SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT AUTHORITY

THEMATIC RESEARCH PLAN

FOR

SEDIMENT QUALITY

Last revised May 2019

Table of Contents

Introduction

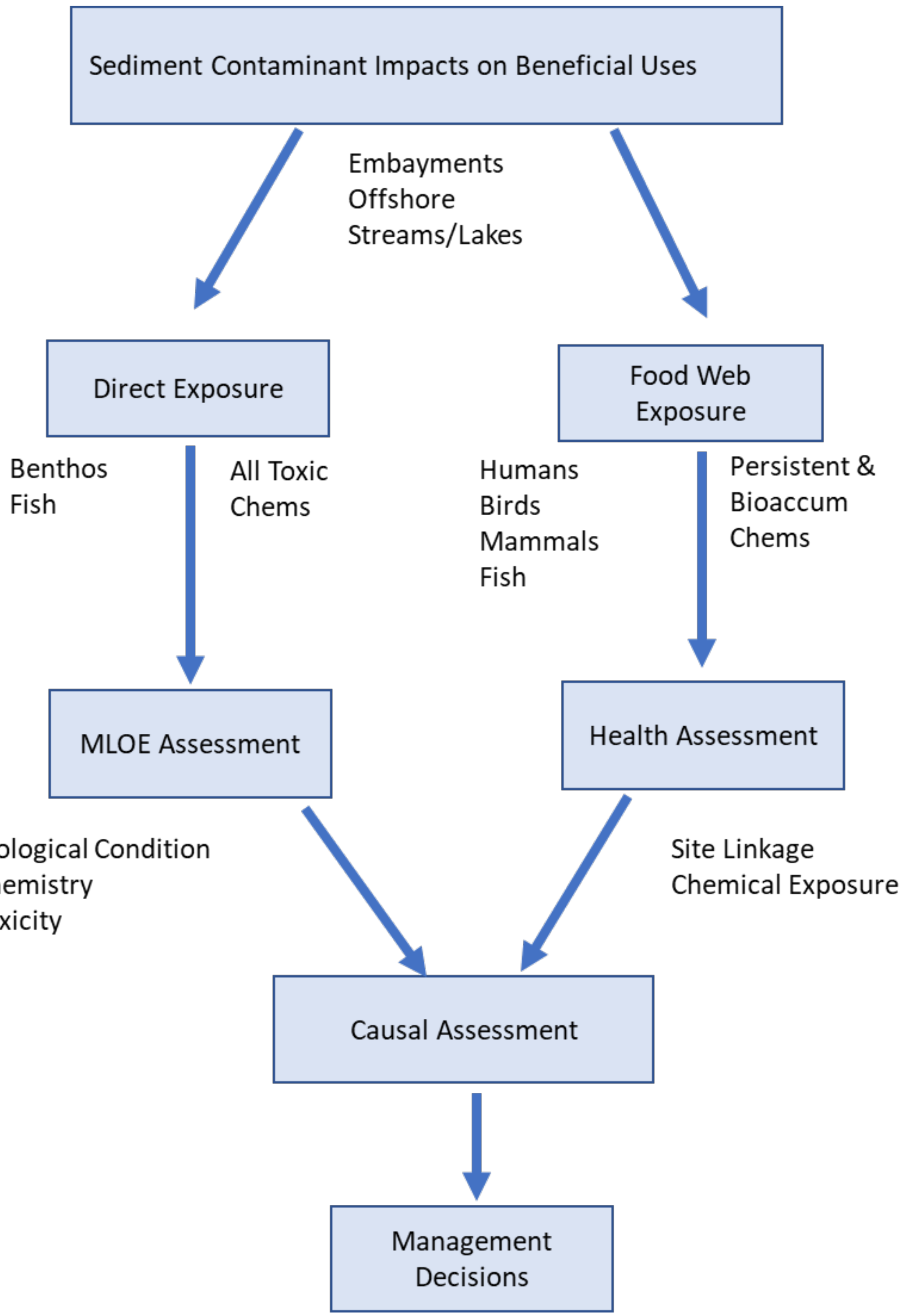
The quality of the water column is typically assessed using standard chemistry methods that quantify contaminant concentration and that are then related to potential biological effects via a wealth of historical toxicological information. The same, however, is not true of sediment contamination, where the chemical-toxicological relationship is confounded by differences in chemical binding capacity among a range of sediment types that affect the bioavailability of the chemicals. This presents challenges to managers tasked with maintaining sediment quality to support healthy ecosystems. Without an agreed-upon approach for assessing sediment quality, managers have taken disparate courses of action to resolve key challenges, such as defining how degraded a site must be to warrant regulatory action, identifying the contaminants of greatest concern, and setting appropriate clean-up levels. SCCWRP is focused on providing the necessary foundation to develop a common approach for assessing sediment quality and for assisting managers in translating sediment science into decisions.

