SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT AUTHORITY

THEMATIC RESEARCH PLAN

FOR

EUTROPHICATION

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Introduction

Eutrophication of freshwater and coastal habitats is a global environmental issue (Figure 1), with demonstrated links between anthropogenic changes in watersheds, increased nutrient loading to surface waters, harmful algal blooms, hypoxia, and impacts on aquatic food webs. Defined as an accelerated accumulation of organic matter from an overgrowth of plants and algae (Nixon 1995), these ecological impacts of eutrophication can have far-reaching consequences. These include fish-kills, loss of keystone habitats (e.g., seagrass), poor benthic habitat quality, smothering of benthic organisms, nuisance odors, and impacts on human and marine mammal health from increased frequency and the extent of harmful algal blooms and poor water quality, all of which modifications have significant economic and social costs.

While nutrients themselves are not inherently harmful, excess nutrients (i.e., nitrogen and phosphorus) introduced to aquatic habitats through human activity are one of the principal causes of eutrophication. Other human activities in watersheds can accelerate eutrophication, such as habitat degradation, hydromodification, excessive sedimentation, etc. These local impacts are heightened by global climate change, which can further exacerbate hydromodification, increase temperatures, and alter other fundamental drivers controlling biological productivity, such as oceanic upwelling. Disentangling the relative influence of natural variability, global climate change, and local anthropogenic influences on eutrophication is challenging, but necessary to identify cost-effective strategies, such as nutrient management, to prevent and mitigate eutrophication.

SCCWRP's goal is to build a comprehensive eutrophication research program that spans watersheds to oceans, encompassing **streams, lakes, estuaries** and **coastal waters**, enabling environmental managers to better protect aquatic ecosystems, identify and control deleterious eutrophication drivers, mitigate adverse effects of climate change, and foster sustainable ecosystems.

Approach to Eutrophication Research

SCCWRP's approach for eutrophication research is driven by the ecosystem services and beneficial uses that environmental managers are legally mandated to protect. These goals, and the need to identify symptoms and manage drivers that accelerate eutrophication (Figure 1), form the foundation of a research program that is comprised of three distinct areas, which work in coordination to seamlessly transition science into products optimized for widespread management adoption (Figure 2): (1) assessing waterbody condition (**Condition Assessment**), (2) assessing major causes of waterbody impairment and predict future conditions (**Modeling**), and (3) providing assistance to transition science in support of setting and measuring progress toward achieving beneficial-use goals (**Implementation Assistance**).

Condition Assessment

All water-quality management programs across California are founded on the expectation that they will protect and restore the many ecosystem services and related beneficial uses that waterbodies provide. A key need for SCCWRP research is to provide a strong conceptual framework and specific tools to diagnose eutrophication symptoms and related ecosystem effects, linking them with specific ecosystem services and beneficial uses, including: (1) habitat for aquatic life (COLD, WARM, EST, MAR), (2) protection of biodiversity (COLD, WARM, EST, MAR), including rare, threatened and endangered species and migratory and spawning habitat (RARE, SPWN, MIGR), (3) productivity of commercial and recreational fisheries (SHELL, COMM, AQUA), (4) good aesthetics and lack of odors (REC2), and (5) maintenance of good water quality (MUN, REC1, COMM, AQUA, SHELL). Protection of these goals depends upon a manager's ability to accurately and comprehensively assess the biological and chemical condition of each waterbody.

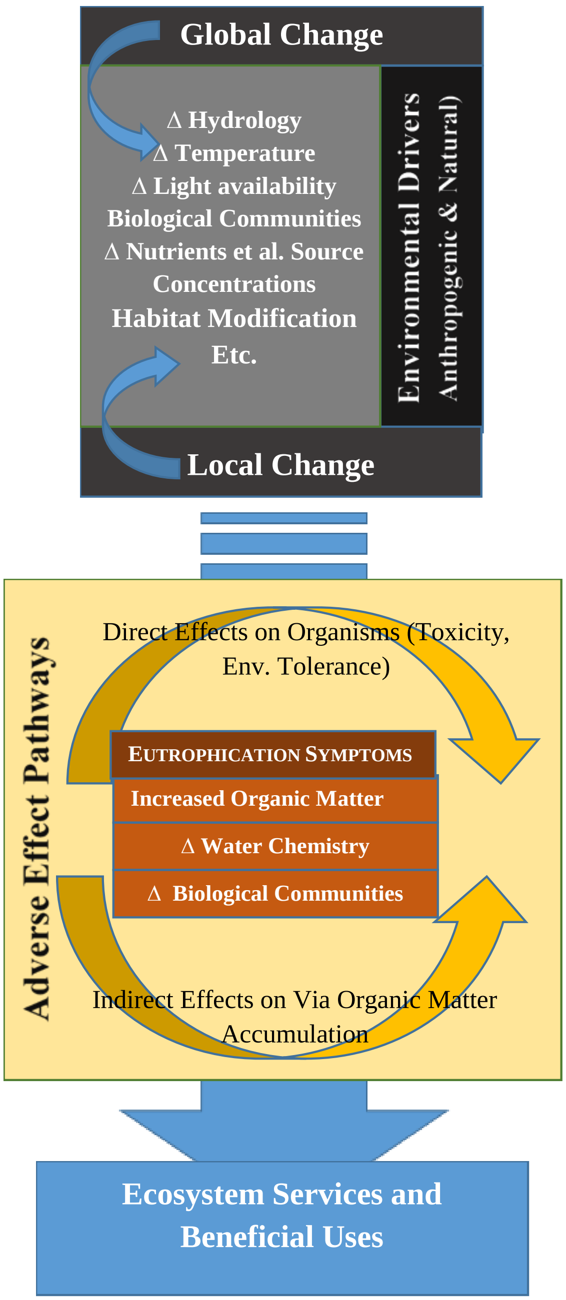

Figure 1. Generalized conceptual model of eutrophication drivers, symptoms, ecological effects and linkage to ecosystem services and beneficial uses, applicable across the watershed to ocean continuum. Environmental drivers of eutrophication (both natural and human-impacted) are represented in the top panel. Those drivers can be local, at the scale of the watershed or near-field influences to coastal water in which local management practices can conceivably wield environmental benefit, or global, in which drivers are operating at a scale that is beyond the reach of local management agencies. These environmental drivers result in the expression of eutrophication via a number of pathways of direct and indirect adverse effects, the primary symptoms of which are expressed as 1) changes in live and dead organic matter, 2) changes in water chemistry (e.g. DO, pH, carbonate chemistry, toxins), or changes in structure and functional capacity of biological communities (middle panel). The environmental symptoms have direct linkages to ecosystem services and beneficial uses (bottom panel).

