-scale vertical variability of a wastewater plume in stratified coastal waters. Estuar. Coast. Shelf Sci. (accepted).

McLaughlin, K., Nezlin, N.P., Howard, M.D.A., Beck, C.D.A., Kudela, R.M., Mengel, M., Robertson, G.L., 2016. Tracking the fate of anthropogenic N from wastewater discharge into the coastal ocean, Southern California, USA. Estuar. Coast. Shelf Sci. (accepted).

Nezlin, N.P., Sutula, M.A. Stumpf, R.P. Sengupta, A., 2012. Phytoplankton blooms detected by SeaWiFS along the central and southern California Coast. J. Geophys. Res. 117, C07004.

Noble, M., Xu, J.P., 2004. Huntington Beach Shoreline Contamination Investigation, Phase III, Final Report, Coastal circulation and transport patterns: the likelihood of OCSD’s plume impacting Huntington Beach shoreline. US Geological Survey Open-File Report 2004-1019 (http://pubs.usgs.gov/of/2004/1019/S).

Orange County Sanitation Division (OCSD), 2011. Outfall Land Section and OOBS Piping Rehabilitation Draft Environmental 718 Impact Report, Volume 2: Appendices (http://www.ocsd.com/Home/ShowDocument?id=10785).

Paerl, H.W., Piehler, M.F., 2008. Nitrogen and marine eutrophication. In: Capone, D., Bronk, D., Mulholland, M., Carpenter, E. [Eds.], Nitrogen in the marine environment. Elsevier, pp. 529-567.

Reifel, K.M., Corcoran, A.A., Cash, C., Shipe, R., Jones, B.H., 2013. Effects of a surfacing effluent plume on a coastal phytoplankton community. Cont. Shelf Res. 60, 38-50.

Rogowski, P., Terrill, E., Thomas, J., Rosenfeld, L., Largier, J., 2014. 2012 Orange County Sanitation District (OCSD) Outfall Diversion –Summary Report. Final Report prepared for the Orange County Sanitation District. March 25, 2014, 92 p., plus appendices.

Ryther, J., Dunstan, W., 1971. Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171, 1008-1112.

Scavia, D., Bricker, S.B., 2006. Coastal eutrophication assessment in the United States. Biogeochem. 79, 187-208.

Schiff, K.C., Allen, M.J., Zeng, E.Y., Bay, S.M., 2000. Southern California. Marine Pollution Bulletin, 41, 76-93.

Schnetzer, A., Miller, P., Schaffner, R., Stauffer, B., Jones, B., Weisberg, S., DiGiacomo, P., Berelson, W., Caron, D., 2007. Blooms of *Pseudo-nitzschia* and domoic acid in the San Pedro Channel and Los Angeles harbor areas of the Southern California Bight, 2003-2004. Harmful Algae 6, 372-387.

Schnetzer, A., Jones, B.H., Schaffner, R.A., Cetinic, I., Fitzpatrick, E., Miller, P.E., Caron, D.A., 2013. Coastal upwelling linked to toxic *Pseudo-nitzschia australis* blooms in Los Angeles coastal waters, 2005 – 2007. J. Plankton Res. 35, 1080-1092.

Seegers, B.N., Teel., E.N., Kudela, R.M., Caron, D.A., Jones, B.H., 2016. Glider and remote sensing perspective of the upper layer response to an extended shallow coastal diversion of municipal wastewater effluent. Estuar. Coast. Shelf Sci. (accepted).

Seubert, E.L., Gellene, A.G., Campbell, V., Smith, J., Robertson, G., Caron, D.A., 2016. Incubation experiments to determine the response of a natural plankton community to treated sewage effluent. Estuar. Coast. Shelf Sci. (submitted).

Seubert, E.L., Gellene, A.G., Howard, M.D.A., Connell, P., Ragan, M., Jones, B.H., Runyan, J., Caron, D.A., 2013. Seasonal and annual dynamics of harmful algae and algal toxins revealed through weekly monitoring at two coastal ocean sites off southern California, USA. Environ. Sci. Pollution Res. 20, 6878-6895.

Sengupta, A., Sutula, M.A., McLaughlin, K., Howard, M.D.A., Tiefenthaler, L., Bitner, T.V., 2013. Terrestrial nutrient loads and fluxes to the Southern California Bight, USA. In: Schiff, K.C., Miller, K. (Eds.), Southern California Coastal Water Research Project 2013 Annual Report, edited by pp. 245-258, Southern California Coastal Water Research Project, Costa Mesa, CA.

Tegner, M.J., Dayton, P.K., Edwards, P.B., Riser, K.L., Chadwick, D.B., Dean, T.A., Deysher, L., 1995. Effects of a large sewage spill on a kelp forest community: Catastrophe or disturbance? Mar. Environ. Res. 40, 181-224.

Uchiyama, Y., Idica, E.Y., McWilliams, J.C., Stolzenbach, K.D., 2014. Wastewater effluent dispersal in Southern California Bays. Cont. Shelf Res. 76, 36-52.

Ward, B.B., 1987. Nitrogen transformations in the Southern California Bight. Deep-Sea Research Part A 34, 785-805.

Figure Legends

Figure 1. Map of the study area illustrating instruments comprising the sensor network. The gray dashed line and gray dashed railroad lines show offshore and nearshore glider transects, respectively. Fixed platforms consist of water-quality moorings, including ADCPs (dark gray triangle), ADCPs only (open circles), Wirewalkers (white stars) and the ESP (gray square).

Figure 2. Photographs of the wastewater effluent surfacing during the OCSD diversion. Courtesy of Mike McCarthy and Michael Mengel (OCSD).