Conceptual Model

Direct vs. indirect effects: SCCWRP's conceptual model for sediment quality research revolves around two major routes of exposure and effect: (1) direct exposure, where contaminants impact animals living in or on the sediment, and (2) indirect exposure, where the consumption of prey living in or on contaminated sediment triggers contaminant transfer through the food web (Figure 1). For both direct and indirect exposure routes, assessing sediment quality in enclosed bays and estuaries is a priority, as these are locations where sediment contamination and impacts are greatest. Sediment quality assessment tools are also needed for inland surface waters (streams/lakes) as well as for offshore habitats, as there are contaminant assessment and management needs for all areas. Some receptors, such as fish, may be impacted by a combination of direct and food web exposure, requiring the application of multiple assessment frameworks.

Building a complete picture of how sediment contamination directly and indirectly impacts ecosystem health is a key step toward improved management decision-making, including sediment-quality management, remediation planning and clean-up activities.

Figure 1. SCCWRP's conceptual model for sediment quality assessment revolves around studying both the direct and indirect (food web exposure) effects of sediment contamination. An assessment framework is developed for each that guides management decisions.



Direct Exposure

Multiple lines of evidence (MLOE): To accurately assess the impacts of sediment contamination from direct-exposure routes, multiple lines of evidence (MLOE) are required. MLOE are evaluated using the **sediment quality triad**, a three-pronged strategy consisting of sediment contaminant chemistry (chemical exposure), sediment toxicity, and impacts to benthic macrofauna communities or fish (biological assessment). Each line of evidence has limitations, and no single line of evidence can definitively measure impacts of sediment contamination; hence, multiple evidence lines are pursued to balance the strengths and limitations of each type of measurement:

- **Chemical exposure** requires tools that can quantify the multitude of potential sediment contaminants, and then relate their chemical concentrations to adverse biological effects. These chemical exposure tools, also called sediment-quality guidelines, attempt to simplify the many complexities by creating thresholds of impact based on predictions of biological responses at increasing contaminant concentrations. While some national sediment-quality guidelines have existed for many years, they include a dearth of extensive data collected from California chemical monitoring programs and have not necessarily been calibrated to the other two legs of the triad: sediment toxicity and benthic community response.
  Limitations: Chemistry alone cannot measure every possible contaminant, cannot account for potential effects from chemical interactions, and cannot determine the bioavailable portion of contaminant responsible for impacts.
- **Sediment toxicity** makes use of standardized lab tests with sediment-dwelling organisms to methodically and repeatedly measure biological responses to assess contaminated sediment. Toxicity testing is advantageous in that it can evaluate impacts from the combination of contaminants found in sediment, and in that the organisms will respond only to the bioavailable portion of these contaminants. Typically, sediment toxicity testing focuses on organism survival, growth or reproduction; methods vary for each habitat type (such as marine or fresh water).
  Limitations: Toxicity approaches rely on individual test species that may not represent all species found in nature. Additionally, samples are tested under controlled conditions that may not mimic the complexities of exposure found in nature. And traditional toxicology methods cannot identify the specific contaminant(s) responsible for the observed toxicity.
- **Biological assessment** entails measuring the abundance, diversity, and health of the resident organisms. For sediment quality assessments, these assessments are focused on benthic habitats where the invertebrates that live in the sediment are largely immobile and short-lived, making them particularly susceptible to sediment contamination. Benthic assessment tools attempt to reduce the many species and thousands of organisms that might live in a single square meter of sediment into an index value that indicates the health of the community. Because differing habitat types differ in their mix of resident species, which in turn differ in their responses to sediment contamination, benthic indices must be developed and calibrated for a series of specific habitats. While biological assessment of fish can employ indices based on abundance and diversity, it is sublethal measures such as histopathology, endocrine disruption, and gene expression that offer greater sensitivity and greater ability to associate effects with contaminant exposure.
  Limitations: Because this line of evidence is a direct measure of impacts to beneficial uses, biological assessments may not provide a sufficient margin of safety for environmental

protection. Biological methods alone may not be able to distinguish between the impact of contamination vs. natural stressors, including physical disturbances, drops in dissolved oxygen content, and food availability. Additionally, before assessment tools can be used effectively, they often need to be adapted to each habitat/region/species where they're being applied.

MLOE assessment frameworks: To integrate technical results from MLOE testing in a way that produces answers relevant to management questions, data interpretation frameworks are needed. In California, the MLOE assessment framework developed for direct effects integrates chemistry, toxicity and biological assessment of benthic macrofauna to produce a categorical assessment of impact in enclosed bays and estuaries (Figure 1). Expansion and refinements to MLOE assessment frameworks are needed to effectively integrate results from other habitat types (e.g., streams/lakes and offshore) and/or to apply them to fish.

Food Web Exposure

Bioaccumulation in organisms consumed by humans and wildlife that derives from sediment contamination is a common factor driving many ecological risk assessments. This indirect, food-web mode of exposure to sediment contamination requires a different conceptual approach for assessment than for direct exposure. Indirect effects are influenced by numerous factors, including the fraction of sediment contaminants biologically available to prey species, complexity of the food web, movement of receptor organisms, food consumption rates, and species-specific variations in chemical sensitivity. To conduct an accurate assessment of the impacts from indirect exposure to contaminated sediment, including for human health protection, two key indicators are needed: chemical exposure and site linkage. Calculation and use of these indicators present challenges related to uncertainty in model parameters and variability in chemical and biological characteristics.