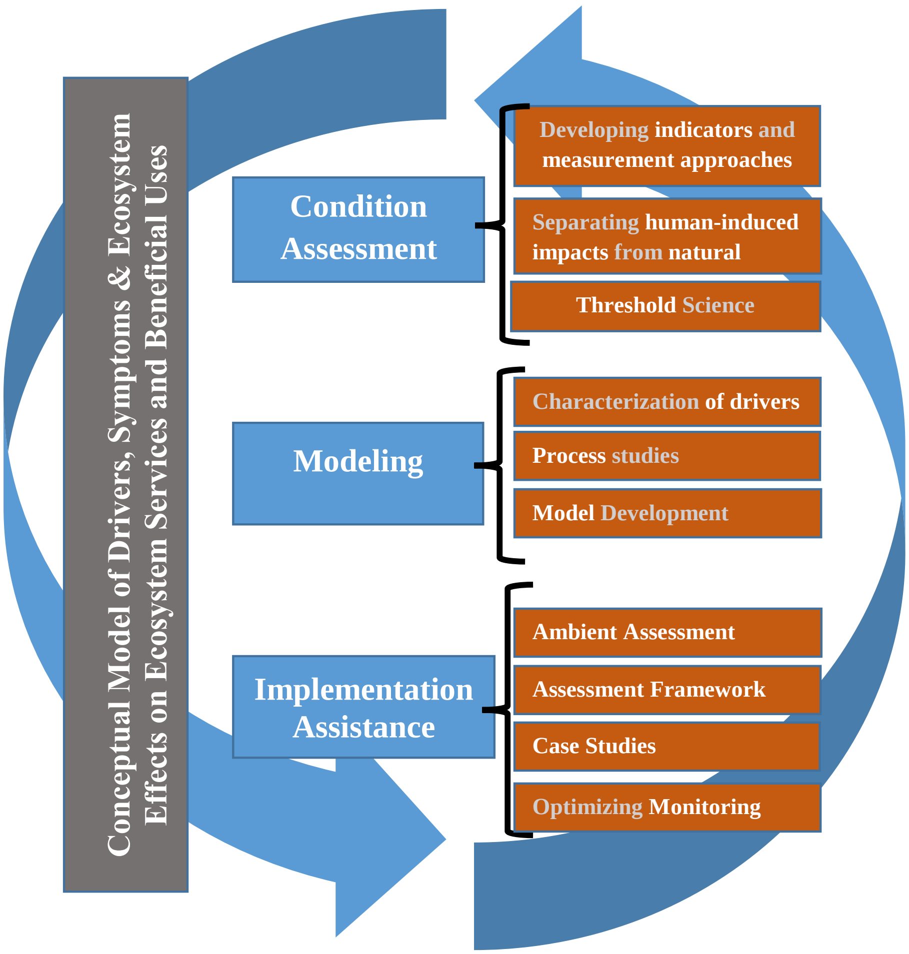

Figure 2. SCCWRP's eutrophication research is driven by the need to support ecosystem services and achieve beneficial-use goals for waterbodies. SCCWRP works across three main areas – condition assessment, modeling, and implementation support– to design solution-oriented, managerially relevant tools that help achieve these beneficial-use goals. The research is continuously informed by evolving conceptual models of eutrophication drivers, symptoms (biological effects) and their linkage to beneficial use goals and related ecosystem services (see Fig. 1).

SCCWRP builds capacity for environmental managers to assess the condition of a waterbody type via three major components. First, SCCWRP **identifies indicators** and **develops and standardizes assessment approaches** to measure condition vis-à-vis eutrophication. Second, since eutrophication can be a natural process, SCCWRP works to **characterize the magnitude and variability of eutrophication indicators** relative to those of waterbodies that are in **"reference condition,"** without human-induced impacts. Third, SCCWRP conducts science and synthesizes information on how **thresholds** associated with the **magnitude, extent and duration** of **eutrophication symptoms** translate to degradation of ecosystem services and beneficial uses, across the spectrum of the biological condition gradient, in a way that can be readily interpreted and used by managers.

Modeling

While condition assessment reveals the degree to which a waterbody is impacted by human and natural processes, it cannot quantify the relative contribution of environmental drivers, predict future trends, nor help to quantify the impact of management actions like loading allocations or restoration actions. Hence, researchers need tools to identify, evaluate and quantify the relative importance of potential environmental drivers on a waterbody, a research area known as modeling. For eutrophication, these models can span the gamut from empirical, statistical models representing stressor-response relationships, simple, steady state, one-dimensional box models, to dynamic, 3-D causal models that integrate physics, biogeochemical processes, and ecosystem response. Modeling relies on the biological data generated through condition assessment to establish what biological impacts have occurred. It relies on characterization of the environmental drivers, the major pathways by which those drivers can impact the waterbody synoptically with measures of biological condition. In practice, modeling can serve to highlight gaps in routine monitoring data and focus scientific research around key areas of uncertainty.

SCCWRP builds capacity for environmental managers to develop models by focusing its research around three main areas: First, SCCWRP works to identify and quantify the major **environmental drivers** of eutrophication and how they relate to biological degradation. Second, SCCWRP characterizes important rates of transformation (a.k.a**. process studies**), which help to calibrate and validate key mechanisms in the transformation of nutrients and carbon within the waterbody as they influence pathways of biological impact. Together, these data sources support the **development of models**, which are used explicitly in the process of environmental decision-making. Choice of modeling approach is driven by the research or management question, existing data and resources to collect new data, desired modeling endpoints, and the precision required in the answer.

Implementation Assistance

Underlying all of SCCWRP's research is a need to design tools and collect data that inform management decisions. SCCWRP's eutrophication program aims to support the transition of findings of condition assessments and modeling to regulatory, restoration and management programs. SCCWRP also works to build capacity among our partners to utilize these tools to support environmental management on an ongoing basis. SCCWRP is working to provide this assistance by focusing on four areas: First, SCCWRP works with partners to conduct ambient assessments of eutrophication and its impacts on ecological condition to characterize the magnitude of the risk to ecosystem services and beneficial uses. Second, SCCWRP is working to support the translation of condition assessment data and threshold science by developing **assessment frameworks**, which provides a clear path for their use to set goals for water quality programs, natural resource assessments, and restoration. Third, SCCWRP provides assistance and capacity building via **case studies to demonstrate application** of these assessment tools and models in management settings to support environmental decision-making. Finally, SCCWRP works with partners to **optimize monitoring** programs to achieve a balance between cost and robust, high-quality data that provides precise and accurate answers to assessment questions.

Research Status and Directions

SCCWRP eutrophication research focuses on building eutrophication tools for every major aquatic waterbody and habitat type of management concern, as well as developing an integrated framework that allows managers to effectively and efficiently synthesize results from multiple tools to assess and manage overall waterbody condition. This document presents an overview of the status of SCCWRP's eutrophication research, including detailed accomplishments, ongoing projects and future directions.

Condition Assessment

The process of identifying indicators of eutrophication begins with the development of conceptual models that specify eutrophication symptoms (indicators), environmental drivers, and the biological impacts that are linked to ecosystem services and related beneficial uses. As the science supporting these conceptual models evolves, SCCWRP will continually refine the toolkit of optimal eutrophication indicators and provide a suite of standardized protocols to facilitate management adoption.

Developing Indicators and Standardized Measurement Approaches

Science has converged on the need to assess eutrophication based on the ecological responses, rather than nutrient over-enrichment per se or other environmental drivers. The growing body of research on the biological and biogeochemical impacts of eutrophication spans from organismal responses to ecosystem-scale responses. The science of eutrophication assessment is evolving rapidly to produce more precise diagnostic measures, often at a reduced cost. Therefore, SCCWRP's research is focused on refining conceptual models that link environmental drivers to ecosystem responses, identifying appropriate eutrophication indicators, and both developing and standardizing the measurement of these indicators in order to accurately assess condition. Four major categories of indicators are generally applicable across waterbody types: (1) **biological communities**, including the taxonomic composition and relative abundance of algae, benthic and pelagic invertebrates, and prokaryotes (bacteria and archaea), (2) **harmful algal blooms (HABs) and toxin concentrations**, **(**3) **organic matter (OM) accumulation**, including algal biomass, percent cover, and OM concentration, and (4) water column and benthic **physiochemical changes** such as dissolved oxygen, pH and carbonate saturation state (linking to the effect of ocean acidification on shell-forming organisms).While the general conceptual model of eutrophication indicators is broadly applicable across waterbody types, the specific pathways of impairment, the appropriate indicators, and how they are measured will vary greatly by waterbody type and major habitat class. Robust condition assessments include multiple indicators (i.e., microbes, plants, invertebrates and vertebrates), so there is a need to develop approaches that enable the use of these indicators as multiple lines of evidence.

Accomplishments

Evaluations of the relative health of an ecosystem by assessing its biological diversity is referred to as bioassessment. Investments in bioassessment research and protocol development in regional monitoring programs has led to a solid foundation for eutrophication assessment in wadeable streams, and the elements of this foundation in estuaries and coastal waters. In California streams, SCCWRP has been instrumental in the development of bioassessment assessment methods focused on the lower trophic level organisms such as stream benthic macroinvertebrates (BMI) and diatoms and soft-bodied algae (Fetscher et al. 2014a, Ode et al. 2016a). The BMI and algae-based bioassessment protocols have been widely adopted into ambient monitoring, permit monitoring and compliance monitoring. In estuaries, sediment quality assessment methods are routinely used to assess BMI communities, albeit focused on toxic contaminants (Bay and Weisberg 2012). In marine waters, the POTW Central Bight working group uses a standardized collection protocol and has a long-term record of DO, pH, and chlorophyll-a, representing an important foundational dataset for eutrophication assessment.