Figure 3. Image of the effluent breach in San Diego, California on 25 February 1992 from the NASA Airborne Ocean Color Imager (AOCI). Courtesy of Jeff Myers (NASA Ames Research Center).

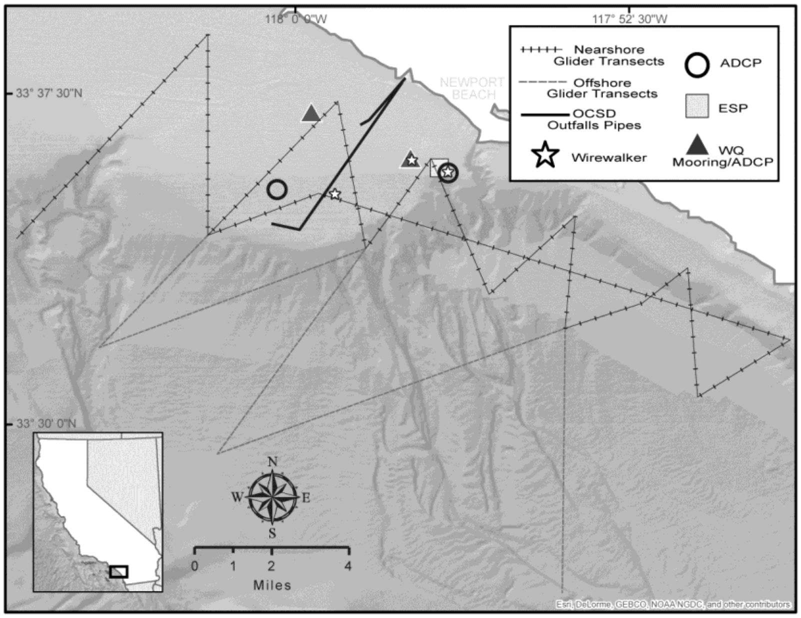
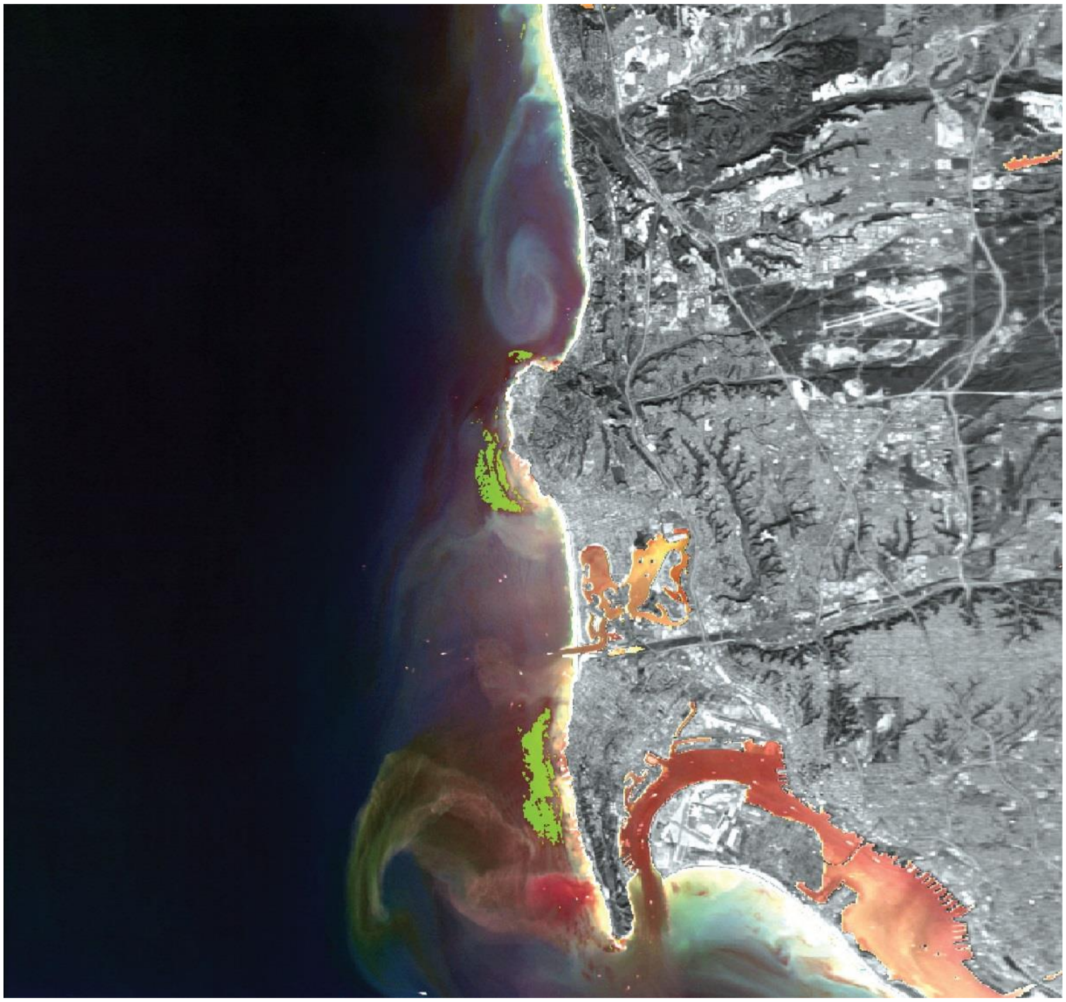

118° 0' 0"W
117° 52' 30"W
33° 37' 30"N
33° 30' 0"N
NEWPORT BEACH
Nearshore Glider Transects
Offshore Glider Transects
OCSD Outfalls Pipes
Wirewalker
ADCP
ESP
WQ Mooring/ADCP
N
W
E
S
0
1
2
4
Miles
Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

Fig. 1

Fig. 2

554


555

556 Fig. 3