- **Chemical exposure** uses thresholds and exposure models to predict contaminant exposure impacts on wildlife – particularly birds and mammals – and health risks to humans who consume seafood (fish and shellfish). The thresholds used by SCCWRP are based on models developed by the U.S. EPA and California's Office of Environmental Health Hazard Assessment (OEHHA). For humans, two types of health risks are considered: the number of additional occurrences of cancer and the likelihood of risk for other types of adverse health effects (hazard quotient). These risk estimates are based on exposure throughout the typical lifespan of an individual, and take into account modifying factors related to food preparation methods, toxic potency, consumption rate and body size.
  Challenges: Challenges to determining the potential health risk from chemical exposure include uncertainty in the cancer and noncancer reference values for various contaminants (particularly for different wildlife species), variation in human seafood consumption rates among different geographic or ethnic groups, and accounting for the additive effects of exposure to multiple contaminants. Another challenge is determining which thresholds represent an unacceptable level of risk; these thresholds, which are set by policymakers but based on science, typically consider some combination of the following factors: health risk, benefits from consuming seafood, background contamination, and economic factors.
- **Site linkage** describes the influence of sediment contamination within the assessment site on the bioaccumulation and movement of contaminants through the food web. Linkage is determined by

applying bioaccumulation models that use a combination of physical, chemical and physiological processes to predict the uptake and loss of contaminants through various steps of the food web (e.g., between sediment and benthic invertebrates, or between small fish and larger fish). The rates of uptake of contaminants dissolved in the water or ingested with food are combined with rates of contaminant loss from excretion, growth or metabolism to estimate the steady state concentration of contaminants in the tissue of seafood or wildlife prey. A comparison of the estimated concentration with that measured in resident organisms provides a measure of the site linkage.

Challenges: A major challenge to determining site linkage is accounting for variations in the composition of food webs associated with different types of seafood or prey species. The diets, movement patterns, and physiological characteristics of many food web components are poorly known, and estimates obtained from other studies may introduce significant amounts of error in the analysis. In addition, changes in movement patterns, diet or sediment concentrations over time are not accounted for in most models and may lead to inaccurate results. The models need to be validated by comparing predicted tissue concentrations to those obtained from other models or through field studies.

Health assessment framework: The assessment framework for food web exposure integrates the chemical exposure and site linkage indicators to produce a categorical outcome relevant to management questions regarding whether sediment contamination poses an unacceptable risk to human or wildlife health (Figure 1). Indirect exposure assessments differ from direct exposure analyses in that a single assessment is produced for a defined spatial region (site) encompassing multiple sampling stations, to reflect the movements of some elements of the food web. Refinement of the assessment framework is needed to determine specific thresholds for site classification and to provide guidance for selecting site boundaries and determining which tier of assessment is needed.

Causal Assessment

The data collected from sediment-quality assessments would not be of full value to water-quality managers without first determining the specific cause of sediment-quality impairment, a concept variously known as causal assessment, stressor identification, or toxicity identification. Causal assessment is critical to guiding effective management actions such as TMDL development. Traditionally, toxicity identification evaluation (TIE) has been used to determine the cause of sediment toxicity. The TIE process uses a variety of chemical/physical separation methods and treatments to remove or enhance one or more toxicant classes, coupled with toxicity testing following each manipulation. Different causal assessment methods are needed to determine the cause of impacts to benthic macrofauna or fish, as laboratory toxicity test methods may not be applicable. The development of molecular causal assessment methods, or molecular TIE, offers the potential to improve the sensitivity and specificity of traditional TIE methods by using patterns of gene expression in the test organism to indicate the type of toxicants causing biological impacts. Causal assessment for impacts related to food web exposure is less complicated, as the impacts are usually identified using chemical-specific bioaccumulation models and thresholds.

Management Decisions

Sediment condition reflects the cumulative effects of contaminant inputs over time and thus provides an integrated measure of habitat quality. This information is used in multiple ways, including in monitoring programs to assess spatial, regional and temporal patterns in the effects of sediment contamination. Sediment quality assessments also have applications in regulatory programs. The California State Water Board has established narrative Sediment Quality Objectives (SQOs) for the protection of aquatic life, human health and wildlife in enclosed bays and estuaries. SQOs, which have the same regulatory applications as other water-quality objectives, are used for identifying impaired water bodies (303(d) listing), developing TMDLs (Total Maximum Daily Loads), and determining discharge permit compliance. Sediment quality assessment frameworks provide a quantitative and consistent method for evaluating compliance with narrative SQOs in regulatory programs.

The categorical output of the sediment quality assessment frameworks developed to date presents a challenge for implementation in regulatory programs. TMDLs or site clean-ups typically use chemical concentrations to calculate load reductions or determine clean-up targets. To adapt these approaches for regulatory application, guidance for causal assessment and development of cleanup targets need to be developed.