Early SCCWRP research on eutrophication monitoring focused on developing conceptual models, identifying indicators, and developing assessment methods for California estuaries in support of statewide nutrient objectives. This work began with a comprehensive synthesis to inventory estuaries, establish estuary classification, review and recommend key indicators of eutrophication by major habitat types, and identify major knowledge gaps (Sutula 2011). Partner investments in a regional estuarine eutrophication assessment as part of Bight '08 fueled the development of standardized protocols to monitor eutrophication indicators, including training, quality assurance and data management protocols (McLaughlin et al. 2012).

As toxic HABs have gained public attention for their impacts on shellfish, fish, benthic organisms, marine mammals and drinking water, SCCWRP has provided important leadership to establish a statewide marine Harmful Algal Bloom Monitoring and Alert Program (HABMAP; Kudela et al. 2015). HABMAP provides coordination of HAB researchers, managers, and the general public in California and has created a centralized website where all HAB data and predictive modeling information can be visualized, conducted a comparison of analytical methods in order to combine and compare datasets throughout California. SCCWRP recently led the creation of a statewide monitoring and assessment strategy for freshwater HABs in collaboration with SWAMP (Anderson-Abbs 2016). This strategy has laid the groundwork for a long-term response to HABs and has provided a roadmap of infrastructure needed to ultimately create a statewide monitoring program.

Ongoing Research

***Focus Area*: Development of a Statewide Algal Stream Condition Index**
SCCWRP's research is currently focused on developing a statewide, predictive freshwater Algal Stream Condition Index (ASCI), leveraging previous efforts to develop a southern California algal index of biotic integrity (Fetscher et al. . 2014a). The new algal index will adopt an approach used in the development of the statewide BMI-based California Stream Condition Index (CSCI, Mazor et al., 2016), and will provide reference-based expectations of biological condition for the diverse stream types found in California. The ASCI and CSCI will directly support the State Water Resources Control Board's (Water Board) efforts to develop a combined Biostimulatory (Nutrients) and Biointegrity policy for streams by serving as assessment endpoints for developing nutrient numeric targets.

***Focus Area*: Transitioning Algal Assessment to Molecular Methods**
In streams, SCCWRP is focused on expanding the State's capacity for generating algae taxonomy data, a process that is severely limited by the available number of specialist algae taxonomists. To alleviate this strain, SCCWRP is focused on transitioning traditional morphological-based taxonomic methods for identifying diatoms and soft-bodied algae to novel molecular, or DNA-based methods that use unique genetic signatures from each species to rapidly analyze bioassessment samples (Stein et al. 2014). SCCWRP has already developed a DNA collection method that has been integrated into stream bioassessment protocols, and in partnership with multiple monitoring programs throughout the state, these new efforts have resulted in the collection of hundreds of DNA samples from stream algal communities. SCCWRP scientists are also focused on building the State's capacity to generate reliable, comparable, and accurate algae taxonomy data through improving taxonomy assignment harmonization and quality control. This taxonomic harmonization allows for a direct crosswalk of the existing algae bioassessment database, generated using

algae morphology, to the forthcoming DNA sequence-based bioassessment surveys, paving the way for a smooth transition from morphology to molecular data use in the statewide algae index.

***Focus Area*: Incorporation of HABs into Standardized Assessment Eutrophication Protocols**

In lakes and estuaries, SCCWRP research is supporting SWAMP adoption of the core set of eutrophication assessment protocols in lakes and estuaries, specifically focused on HABs. In lakes, SCCWRP is developing standard protocols for lake eutrophication assessment and linking these to cyanotoxin monitoring protocols. In estuaries, SCCWRP is working with partners to develop standardized protocols for macroalgal bloom monitoring on intertidal flats, and subtidal and seagrass habitats. At the same time, SCCWRP is trialing the use of solid phase absorption toxin tracking (SPATT) for cyanotoxin screening assessments across freshwater and marine habitats (Kudela 2011). Scientists are working towards the rapid automated analysis and processing of images derived from in-the-field microscopy of algal samples via a CellScope, which is a field-portable cell phone microscope.

***Focus Area*: Protocols for Improved Sensor Technology to Measure Ocean acidification (OA), pH and CDOM**

SCCWRP and its partners are working to improve measurements of pH for routine monitoring that meet the necessary requirements for OA monitoring. The current methodologies employed for routine monitoring of pH do not possess the required accuracy to measure changes in seawater pH needed to understand vulnerability and risk associated with OA (McLaughlin et al. in review, a). While current research has provided a near-term strategy to improve the calibration of existing pH sensors, new technology is needed to collect measurements at the accuracy necessary to document small scale changes in pH. New technologies have recently been developed for accurate monitoring of seawater pH on moorings (ISFET pH sensors) and SCCWRP is working with member agencies to develop protocols to deploy this technology within emerging programs with moored sensors, and it is expected that this technology will be adapted for profiling applications in the near future (McLaughlin et al. in review b). SCCWRP partners also routinely measure CDOM and have been increasingly required to measure nutrients such as ammonium, nitrate and phosphate. Therefore, SCCWRP is seeking to undertake sensor testing and protocol development that would service partner needs and specifications for monitoring of these parameters across the freshwater-marine continuum, whether by ship-based CTD, pier or moored sensors.

***Focus Area*: Indicators of OAH Biological Impacts**

The West Coast OAH Expert Panel (westcoastoah.org/) strongly urged the co-location of long-term, chemical and biological OAH monitoring in order to differentiate declines in marine organisms between natural population cycles and acidification-related stress. In the SCB, SCCWRP and partners have begun to document the trends in abundance of calcifying benthic infauna, sea urchins and pteropods relative to corrosive conditions in order to document whether OA is a potential cause of these sentinel organisms' decline.

Priorities for Future Research

***Future Focus Area*: Expansion of Biological Community Metrics into Eutrophication Assessment**

SCCWRP's expansion of molecular methodologies in bioassessment approaches is paving the way for their use in routine eutrophication assessments. In streams, benthic invertebrate and algal species responses to specific eutrophication pathways can be detected using the CSCI and ASCI, thus allowing a rapid assessment of probable causal pathways that can be further investigated for possible management response. In estuaries, there is a need to expand the current toolkit beyond macroalgal biomass to include additional lines of evidence, such as adverse effects to invertebrate communities. Existing estuarine benthic invertebrate and sediment quality protocols have been optimized for sediment toxicity assessments, but represent an untapped resource to leverage existing monitoring programs for assessment of organic matter accumulation in sediments. DNA barcode sequencing and genome sequencing (i.e., metagenomics) can speed the expansion of benthic and planktonic algae as a eutrophication assessment tool in estuaries and coastal waters, and can be particularly useful for rapid assessment of HABs and the risk of toxin production. Prokaryote (i.e., bacteria and archaea) communities can also be used to indicate the status of organic matter enrichment in streams, estuaries, and coastal waters, signaling impacts on nutrient biogeochemical cycling and the linkages to pH and dissolved oxygen concentrations.

***Future Focus Area*: Remote Sensing Technologies to Identify and Characterize CyanoHABs**

Monitoring data that support environmental management decisions are often collected at spatial and temporal scales that are too coarse or too infrequent to adequately characterize risk or capture the triggers that leads to cyanobacteria dominance and toxin production. Importantly for this work, rapid improvement of remote and in situ sensing equipment will allow for HAB event forecasting and rapid management response. Improvements in the provision of remote sensing products characterizing cyanoHABs can be supplemented by products derived from small unmanned aerial system (sUAS), which offers advantages over these traditional technologies, notably: (1) imagery may be collected essentially on demand without the constraints of satellite orbital repeat times and/or scheduling of aircraft, (2) the low altitude of sUAS systems permits data collection even during weather conditions when other imaging platforms are not feasible, and (3) sUAS systems can be programmed to fly the same flight paths every time, providing for consistent and comparable imagery throughout the sampling season.

Separating Human-Induced Eutrophication from Natural Background

Interpreting the ecological significance of eutrophication requires an understanding of the natural background concentration of eutrophication indicators a waterbody *should* have, if not for human impacts. In addition, like any type of ecological indicator, measures of eutrophication are subject to inherent temporally and spatially variable external forcing such as wind-driven coastal upwelling, tidal circulation and riverine and atmospheric climatic forcing of river discharge and hydroperiod, all of which interact strongly with internal biogeochemical processes such as algal blooms, organic matter decomposition, etc. These interactions give rise to a complex temporal and spatial mosaic of variability, some of which is inherently natural. This natural variability can dramatically affect the abundance, composition and condition of biological communities. An important component of the SCCWRP research is to document the magnitude and variability of key eutrophication indicators along the biological condition gradient, with a goal of understanding which impacts are triggered by human activity and which are the result of natural variation. To make this determination, scientists must characterize the eutrophication state vis-à-vis natural and human-influenced gradients in the major environmental drivers of eutrophication, e.g. physical habitats (i.e., change to habitat structure), hydrology and hydrodynamics (i.e., hydromodification), temperature, light and biogeochemical elements (i.e., nutrients, carbonate system).