Research Directions

Direct Exposure

A long-standing focal point of SCCWRP research and tool development relates to using multiple lines of evidence (MLOE) to assess the direct effects of sediment contamination. The strategies that SCCWRP has taken to create a standardized framework for sediment quality assessment include developing methods for assessing sediment toxicity and benthic community condition, and facilitating demonstrations of these tools in regional monitoring programs. The direct-effects framework and supporting analysis methods have been adopted by the State Water Board for use in implementing California's Sediment Quality Objectives for Enclosed Bays and Estuaries policy for benthic community protection, and are being implemented into compliance monitoring and TMDLs (Total Maximum Daily Loads) in various water bodies. With this progress, SCCWRP is now focused on expansion and refinements to the assessment framework and on case studies that facilitate the transfer of science to management uses.

Sediment Chemistry

Accomplishments

Previous research has resulted in the refinement and development of sediment quality guidelines (SQGs) and interpretation thresholds based on bulk sediment contaminant concentrations. The ability of existing SQGs to predict Southern California sediment toxicity based on both empirical and equilibrium partitioning approaches has been evaluated (Vidal and Bay 2005). The best-performing guidelines were further calibrated to regional sediment characteristics, and a new SQG approach based on benthic community response was developed for use in sediment quality triad assessments (Bay et al. 2012a, Ritter et al. 2012).

Ongoing Research

SCCWRP's priority is the development of more accurate chemical exposure tools based on measurement of the bioavailable fraction of sediment contamination. The use of passive sampling technology to measure contaminant concentration in sediment pore water is a key asset in this effort.

***Project*: Passive sampling methods to determine C_{free} in sediments**

This project is evaluating whether passive samplers can be used in coastal sediments to provide a more accurate measurement (i.e., the "freely dissolved" concentration, or C_{free}) of exposure to sediment-associated contaminants than do methods that analyze the bulk concentration. Sediment samples from contaminated sites in San Diego Bay and Los Angeles Harbor are being tested *ex situ* with passive sampling materials to estimate C_{free} for target hydrophobic organics (PCBs, PAHs) and compare the results to bioaccumulation and toxicity responses in benthic invertebrates.

Priorities for Future Research

Tools for assessing contaminant exposure need to be improved to address two types of limitations. First, the SQGs used in the existing assessment framework do not accurately measure bioavailable contaminant exposure. Second, sediment chemistry analytical methods and assessment tools do not include exposure to contaminants of emerging concern (CECs), especially current-use pesticides.

***Future focus area*: Bioavailable contaminant measurement**

Existing sediment chemistry monitoring methods are based on total concentration and provide an inaccurate measure of the actual chemical dose to the organism, which may be a small fraction of the total concentration. The accuracy of SQGs for predicting biological impacts can likely be greatly improved through the use of passive sampling technology to measure the dissolved contaminant concentration present in sediment pore water and account for interactions with particulates. Other approaches to measure contaminant exposure, such as tissue residue analysis, should also be explored. Additional research is needed to develop, calibrate and validate passive sampling methods for trace metals, legacy trace organics and current-use pesticides for use in routine monitoring programs. Future research also should include transfer of passive sampling technology to other laboratories, as well as development of collaborative projects to expedite method development and validation. Finally, future research also should include development of next-generation SQGs and interpretation guidance based on bioavailability to produce improved methods for monitoring and regulatory programs.

***Future focus area*: Assessment methods for contaminants of emerging concern**

The use of pesticides and other contaminants of emerging concern (CECs) that may accumulate in sediments in urban and agricultural settings is changing over time, yet these compounds have not been integrated into existing SQGs. Consequently, the predictive ability of SQGs to indicate chemical exposure is likely to decline as contaminant mixtures change over time. Research is needed to identify priority CECs, determine biological effect thresholds for fish and benthic macrofauna, and incorporate such information into chemical indices. One promising area is the use of bioanalytical tests based on cell receptor assays to rapidly and cost effectively screen for the presence of unidentified CECs in sediments having common modes of action.

Sediment Toxicity

Accomplishments

A suite of short-term test methods focused on survival or development of marine species has been selected and calibrated for use in sediment quality assessment. The test methods recommended for use include amphipod survival tests, a sediment-water interface test using mussel embryo development, and a polychaete growth test (Greenstein et al. 2008; Bay et al. 2007a). These methods have been applied in multiple regional monitoring surveys and other assessments to describe the magnitude and spatial extent of sediment toxicity in the Southern California Bight (Greenstein et al. 2013, Bay et al. 2015).

Ongoing Research

SCCWRP's ongoing research is focused on applying sediment toxicity methods to assess regional condition and on improving data quality and comparability. This work is being conducted through the Southern California Bight Regional Monitoring Program.

***Project*: Southern California Bight regional sediment toxicity assessment**
Multiple methods are being used in the Southern California Bight Regional Monitoring Program survey to assess the spatial extent and temporal changes in sediment toxicity. Regional surveys are conducted on an ongoing five-year cycle and involve multiple testing laboratories. Each survey includes a robust quality assurance component that aims to improve quality assurance and interlaboratory comparability of sediment toxicity tests. These surveys also provide a platform to test new toxicity measurement methods, such as *in situ* tests or molecular responses.

Priorities for Future Research

Additional sediment toxicity test methods need to be developed and refined to allow expansion of the MLOE assessment to additional estuarine and freshwater habitats. Sublethal toxicity tests that include long-term exposure and that measure reproduction and molecular responses are also needed to help assess impacts from low-level exposure to priority pollutants and CECs.

***Future focus area*: Sublethal and life-cycle sediment test method development**
Relatively few marine sediment toxicity tests methods that measure reproduction or molecular responses are available and feasible for monitoring use. These types of tests are needed to support new monitoring frameworks for CECs and to assess potential impacts from discharges related to desalination and recycled water projects, as well as climate change interactions. Promising life-cycle tests using amphipods, copepods and polychaetes need to be evaluated or refined. In addition, linkage studies need to be conducted to determine the relationship between molecular responses of invertebrates, such as gene expression, and ecologically relevant endpoints of survival, growth, and reproduction in the laboratory and field.

***Future focus area*: Sediment toxicity methods for freshwater habitats**
A variety of acute and sublethal test methods are available to evaluate sediment toxicity in freshwater habitats such as streams and lakes. Similar to previous research on marine toxicity tests, comparative studies are needed to select a suite of recommended standard methods and to develop data interpretation thresholds to permit full application of the California SQO benthic community assessment framework to additional habitats. This work could build upon the sediment toxicity monitoring programs that have already been established, including California's Stream Pollution Trends (SPoT) Monitoring Program.

Biological Assessment

Accomplishments

Research and collaboration with local benthic ecologists have produced a comprehensive understanding of the occurrence and distribution of benthic macrofauna assemblages in offshore and embayment sediments throughout California (Thompson et al. 1993, Ranasinghe et al. 2012). These efforts have resulted in the development and calibration of several types of indices and data interpretation tools to assess benthic community condition in bays and polyhaline estuaries (Ranasinghe et al. 2009, Teixeira et al. 2012). Some of these benthic indices have been incorporated into regional monitoring programs and the benthic community SQO assessment framework. Extensive surveys of Southern California demersal fish communities have also been conducted that included the development of a fish biointegrity index for the coastal shelf (Allen et al. 2001). Targeted studies have been conducted to evaluate fish contaminant exposure and molecular responses (Bay et al. 2012b).

Ongoing Research

In support of management application, work is ongoing to refine data analysis tools and update benthic indices with respect to taxonomy changes. DNA barcoding also is being developed and evaluated to improve taxonomic analysis of invertebrates.

***Project*: DNA barcoding of marine invertebrates**
Collaborative studies are assessing the efficacy of DNA barcoding for rapidly identifying marine benthic invertebrates and for determining whether these data can be used for assessing community condition. This project also involves developing DNA sample preservation methods that are compatible for routing monitoring programs.

Project: Extension of benthic indices to other habitats
Collaborative studies are underway to evaluate the performance and comparability of additional benthic index approaches for application in low-salinity and freshwater habitats. One such index being evaluated is the multivariate AZTI Marine Biotic Index (M-AMBI). Application of this index is less constrained by habitat variations, and work is underway to evaluate the feasibility and comparability of applying this index for SQO evaluations.

Priorities for Future Research

Future work will focus on the development of benthic indices for use in habitats with differing salinity regimes, such as the San Francisco Bay and Delta, freshwater lakes, and streams. Improved tools and indices to assess fish health are needed for the expected development of a sediment quality assessment framework focused on fish and wildlife impacts.

***Future focus area*: Benthic indices for freshwater and estuarine habitats**
Reliable benthic indices for assessing community condition have not been developed or calibrated for many estuarine habitats in California, especially mesohaline, oligohaline and tidal-fresh environments. This lack of indices hinders full application of the benthic community MLOE assessment framework for a majority of the areal extent of California's bays and estuaries. Research is needed to characterize stressor response gradients of benthic macrofauna in these habitats and develop or adapt benthic indices to describe these responses. Existing monitoring data are available to support these analyses. Bioassessment tools and indices for freshwater macrofauna and epibenthic algae have been developed for perennial streams in California, but these indices have not been integrated into the MLOE assessment framework used for SQO assessments. Research is needed to adapt these new tools for use in the MLOE framework in a manner that yields comparable outcomes to those for enclosed bays and estuaries.