Accomplishments

SCCWRP has long invested in documenting natural background concentrations of environmental gradient and biological states in minimally impacted "reference" sites, starting with the agency's 1976 "reference surveys" (Word et al. 1979) , continuing with the wadeable streams Reference Condition Management Program (Ode and Schiff 2009, Ode et al. 2016b), and marine and estuarine soft bottom habitats (Bay and Weisberg 2012). Collectively, these studies have illustrated the need to account for loading from natural landscapes and to interpret existing water quality objectives within the lens of natural background concentrations of regulated biological and chemical constituents like fecal indicator bacteria and nutrients (Yoon and Stein 2008, Tiefenthaler et al. 2015, 2016). These investments have already resulted in dividends for SCCWRP eutrophication science, since the approach relies on the assessment of biological indicators to assess beneficial use support, relative to "reference" conditions and the inherent natural variability in that state. For example, documentation of elevated cyanotoxin concentrations in reference streams has provided important context for interpretation of cyanobacteria and cyanotoxin concentrations in human-impacted sites (Fetscher et al. 2015).

Ongoing Research

***Focus Area*: Documenting Natural Background Levels of Eutrophication Indicators and Environmental Drivers in Streams and Estuaries**

Investments continue in wadeable stream reference networks and this work is particularly important to support the transition of molecular methods to stream algal bioassessment, the cornerstone of eutrophication assessment in this aquatic habitat. However, improved characterization of natural variability of DO and pH in reference wadeable streams, relative to impacted streams, is needed to inform interpretation of existing water quality objectives, and optimize monitoring conducted under permit requirements. While no programmatic investment has been made of comparable levels in estuaries, research is ongoing to document the natural background levels and timescales of variability of basic eutrophication indicators such as macroalgal and phytoplankton biomass and dissolved oxygen in intermittently tidal, bar-built estuaries. These studies are being conducted with synoptic measures of tidal exchange, wet and dry weather measures of freshwater flow, nutrient and organic carbon loading from these reference watersheds, in order to better understand the sources of natural variability. Ultimately, this work will inform establishment of assessment endpoints and nutrient targets that will comprise nutrient objectives for this class of estuaries.

Priorities for Future Research

***Future Focus Area*: Natural variability in pH, carbonate saturation state, and DO in the coastal ocean**

Geographic characterization of the exposure that marine organisms have to ocean acidification and hypoxia (OAH) stress is important to document adverse effects, but remains constrained by key gaps in our understanding of: 1) how current exposure to OAH stress varies across the system, 2) how this has deviated from the past, 3) at what time point assessment endpoints or thresholds will be exceeded, and 4) how this spatial pattern of exposure will change in the future. While mooring data can provide characterization of fine scale temporal variability, it cannot alone adequately characterize exposure over the range of spatial scales (e.g., among ports, essential fish habitats, fishing grounds, or marine reserves, etc.) required to inform management decisions. Three-dimensional numerical models of the carbonate system and DO can provide the ability to spatially resolve the exposure regime to OAH stress that organisms face today, how this has changed from pre-industrial exposure (natural variability), and how the exposure patterns may change in the future. SCCWRP seeks to prioritize research to conduct spatially-explicit evaluations of OAH exposure regimes, using a combined network of moored observations and modeling approaches.

Threshold Science

An important management decision is the selection of numeric targets that represent water quality goals, either for indicators of biological condition (hereto referred to assessment endpoints) or the stressor (referred to as numeric targets, e.g., for nutrients). An important foundation for these decisions is the synthesis of information on thresholds. As used here, thresholds are defined as "the point at which there is an abrupt change in an ecosystem property or where small changes in an environmental driver produce large responses in the ecosystem" (Groffman et al. 2006). This decision-making on assessment thresholds and numeric targets is facilitated by: 1) experiments and field studies characterizing pathways of adverse effects and identifying thresholds or tipping points at which those ranges of effects occur, 2) key graphics that summarize the magnitude and duration of exposure that result in a cascade of biological responses along gradients of increasing stress (i.e., biological condition gradient, Davies and Jackson 2006), to establish thresholds of impact.

Accomplishments

Research on eutrophication thresholds, key for policy decisions on biostimulatory (nutrient) objectives for wadeable streams, was catalyzed by the findings of Fetscher et al. (2014b). She used an extensive statewide database of ambient and reference data to identify statistical thresholds for adverse effects from nutrients concentrations and primary producer abundance on aquatic life (via the CSCI and the southern California algal IBI). The statistical thresholds were at a magnitude of nutrient and benthic chlorophyll-a much lower than previously believed (Tetra Tech 2006).

Understanding the thresholds at which algal blooms can adversely affect estuarine ecosystem services and beneficial uses constitutes an important knowledge gap (Bricker et al. 2003). To begin to address this gap, SCCWRP and its collaborators investigated thresholds of adverse effects of macroalgal blooms on estuarine benthic habitat quality (Green et al. 2014, Sutula et al. 2014). This science has been a focal point for early adoption of a macroalgal assessment framework, used in several TMDLs to support decision-making on estuarine habitat restoration. Similarly, a USGS 20-year monitoring dataset in San Francisco Bay was used to derive chlorophyll-a thresholds that increase the risk of low DO and toxic HABs (Sutula et al. in review); this study is the basis for a phytoplankton assessment framework that is being tested to assess the status of eutrophication in nutrient-enriched San Francisco Bay.

Dated science underpins a lack of consistency among Regional Board freshwater and estuarine DO objectives. A review by SCCWRP and partners of science supporting DO objectives in California estuaries (Sutula et al. 2013a) has been a catalyst for further focused analyses supporting site-specific objectives in habitats that can naturally have low dissolved oxygen, such as Suisun Marsh in San Francisco Bay (Bailey et al. 2014).

Ongoing Research

***Focus Area*: Thresholds Supporting Biostimulatory Objectives and a Program to Implement Biointegrity for Wadeable Streams**
SCCWRP and its partners are seeking to use expert consensus as a means to further interpret CSCI and ASCI scores using a biological condition gradient modeling approach (BCG, Davies and Jackson, 2006), in order to support decisions on assessment endpoints for a combined statewide biointegrity and biostimulatory (nutrient) policy for wadeable streams. The BCG modeling approach, in which experts come to consensus on the assignment of stream sites to six bins of ecological condition based on invertebrate and algal taxonomic composition, is intended as decision support to help stream managers more meaningfully interpret their stream bioassessment scores. With the BCG interpretive framework, stream managers will have an improved understanding of the consequences of the loss of various biological attributes of stream health as stream bioassessment scores decrease with increasing stress, particularly in agriculture- and urban-dominated landscapes. The intent is to combine BCG modeling results with additional analyses that inform discussions of appropriate expectations for channels in developed landscapes, which have been modified to maximize other services.

***Focus Area*: Thresholds Supporting Dissolved Oxygen Objectives in Estuaries**
Previous science has continued to catalyze investigations supporting appropriate DO objectives for estuarine habitats naturally low in DO, such as tidal sloughs and marshes. This work continues in Suisun Marsh and in South San Francisco Bay, where SCCWRP and partners are working to: 1) conduct a synthesis of the sensitivity of lower south Bay species and associated habitats to oxygen stress, 2) quantify present day DO exposure regimes that species are experiencing via observational data, and 3) compare how DO exposure regimes differ between impacted and minimally-disturbed sloughs or tidal creek.