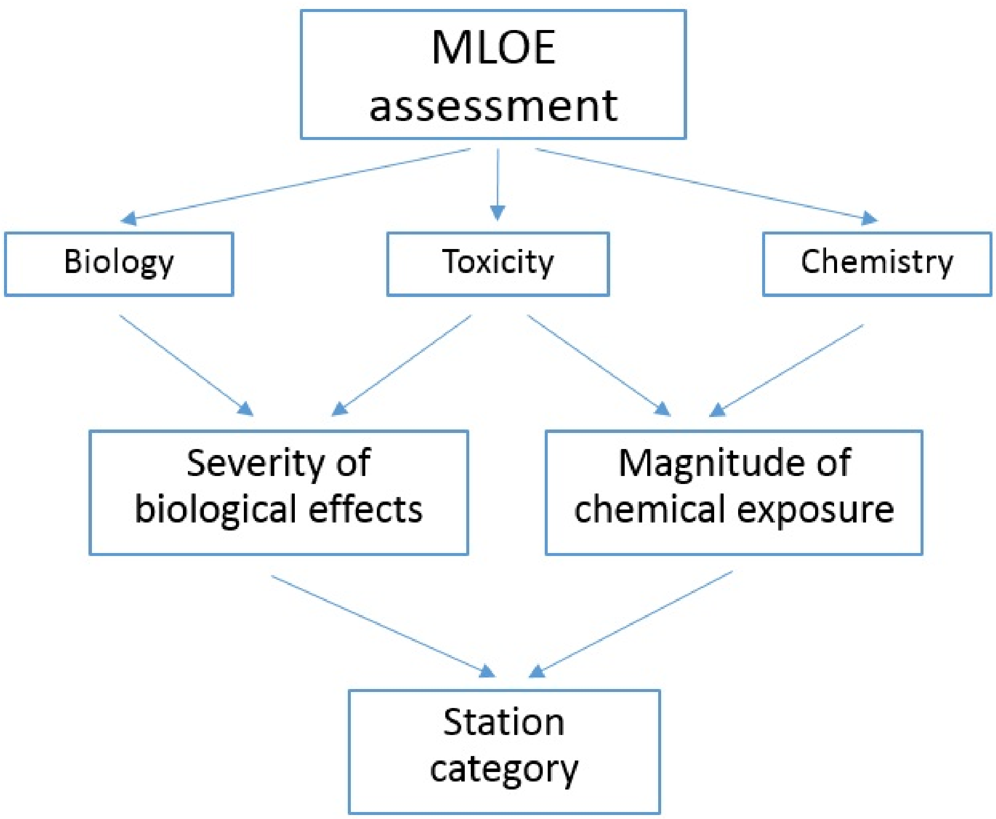
***Future focus area*: Indices of fish health**
Improved tools for assessing the health of fish populations and communities – analogous to those available for benthic macrofauna – are needed to support inclusion of fish into sediment quality assessment frameworks. The fish biointegrity index currently being used for monitoring programs has limited applicability for bays and estuaries and is likely not sensitive to the sublethal impacts of sediment contaminants. Improved community assessment tools need to be developed that can be applied to ocean monitoring programs to identify contamination-related impacts. Development might involve collaborative studies with monitoring agencies that involve analysis of existing monitoring data. Additional research also is needed to develop organism-level response indicators (e.g., gene expression, tissue pathology, hormones) for target fish species, and for data interpretation tools to assess contaminant-related adverse effects on individual fish. Research in this area is expected to overlap with similar efforts to develop fish testing and assessment methods needed to evaluate the impacts of CECs.

MLOE Assessment Framework

Accomplishments

An MLOE assessment framework for direct effects has been developed that integrates chemistry, toxicity, and biological assessment results (Bay and Weisberg 2012). The framework utilizes the results of sediment quality triad measurements to describe two key aspects of sediment quality: the severity of biological effect and magnitude of chemical exposure (Figure 2). The results of benthic community analyses and toxicity tests are interpreted using response thresholds and integrated to classify the severity of biological effects into categories ranging from Unaffected to High Effect. Toxicity data also are used as an indicator of chemical exposure because these tests respond to the joint effects of all chemical contaminants in the sample (both measured and unmeasured). Results from interpretation of sediment chemistry data are combined with the toxicity results to classify the magnitude of chemical exposure in terms of potential for adverse biological effects, ranging from Minimal to High. A final integration of the categorical results for biological effects and chemical exposure results in the classification of the station into one of five categories that indicates whether sediment quality is impacted by contamination and the relative severity of impact: Unimpacted, Likely Unimpacted, Possibly Impacted, Likely Impacted, and Clearly Impacted. This framework was validated by comparisons to expert opinion (Bay et al. 2007b) and is being used in monitoring and regulatory programs. The framework also has been applied to regional monitoring data to provide statewide assessments of sediment quality in enclosed bays and harbors (Barnett et al. 2007, Bay et al. 2013a, Schiff et al. 2015).

Figure 2. The multiple lines of evidence (MLOE) assessment integrates the results of biology, toxicity and chemistry measurements to interpret the severity of biological effects from sediment contamination and the magnitude of the chemical exposure. The interpretations are integrated to categorize the overall relative impact at a specific sampling station, ranging from unimpacted to clearly impacted.



Ongoing Research

Ongoing activities are focused on providing support for application of the framework to regional monitoring and regulatory programs (see Translating Science to Decision-Making). No research related to assessment framework development is in progress.

Priorities for Future Research

Future work will focus on the refinement and extension of MLOE assessment frameworks. Refinements will be needed in response to the development of new tools that measure chemical exposure, toxicity and biological effects in various habitats. The highest-priority needs are to update the assessment framework for low-salinity habitats and to develop an assessment framework relevant to impacts on fish.