Priorities for Future Research

***Future Focus Area*: Thresholds Supporting Assessment Endpoints for Acidification and Dissolved Oxygen in Estuaries and Coastal Waters**
The California Current System (CCS) is one of the most productive regions of the

world's ocean, but upwelling of low-dissolved oxygen (DO), low-pH waters makes it vulnerable to these parameters. Multiple stressors from ocean acidification and hypoxia (OAH), as well as warming, can trigger dramatic responses in coastal ecosystems. Characterizing ecosystem vulnerability to multiple stressors, and the societal impacts of that vulnerability, is a critical line of investigation for coastal managers. However, scientific consensus is lacking on the thresholds for acidification and oxygen stress (i.e., assessment endpoints) that can result in the decline of marine ecosystems. Assessment endpoints are urgently needed to provide consistent interpretation of monitoring data and model output that help evaluate the effects of SCB anthropogenic nutrient loads on OAH. They are an important precursor to regional assessments of vulnerability and, in the future, biologically-relevant OAH water quality criteria. SCCWRP and its partners will prioritize three principal, complementary lines of research supporting OAH-relevant endpoints, focusing on SCB organisms: 1) meta-analysis and synthesis of the magnitude and duration of acidification, hypoxia, and temperature that result in variable impacts to CCS species along a gradient of biological condition, 2) experiments to investigate interactive effects of these combined stressors on selected CCS organisms, and 3) field studies of the effects of these combined stressors condition and distribution of CCS organisms.

***Future Focus Area*: Benthic Habitat Quality Thresholds for Eutrophication Assessment**

Sediment organic matter (SOM) enrichment, occurring from legacy disposal, sewage spills, or other eutrophication processes, is a major stressor in California estuaries. Benthic habitats highly enriched with SOM typically have poor benthic habitat quality, with a cascade of effects on biogeochemical cycling, DO, and estuarine food webs. Assessment of the biological impacts of SOM enrichment in enclosed bays and estuaries require benthic habitat quality assessment endpoints to complete the toolkit supporting the State Water Board's biostimulatory policy. California has existing sediment quality assessment (SQA) tools comprised of interpretive indices of benthic macroinvertebrates, sediment chemistry, and toxicity, but these tools are optimized for toxic contaminants, not SOM enrichment. Furthermore, the existing SQA tools do not work well in estuaries with lower salinity regimes (< 17 ppt) and use of marine enclosed bays to establish reference expectations for benthic invertebrates in hyposaline estuaries may be setting unreasonable expectations. SCCWRP seeks to prioritize research that: 1) refines benthic macroinvertebrate reference expectations for bar-built, hyposaline estuaries, and 2) creates causal assessment tools and supporting thresholds that identify impacts from SOM enrichment. This work can proceed through the analysis of an abundance of existing data, plus targeted studies or enhancements of existing SQA methods to incorporate traditional or molecular-based analytes that are causal to SOM enrichment.

***Future Focus Area*: Cyanotoxin Aquatic Toxicity Thresholds**

Cyanotoxins can severely impact beneficial water uses, and for this reason the State Water Board staff is considering how to incorporate cyanotoxins into biostimulatory objectives and routine ambient water quality monitoring programs. EPA released health advisory thresholds for cyanotoxins in drinking water and has recently proposed criteria for recreational waterbodies (EPA 2015), but currently no guidelines exist for cyanotoxins levels protective to aquatic life. This is in part due to the limited ecotoxicological data available for aquatic species, especially in freshwater ecosystems. While the hepatotoxic microcystins are well studied, other cyanotoxins with different mechanisms of toxicity are not routinely measured or assessed for toxicity. SCCWRP research seeks to: 1) identify responsive and relevant toxicity endpoints for a range of aquatic organisms to cyanotoxins, 2) determine acute and sub-chronic thresholds of effects of cyanotoxins, and investigate how these thresholds change in exposures to different mixtures of cyanotoxins, 3) characterize the linkage between changes in organismal gene expression via meaningful adverse outcomes, and 4) convene a panel of scientists and managers to develop scientific consensus on relevant toxicity endpoints and key data gaps for cyanotoxin assessment, and protection of aquatic life in freshwater ecosystems.

Modeling

Characterization of Environmental Drivers

The environmental drivers are the external and internal factors that influence the development and persistence of eutrophication symptoms within a waterbody. The important drivers will vary by landscape setting, waterbody type and its hydrogeomorphology, as well as the major habitats it comprises. The hydrodynamic (e.g., surface and groundwater, tidal exchange, ocean currents) and material exchanges (e.g., nutrients, sediments, organic carbon) of the waterbody with other connected aquatic habitats, basin bathymetry or channel dimensions, light availability, temperature, and the biomass and composition of the dominant primary producer communities are among the most important drivers, common to all waterbody types. Documentation of external and internal inputs and exchanges, synoptically with the magnitude, extent and duration of indicators of eutrophication, constitutes the primary dataset used to develop models. Environmental drivers such as nutrient loads can be quantified by pathway (e.g., river, groundwater, oceanic exchange), but source attribution (natural, point source, non-point source (agricultural, urban, open, etc.)) is typically required in order to thoroughly understand and evaluate management options. Research on environmental drivers is key to ongoing refinement of conceptual models driving adaptive management decisions in all aquatic habitats across the watershed to ocean continuum.

Accomplishments

At a regional scale, understanding the role of nutrient loading in driving eutrophication across Bight estuarine and marine habitats was informed by SCCWRP research to develop GIS models of mass wet weather nutrient loads from SCB watershed, coupled with a synthesis of decade-long wet and dry weather MS4 and POTW mass loading monitoring data (Sengupta et al. 2013). Howard et al. (2014) utilized this work to document that POTW nutrient loads via ocean outfalls represented greater than 95% of anthropogenic nutrient discharge to the ocean, in quantities that equal the amount of available nitrogen reaching the nearshore from natural upwelling.

Further investigations of nutrient sources, utilizing stable isotopes as source tracking tools, have expanded the understanding of contributions from wet versus dry weather atmospheric nutrient deposition to watersheds (McLaughlin et al. 2014) and coastal waters (Howard et al. 2014). Stable isotopes have also been used to detect non-point source inputs of irrigated agricultural runoff in Santa Margarita River estuary (McLaughlin et al. 2013), which led to the use of groundwater modeling to further quantify this source in the estuary (Sutula et al. 2016a), and direct management action to reduce this source.

Within river mouth estuaries and coastal lagoons, SCCWRP studies of and wet weather deposition of organic matter and its influence on dry weather benthic nutrient flux were instrumental to inform nutrient allocations and sediment management options to mitigate eutrophication symptoms in Malibu Lagoon (Sutula et al. 2004), Upper Newport Bay (Sutula et al. 2006), and five San Diego estuaries (McLaughlin et al. 2010, 2011 a,b,c, 2013).

Blooms of harmful and toxic algae (i.e., harmful algal blooms (HABs)) have increased in frequency over the last several decades. California has several toxin-producing HAB organisms present, however, *Pseudo-nitzschia*, a diatom that produces the neurotoxin domoic acid (DA), is now considered to be the leading HAB threat and problem for human and ecosystem health. DA causes devastating effects to human and aquatic life via bioaccumulation in the food web, and is part of the California statewide biotoxin monitoring program. The record-breaking concentrations of DA and the U.S. west coast wide bloom of *Pseudo-nitzschia* (from Alaska to Santa Barbara, CA) in 2015 caused unprecedented widespread closures of commercial and recreational shellfish and finfish fisheries as well as the stranding of numerous marine mammals along the U.S. West Coast. SCCWRP and partners have been actively investigating the environmental drivers leading to bloom initiation and persistence, and the ecophysiological conditions that induce toxin production (Seegers et al. 2015, Seubert et al. 2013), culminating in the development of preliminary HAB prediction models (Anderson et al. 2011). Similar questions have been posed for chronic blooms of cyanobacteria in the Sacramento-San Juaquin Delta, a subject of recent review aimed at informing a long-term research and monitoring program (Berg and Sutula 2015). Their demonstrative impacts, and the lack of knowledge regarding their environmental drivers to minimize and control these impacts, highlights the need for a long-term research agenda of freshwater and marine HABs.

Ongoing Research

***Focus Area*: Environmental Drivers of Eutrophication in Wadeable Streams**
SCCWRP has been working to expand our understanding of environmental drivers of eutrophication in wadeable streams. Research to support discussion of nutrient numeric targets in the Santa Margarita River watershed has focused on capturing changes in the major environmental gradients (e.g., geology, surface and groundwater hydrology, nutrient concentrations), which influence eutrophication symptoms in the main stem.

Priorities for Future Research

***Future Focus Area*: Environmental Drivers of HAB toxicity in Aquatic Habitats Across the Watershed to Ocean Continuum**
In order to manage and mitigate increasing toxic marine and freshwater HABs, managers need tools to allow rapid response to blooms and to understand potential management controls. Methods are needed to better identify and understand the potential for toxin production by cyanobacterial populations and, at the same time, provide an early warning system for cyanobacterial blooms and toxin production. Models are once such tool, but still in their infancy due to the minimal understanding of physical, chemical and biological factors influencing community composition and

toxin production. Increased understanding will require data sources and measurements that extend beyond typical monitoring programs. SCCWRP will continue its collaboration with partners to conduct research identifying these fundamental drivers, refining conceptual models and developing a more comprehensive set of marine and freshwater HAB prediction tools. Key drivers, which are also linked to climate change, include nutrient loads and dominant nutrient form, temperature, hydrology and PCO_2 concentrations.

Process Studies

Process studies quantify key rates of the fate and transformation of nutrients and carbon within the waterbody as they influence pathways of biological impact. These rates are important because they either accelerate or slow the expression of eutrophication symptoms, and are inherently influenced by the same time-variable and space-variable environmental drivers. Which processes – and how they are quantified – depends on the waterbody type and other site specific factors, well as the modeling endpoints of interest (DO, pH or aragonite saturation state, algal biomass, sediment organic matter accumulation, etc.) Process studies are typically conducted synoptically with characterization of environmental drivers, in order to provide a robust dataset for model development and calibration. When process study data are not available, modelers often rely on rates documented in the literature to parameterize the model, which can be problematic if those rates are not representative of the dominant ecological processes in the waterbody being modeled. Model sensitivity analyses can help prioritize which process rates are most important to quantify, because of their relative influence on desired modeling outcomes.

Accomplishments

SCCWRP and its partners have been developing and implementing new technologies to measure process rates that result in the transformations and fluxes of nutrients and organic matter from sub-environments in oceans and estuaries. This work began in estuaries, where SCCWRP documented that benthic fluxes were a significant source of inorganic nutrients to the water column in lagoonal estuaries, fueling observed large macroalgal blooms (Sutula et al. 2004, 2006; McLaughlin et al. 2010, 2011a, 2011b, 2011c, 2013), and limiting the potential for denitrification, a major natural pathway to transform bioavailable nitrogen to nitrogen gas.

The Orange County Sanitation District's outfall diversion provided a unique opportunity to investigate the processes and rates of anthropogenic nutrients on a nearshore coastal ecosystem. The diversion of wastewater effluent from a primary, offshore outfall to a secondary, nearshore outfall created a large scale, *in situ* experiment which allowed SCCWRP and its partners to track the fate of the wastewater plume as it was "turned off" in one area and "turned on" in another. The findings demonstrated that point source discharges from ocean outfalls impact biogeochemical processes, phytoplankton and bacterial community composition, phytoplankton physiology, and nitrogen cycling (Caron et al. 2017, Howard et al. in review, Kudela et al. 2017, McLaughlin et al. 2017). Wastewater ammonium was rapidly converted to nitrate in close proximity to the outfall (McLaughlin et al. 2017), stimulating a large growth in heterotrophic bacteria (Caron et al. 2017), demonstrating the importance of this usually overlooked fraction of the planktonic community (Howard et al. in review). Furthermore, the effort to mitigate fecal indicator bacteria and other pathogens by employment of enhanced chlorination and de-chlorination of the discharge was successful (Rogowski et al. 2014), but had the unintended result of inhibiting phytoplankton biomass and productivity, perhaps preventing a HAB event (Kudela et al. 2017).

Ongoing Research

***Focus Area*: Process Studies Document the Impact of Wastewater Effluent on Nearshore Productivity and Metabolism**

An integrated modeling effort is required to estimate the relative effect of anthropogenic versus natural sources of nutrients on rates of primary production and its linkage to acidification and hypoxia (see below). For managers to have confidence that these models are accurately capturing nutrient cycling, they must have accurate data against which the model output can be validated. SCCWRP and partners are investigating critical carbon and nitrogen transformation rates which will serve as validation data. SCCWRP scientists are comparing the sources and fate of nitrogen in an effluent impacted region to minimally-impacted regions, both in the near and offshore zones, by measuring key rates of nitrogen and carbon cycling including primary production and respiration, nitrogen uptake by primary producers and nitrification (i.e., the biological transformation of ammonia, the dominant nitrogen form in effluent, to nitrate). SCCWRP is using stable isotope tracer techniques to determine the relative influence of effluent versus upwelled nitrogen on biological communities and nutrient standing stocks.

Priorities for Future Research

***Future Focus Area*: Ecosystem Feedback on Biogeochemical Cycles Linked to OAH**

SCCWRP is investigating direct effects of anthropogenic nutrients on lower trophic levels within the SCB nearshore. Less is understood about the impacts to prokaryotes (microbial loop), primary producer and consumer community composition, and the interactive feedbacks that they have on carbon metabolism (DO) and the carbonate cycle (i.e., pH and carbonate saturation state). SCCWRP intends to prioritize this research, given its importance in understanding the interactive effects of eutrophication and global climate change on SCB ecosystem health. Calcifiers, such as pteropods, are expected to experience major declines with increasing OA and are a key functional group to incorporate into marine biogeochemical models given their broad distribution and abundance. Future research will focus on pteropods as an indicator of calcifier feedback in biogeochemical cycles under present day abundances, as well as in the future under climate change stresses.

Model Development

Predictive mathematical models can provide insight into the potential ramifications of the interaction of anthropogenic and natural drivers on aquatic habitats across the watershed to ocean continuum. Modeling tools allow scientists to forecast what future conditions will look like, to interpolate limited data sets in order to build a comprehensive picture of condition, evaluate likely success of potential management actions and prioritize data gaps.

SCCWRP research on model development focuses on two major areas: (1) development of new algorithms or modeling approaches that capture the major relationships between environmental drivers, rates of transformations, and eutrophication response, and (2) use of existing or new modeling approaches applied to novel habitats or key management questions. Models can consist of empirical, statistical models or causal, mechanistic numerical watershed loading or receiving water models. Data are required for model setup, calibration and validation. Model calibration and validation help to provide quantitative estimates of uncertainty in modeling outcomes, an important factor to consider in environmental decision-making.

Accomplishments

SCCWRP and its partners have long invested the development and application of models to foster discussions on management targets and implementation options (Ackerman and Schiff 2003, Ackerman et al., 2005, Ackerman and Stein 2008). Stakeholder understanding of the strengths, limitations and utility of models is a key advantage in crafting a long-term research strategy aimed at incremental refinements to models that support water quality and natural resources management in the SCB coastal watersheds and nearshore.

SCCWRP eutrophication research has built off these investments. McLaughlin et al. (2013) documented via statistical modeling that tidal exchange and sediment organic matter explained over 50% of the variation in macroalgal biomass across 23 Bight estuaries. Following this work, San Diego Lagoon nutrient TMDLs have provided an in-depth opportunity to synthesize the understanding of environmental drivers and key rate processes via modeling of eutrophication in Loma Alta Slough (Wang et al. 2013) and Santa Margarita River Estuary (Wang et al. 2016). In particular, modelers utilized SCCWRP macroalgal science (Kamer et al. 2004, Sutula 2011) to make needed improvements to model code needed to improve predictions of macroalgal growth and fate within the estuary.