***Future focus area*: Assessment framework for low-salinity habitats**
A substantial portion of California's enclosed bays and estuaries is comprised of tidal-freshwater habitats that are subject to multiple types of anthropogenic stress (e.g., urban/agricultural runoff, eutrophication, hydrological modification, and water extraction) and natural stresses related to their position at the interface of freshwater and marine systems (e.g., salinity/temperature variation, sediment transport/resuspension). However, the ability to develop a MLOE assessment framework for these habitats is limited by the availability of effective, sensitive tools for biological assessment, toxicity and chemical exposure. As these tools are developed through related research efforts and applied to monitoring programs, research will be needed to develop an assessment framework to integrate the results and assess sediment quality in a manner consistent with existing frameworks.

***Future focus area*: Assessment framework for protection of fish health**
Given that the existing MLOE assessment framework is focused on sediment contamination impacts on benthic communities, and given that protection of fish health is also a goal of the State's water quality control policy for enclosed bays and estuaries, the State's SQO framework will need to be expanded to include a different type of assessment framework where the protection of fish health is the end goal. Fish are exposed to contaminants from both direct and indirect routes, and their responses to contaminants are likely to be different from those of benthic invertebrates. As improved tools for assessing contamination impacts on fish communities and individual fish are developed through other research efforts, there will be a need to interpret the results via a sediment quality condition assessment. Thus, research will be needed to develop contamination-response relationships for fish and to integrate the tools and relationships into an interpretation framework that can be used to assess attainment of sediment quality objectives.

Causal assessment

Accomplishments

SCCWRP's work on causal assessment has historically focused on traditional approaches to toxicity identification evaluation (TIE), using a variety of chemical/physical separation methods and treatments to remove or enhance one or more toxicant classes, coupled with toxicity testing following each manipulation. This approach has been used in previous research to investigate the cause of sediment toxicity in Southern California embayments, as part of the Bight Regional Monitoring survey (Bay et al. 2011) and through studies related to TMDLs in San Diego Bay (Greenstein et al. 2011) and Ballona Creek Estuary (Greenstein et al. 2014). In each study, current-use pesticides (e.g., pyrethroids) were identified as the most likely cause of sediment toxicity.

Ongoing Research

With recent case studies validating the accuracy and utility of traditional TIE methods, SCCWRP's ongoing causal assessment research is focused on two areas. First, SCCWRP is transitioning its successful traditional TIE research into application by developing guidance documents for its use.

> ***Project*: Sediment toxicity identification guidance development**
> This project will augment SQO guidance documents to provide more specific guidance to regulators and water-quality managers for conducting TIE studies consistent with California's Sediment Quality Objectives policy. Recently completed TIE studies in Marina del Rey Harbor and Los Angeles Harbor, along with experience from previous projects and input from sediment toxicologists, will be used to describe recommended study designs and specific treatment methods shown to be effective for determining the cause of sediment toxicity. Guidance will also be provided regarding data interpretation.

Second, SCCWRP is shifting its research emphasis on causal assessment to include molecular methods. Traditional TIE methods, although helpful in identifying the contaminant classes of greatest concern, have several drawbacks, including cost, low chemical specificity, poor sensitivity to low-level effects, and limited applicability to field exposure situations. The development of molecular stressor identification methods, or molecular TIE, offers the potential to improve the sensitivity and specificity of traditional TIE methods by using gene expression analysis of the test organism to indicate the type of toxicants causing reduced survival or growth. These molecular approaches rely on analysis of the response of the test organism, rather than manipulation of the sediment sample. As a result, molecular methods offer the potential to conduct stressor identification on both laboratory toxicity test organisms and a wide variety of resident organisms exposed in the field. SCCWRP is engaged in research projects that seek to fill knowledge gaps and incrementally expand the suite of tools and lab organisms available for molecular studies.

> ***Project*: Gene expression response of fish to contaminant exposure**
> This project will develop a gene expression monitoring tool for flatfish and begin to establish the technical foundation needed to apply this tool in monitoring studies. In the first phase of the project, a gene expression microarray specific for the hornyhead turbot – a widespread species used for environmental monitoring and research – was developed. The second phase of the research used this microarray to investigate gene expression patterns in hornyhead turbot exposed to contaminants (PCBs and PBDEs) in the laboratory. Ongoing studies are investigating gene expression response in freshwater fish exposed to water from urban rivers in Los Angeles County. Several products are expected from this research: (1) better tools for evaluation of endocrine disruption and other aspects of fish health, (2) improved knowledge of the influence of legacy contamination on potential endocrine disruption, and (3) identification of biological indicators that can be used to detect exposure of fish to contaminants of emerging concern in receiving waters.

Priorities for Future Research

Future causal assessment research will focus on developing stressor-identification methods for resident benthic invertebrates.

***Future focus area*: Benthic invertebrate causal assessment methods**
Impairment to benthic communities living in marine sediments and freshwater streams is an important driver of impaired water body listings throughout California. At the same time, effective tools for causal assessment in such communities are poorly developed. Development of causal assessment tools represents a significant challenge because benthic community health is impacted by multiple types of stressors (including contaminants, habitat alteration, organic enrichment, and altered hydrology) and because laboratory TIE studies at the benthic community level are not feasible. Two types of approaches are needed. First, a rapid causal screening method for marine and freshwater systems must be developed to prioritize and guide subsequent actions. Second, next-generation techniques for benthic community assessment and causal assessment must be developed. These techniques should include development of molecular tools (e.g., gene expression analysis) for resident benthic macrofauna, development of new types of indices with the capability to diagnose stressor type, and use of assessment indices that incorporate other types of biota (beyond benthic macrofauna).