SCCWRP ocean modeling to support nutrient management began with a partnership to investigate the relative contribution of upwelling (natural) vs. anthropogenic nutrient inputs to the SCB. Howard et al. (2014) noted that, in some nearshore locations, natural and anthropogenic sources were of similar magnitude. Given this finding, the effect of anthropogenic nutrient inputs on HABs and OAH should be further investigated. Additional support for large-scale investments in models grew through SCCWRP leadership in workshops to define management questions and modeling strategies (Sutula et al. 2013b, Boehm et al. 2015, Boehm et al. 2016). Furthermore, the West Coast OAH Expert Panel recommended that West Coast managers and the scientific community move forward with OAH modeling work using five main strategies (Boehm et al. 2016): (1) invest in a suite of coupled ocean-margin physical and biogeochemical models, (2) improve ecosystem models,(3) validate existing models using observational data, with a focus on quantifying uncertainties and identifying key gaps with data and modeling infrastructure, (4) collect data to support model development and refinement, and (5) establish a forum to advance coastal ocean modeling

Ongoing Research

***Focus Area*: Statistical and Numerical Modeling to Support Nutrient Numeric Targets in Wadeable Streams**

The BCG model will support decisions on assessment endpoints for bioassessment scoring tools—the CSCI and ASCI—as the basis for crafting a combined statewide biointegrity and biostimulatory (i.e., nutrient) policy governing the health of California wadeable streams. This effort will produce bins of CSCI and ASCI scores spanning the BCG. Statistical models of the relationship between the bioassessment indices to nutrient and organic matter concentrations are needed in order to translate BCG bin thresholds to these stressors, thus producing the basis for statewide "default" numeric guidance on assessment endpoints and nutrient numeric targets. While these statistical models are to be considered "default" thresholds for statewide policy, they can also be the starting point for more focused discussions of applicable endpoints for site-specific waterbody numeric targets. This is the case for the Santa Margarita River demonstration project illustrating this "watershed approach." The outcome of these statistical models will be compared with the output of linked numerical surface and groundwater loading and receiving water models, developed to investigate organic matter levels that support DO and pH basin plan objectives.

***Focus Area*: Development of a Coupled Physical-Biogeochemical Model for the CCS**

Over the past 15 years, there has been a well-documented rise in ocean acidification and hypoxia (OAH) in the CCS. Given these concerning trends, U.S. West Coast marine resource, air and water quality managers who are concerned with these trends need to know what are the marine habitats that are the most susceptible to OAH, how will this susceptibility change over time and to what extent do land-based sources of pollutants exacerbate the problem. SCCWRP is part of a multi-institutional partnership that is: 1) developing and validating an OAH model of CCS (Baja California to British Columbia), comprising the circulation, biogeochemical cycles, and lower-trophic ecosystem of the CCS, with downscaled models covering the SCB, 2) using the model to understand the relative contributions of natural climate variability, anthropogenically induced climate change, and anthropogenic inputs on the status and trends of OAH in the CCS, and 3) transmitting these findings to coastal zone managers to help explore implications for marine resource management and pollution control.

Directions for Future Research

***Future Focus Area*: Ecosystem modeling and Ecosystem Feedbacks on OAH**

Although SCCWRP science is focused on disaggregating the interactive effects of natural variability, climate change and anthropogenic inputs on OAH, there is a pressing need to understand how OAH affects ocean food webs, plus related ecosystem services and beneficial uses. There is an increasing recognition of the potential impact that declines in calcifiers have on biogeochemical cycling linked to OAH. Although West Coast ecosystem models are being developed to evaluate OAH impacts on commercial fisheries, these models do not include biogeochemical algorithms for OAH, and data are not available to fully parameterize the relevant prey-predator interactions. SCCWRP future research on ecosystem modeling of OAH impacts will focus on linking these higher-trophic levels.

***Future Focus Area*: OAH Modeling for Very Nearshore and Estuaries**

OAH model development has focused on large oceanic scales, leaving important knowledge gaps in scientists' ability to predict OAH dynamics in near-coastal waters, estuaries and bays that are the primary location of potential management action. Extension of mechanistic modeling for very nearshore and estuaries, particularly to seagrass dominated estuaries, is important to support conversations about the utility of pollution management in mitigating OAH and the role of seagrass and kelp beds to ameliorate these stressors.

***Future Focus Area*: Extend Biogeochemical Models to Predict Harmful Algal Blooms**
The connection between HABs and coastal processes, nutrient enrichment, OAH and climate forcing at the land-sea interface are critical lines of investigation, yet the relative importance of these drivers has not been systematically evaluated. Disentangling the interaction of these different ecosystem stresses requires an integrated systems modeling approach, carefully validated against available datasets. A call for predictive capabilities for integrated environmental assessments, early warning systems, action plans and mitigation strategies was articulated at the West Coast Governors Alliance Harmful Algal Bloom Summit, and is a major component of the strategic vision for a national Ecological Forecasting Roadmap presented by NOAA. SCCWRP seeks to prioritize expansion of the oceanic biogeochemical OAH model described above to include a predictive HAB component for investigating the degree to which nutrient forms, ratios, temperature, advective processes (horizontal or vertical) and seawater pCO_2 influence the development, frequency and intensity of toxic HABs events.

Implementation Assistance

Ambient Assessment

Accomplishments

SCCWRP and partner investments in early implementation of regional ambient assessment of wadeable streams have resulted in an emerging picture of the importance of eutrophication as a driver for degraded biological condition, particularly in southern California (Mazor and Schiff 2008, Fetscher et al. 2013). In SCB estuaries, McLaughlin et al. (2013) found that eutrophication conditions were pervasive; 96% of segments assessed required future management attention. Regional assessments documenting the prevalence of cyanotoxins in wadeable streams statewide (Fetscher et al. 2015) and lentic waterbodies (depressional wetlands, lakes, reservoirs, estuaries and lagoons) in SCB coastal watersheds (Magrann et al. 2015, Howard et al. in prep) have pointed to the need for increased research on eutrophication drivers and watershed-specific management action.

Ongoing Research

***Focus Area*: Historical Data Analyses**
Use of historical data such as CalCOFI, remote sensing and Central Bight working group regional monitoring data have resulted in important assessments of the status and trends of algal blooms (Nezlin et al. 2012, Nezlin et al. in prep), dissolved oxygen (Booth et al. 2014) and pH and aragonite saturation state (McLaughlin et al.

in prep) over approximately a 20-year period. SCCWRP continues to mine historical data in order to provide improved context for current status and trends, and to provide a rich baseline to better understand the impacts of climate change and local anthropogenic activities.

***Focus Area*: Risk of Cyanotoxins across the Land-sea Interface**
The conventional focus of HAB monitoring has been on toxin detection, according to the waterbody sampled, either as marine toxins or freshwater toxins, but not both. Cyanobacterial toxins have previously been considered a public health issue only for freshwater, with concerns about impacts to drinking and recreational waters and ecosystem impacts. However, recent studies focused in California coastal waters have shown these toxins can have effects far downstream, creating issues in brackish and marine habitats. The goal of this focus area is to understand the importance of the land-sea transfer of cyanoHAB toxins, especially in estuaries. The results of this research will help water-quality managers, who have traditionally considered management of freshwater HABs to be distinct from that of marine HABs, rethink historical HAB management paradigms. SCCWRP and partners will develop best-practice strategies for monitoring and managing HABs at the land-sea interface, including identifying the predominance of toxic marine algae and cyanobacteria and their toxins in estuarine and marine environments throughout California, as well as developing monitoring tools for both marine and freshwater toxins.

Assessment Frameworks

The outputs of condition assessment science are key graphics that provide a quantitative synthesis of the decline in biological condition with increasing eutrophication stress, as measured by the primary causal factors (e.g. nutrients) or an intermediate measure of eutrophication response (e.g. DO, organic matter accumulation). Often, additional steps are needed to transition this science into decisions on water quality goals or actionable thresholds to support resource management. SCCWRP works with partners to support the transition by developing assessment frameworks, a term which embodies waterbody condition assessment and the guidance needed to interpret tools, integrate various condition indicators and scoring data, rank sites along a conceptual condition gradient, apply the results of modeling, and have assurances regarding reliability and confidence estimates. Thus, assessment frameworks must be developed to contextualize and inform issues such as setting water quality goals, restoration targets, performance or compliance targets, evaluating progress toward achieving those targets, and calibrating and validating biological response models aimed at informing management action.

Accomplishments

Estuarine eutrophication assessment frameworks are important output of scientific synthesis to support State and Regional Water Board decisions on biostimulatory (nutrient) objectives. SCCWRP and its partners completed an effort to develop a phytoplankton framework for San Francisco Bay, using phytoplankton biomass (as surface water chlorophyll-a), harmful algal bloom abundance and toxin concentrations and dissolved oxygen as key indicators of condition (Sutula and Senn 2017). This framework is considered to be provisional as scientists pilot the framework and seek to address major uncertainties and data gaps identified through the process.

While San Francisco Bay represents ~75% of the California's habitat by area, shallow coastal lagoons and river mouth estuaries, where macroalgae can proliferate under eutrophication conditions, represent 85% of the state's nearly 400 estuaries. Most of these estuaries are intermittently tidal, making them more susceptible to macroalgal blooms. SCCWRP science on the adverse effects of macroalgal blooms on estuarine habitat, coupled with a revised protocol for monitoring (currently undergoing SWAMP review), is the foundation for a macroalgal assessment framework. Similar to the BCG model and the San Francisco Bay phytoplankton assessment framework, the intent for this framework is to use macroalgal biomass to categorize estuarine intertidal, shallow subtidal and seagrass habitats in bins of ecological conditions. A draft version of the framework (Sutula et al. in review) has being vetted for use in TMDLs (Sutula et al. 2016a), restoration planning (Sutula et al. 2016b), as well as by SWAMP.

Ongoing Research and Priorities for Future Research

SCCWRP is currently, or in the near-term, conducting synthesis supporting decisions on assessment endpoints and nutrient numeric targets for wadeable streams, lakes, estuaries and oceans. SCCWRP anticipates and prioritizes research to support the transition of this information into policy applications, with assessment frameworks as one likely product that can facilitate this transfer. Key to this work is understanding how to utilize multiple lines of evidence, important for robust assessments, in a coherent decision framework. Ambient assessments, particularly through the Bight Regional Monitoring Program, are an important opportunity to pilot these emerging decision frameworks.

Using Case Studies to Demonstrate Management Application

To demonstrate that condition assessment and modeling tools can be effectively implemented in the regulatory and management sectors, case studies are needed. Case studies provide an opportunity to test-drive the conceptual models, conduct model scenario analyses to support conversations about the cost-benefits and related uncertainties of management options, conduct training, build partner capacity and identify barriers to implementation.

Accomplishments

SCCWRP and partners work to improve the use of science in management of intermittently tidal bar-built estuaries, an estuary that is periodically cut off from the open ocean through the natural build-up of sand berms. These estuaries are particularly vulnerable to the impacts of land-based pollution and global climate change due to increased frequency of inlet closures, often resulting in a precipitous decline in water quality (Cloern et al. 2016). SCCWRP research to acquire data, identify environmental drivers and management levers, and develop coupled watershed-receiving water models of eutrophication, have had an early impact on estuarine restoration and nutrient management discussions in a number of southern California estuaries. Modeling scenario analyses have been used to support nutrient load allocations and discussions of implementation options for Malibu Lagoon, Upper Newport Bay, Santa Margarita River Estuary and Loma Alta Slough. SCCWRP threshold science and synthesis of environmental drivers has supported discussions of restoration options in Malibu Lagoon, Upper Newport Bay, Buena Vista Lagoon and Famosa Slough. These discussions provided an example of how to transition science, and how to break down the silos between "habitat restoration" and "water quality" communities, particularly by using water quality models to quantify benefits from restoration scenarios under consideration.

Ongoing Research and Priorities for Future Research

***Focus Area*: Watershed Demonstration of Concepts Supporting a Combined Biostimulatory/Biointegrity Policy**
With the Water Board staff intention to allow for a "watershed" management approach that considers alternatives to pending "default" numeric nutrient targets, there is a pressing need to demonstrate what key components of this approach could entail, including, but not limited to: (1) model monitoring components to support a watershed approach, (2) appropriate use of statistical or numeric models for target setting, (3) appropriate paradigms for setting expectations for channels in developed landscapes, (4) assuring protection of downstream beneficial uses, (5) application of the watershed approach to address numeric limits for wet weather, (6) streamlining monitoring permit requirements, (7) environmental offsets and trading schemes to facilitate achieving numeric limits, and (8) linking environmental outcomes with socio-economic impacts. The Santa Margarita River Watershed Nutrient Management Initiative, already in progress, and Big Bear Lake Watershed demonstration project are two such demonstration projects that will inform the current policy development and provide important case studies. SCCWRP seeks to prioritize additional partnerships to develop additional biointegrity/biostimulatory watershed case studies, particularly those in agriculture-dominated landscapes or with point source discharges.

***Focus Area*: Application of a Network of Estuarine-Ocean System Models**
Numerical models have great utility for the analysis of future environmental scenarios (e.g., climate change) or evaluation of management options (e.g., BMPs, restoration actions). SCCWRP aids partners in applying models for environmental decision-making, supporting both model runs as well as the expert interpretation of model output to support environmental decisions. SCCWRP has two types of priorities for near-term future research. First, in the near-term, SCCWRP seeks to develop a user interface that will allow SCCWRP partners to explore and utilize the rich -dimensional model output from existing biogeochemical (ROMS) model. This interface will be an important tool for water quality agencies to understand the impact of outfall effluents on receiving waters, while natural resource managers can do more in-depth analyses of current and future conditions vis-à-vis MPAs, reserves and commercial and recreational fisheries. Second, SCCWRP seeks to extend ocean models into the very nearshore and connect them with a network of open-source, integrated models of SCB estuaries and enclosed bays. In the near-term, SCCWRP intends to focus on seagrass dominated habitats, which are at risk from sea level rise, increasing temperatures and land-based sources of pollution, but offer an opportunity to remediate rising OA levels. Over the long-term, management applications of these earth-system models include: outfall management, impact assessment of desalinization, mitigation strategy development, and fisheries management, pollution impact assessment (e.g., debris), climate change adaptation and mitigation strategies.

Focus Area: Mitigation strategies for CyanoHABs
In California, toxic HABs caused by cyanobacteria (CyanoHABs) have been a recurring and escalating issue throughout the state that have underscored the pervasiveness of HABs. These increases can be attributed to various anthropogenic and climatic factors, the most significant include climate change (increased temperatures), nutrient loading, water residence time and the drought. Through SCCWRP's participation and leadership role in the California Cyanobacteria Harmful Algal Bloom network (CCHABs), the development and maintenance of a comprehensive, coordinated program to identify and address the causes and impacts of cyanobacteria and HABs in California has begun. The next step is to determine the appropriate management and mitigation strategies, both within watersheds and in waterbody treatments, in order to mitigate the impacts from HABs. Water quality and waterbody managers will come together at a HABs management and mitigation workshop facilitated by SCCWRP to discuss HABs management and mitigation strategies, to minimize health risks and preserve beneficial uses. SCCWRP seeks to prioritize projects that produce a toolkit of mitigation protocols, practical solutions, guidance and strategies for management of toxic HABs.

Optimizing Monitoring Programs

SCCWRP typically develops standard operating procedures (SOPs) to document monitoring and research activities. However, when transitioning these SOPs to routine monitoring and compliance applications, they often require additional optimization in order to maximize the cost-effectiveness while maintaining necessary quality of data to support environmental decision-making in the context of regulatory permit monitoring. Monitoring frequency, spatial extent, desired analytes and preferred technology are all subjects of such optimization, in view of condition assessment frameworks and modeling programs that they can support. Part of this optimization also includes updating data transfer formats, automating data management and quality assurance procedures, and providing data visualizations tools that help to communicate findings to decision-makers.

Accomplishments

In the ocean, SCCWRP research supported improvements of the Central Bight working group'sconductivity, temperature and depth (CTD) monitoring through intercalibration of chlorophyll-a, pH, and DO, improving the reliability of a 20-year record, and improving data quality moving forward (Howard et al. 2012, McLaughlin et al. in review a, Howard et al. in prep).

Ongoing Research and Priorities for Future Research

New technologies have recently been developed for accurate monitoring of seawater pH on moorings (ISFET pH sensors, McLaughlin et al. in review b) and SCCWRP is working with member agencies to deploy this technology within emerging programs with moored sensors, and it is expected that this technology will be adapted for profiling applications in the near future. SCCWRP will continue to support the transition of improved nutrient, pH sensor technology onto moorings, piers and ship-based monitoring programs, coupled to biological monitoring of OAH impacts. In the near-term, SCCWRP will work with the SCB Central Bight working group to expand routine nutrient monitoring beyond the current forms, using a comparable protocol to CalCOFI. Sampling regimes should be optimized by insights from: (1) near where the discharges occur (including trapping depths), and (2) where the preliminary ROMS modeling results may suggest there are impacts (differences between the model runs with and without anthropogenic inputs). In conjunction, some limited collection of water to characterize the phytoplankton in the sub-surface maximum layer, and as much as possible consistent with the pier-end sampling protocol, could be considered.

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