Food Web Exposure

Most of SCCWRP's ongoing research surrounding sediment-quality assessment frameworks and analysis tools is focused on the indirect exposure route, with an emphasis on human health risk. Because emphasis historically has been placed on developing an assessment framework for direct-effects assessment indicators (i.e., sediment chemistry, toxicity, benthic community assessment), much less experience and data are available for indirect effects. Ongoing SCCWRP research is focused on developing bioaccumulation models and establishing an assessment framework that integrates chemical exposure and site linkage indicators to assess attainment of California's sediment quality objective for human health protection. Studies related to adapting these methods for use in wildlife risk assessment also are in progress.

Site linkage

Accomplishments

SCCWRP has evaluated potential approaches for quantifying the influence of site sediment contamination on human health consumption risk. An approach was selected that compares seafood contaminant concentrations predicted using a food web-based bioaccumulation model to concentrations measured in resident fish. The initial scope of the linkage analysis was limited to chlorinated organics (PCBs, DDTs, chlordanes, dieldrin), due to a regulatory focus on these compounds and limitations in the ability of bioaccumulation models to accurately predict bioaccumulation of mercury and other contaminants from the sediment. Then, during Bight '13, chlorinated hydrocarbon (DDTs, PCBs, chlordanes, dieldrin) and mercury concentrations were measured in sediment, benthic infauna, water, forage fish, sport fish, and birds (egg samples) in multiple regions of San Diego Bay. The data were used to determine empirical bioaccumulation factors among food web components and to provide information for evaluating bioaccumulation model assumptions and outputs (Bay et al. 2016).

Ongoing Research

SCCWRP bioaccumulation modeling research is focused on adapting and refining a food web-based bioaccumulation model previously developed for San Francisco Bay for use in other enclosed bays and estuaries. Modifications to the model include expanding its scope to include additional types of fish, improving food web and foraging range parameter estimates, developing a method to communicate the uncertainty in the linkage results, and establishing data interpretation thresholds to categorize the strength of linkage to sediment contamination. Several projects are being conducted in San Diego Bay to document food web contaminant transfer, investigate bioaccumulation model performance and evaluate the importance of water column contaminant exposure pathways.

***Project*: Water column contamination in San Diego Bay and influence on site linkage**

Extensive application of passive sampling technology and integration with sediment/fish tissue analyses in San Diego Bay is being used to investigate the influence of water column contamination on site linkage determinations using the SQO framework. The results will document spatial and temporal variation in the relationships between sediment contamination, water column contaminants, and fish tissue contamination. The results are expected to lead to improved guidance for implementing and interpreting the human health SQO assessment framework for site remediation planning.

Priorities for Future Research

Future bioaccumulation model development will focus on two areas: (1) improving the accuracy of bioaccumulation modeling, and (2) extending the models to birds and mammals, as well as to mercury, PBDEs and other contaminants of concern to humans and wildlife.

***Future focus area*: Improvement of site linkage model for fish**

Initial application of the site linkage analysis approach to fish occasionally results in implausible values (e.g., a predicted concentration more than 10-fold greater than observed concentrations). Additional site-specific studies are needed to determine the cause of these apparent errors and revise the model to improve accuracy. Potential studies may include assessment of site-specific variations in fish diets or movement, development of more sophisticated equilibrium partitioning factors, development of alternate model approaches that incorporate sediment transport or dredging, and inclusion of contaminant exposure influences from areas outside of the assessment site (e.g., regional background).

***Future focus area*: Extension of bioaccumulation models to wildlife**

The anticipated need to develop an assessment framework for sediment contamination impacts on wildlife requires the development of models for different types of food webs and receptors than exist for seafood. While it appears feasible to adapt the existing modeling approach for use with wildlife, research is needed to develop the model parameters, address regional variations, and conduct model validation studies.

Chemical Exposure

Accomplishments

Various methods to calculate chemical exposure and potential human health impacts from consumption of contaminated seafood have been evaluated. Risk thresholds, models, assumptions and parameters used by California's Office of Environmental Health Hazard Assessment (OEHHA) were selected for use to provide comparability to other California programs. The thresholds consider cancer risk and potential for non-cancer health impacts, as well as nutritional benefits of fish consumption. The chemical exposure thresholds are based on long-term (lifetime) exposure of adults consuming locally caught fish (fillets) at rates typical of the population. Potential for health effects are assessed separately for each contaminant type, based on the total concentration of contaminant present. A survey of fishing and seafood consumption patterns in San Diego Bay was conducted to update information on temporal, ethnic, and spatial trends in fish consumption (Steinberg and Moore 2017).

Ongoing Research

Implementation of the new human health SQO assessment framework will require collection of matched fish tissue and sediment data for bays and estuaries. Existing monitoring programs rarely collect enough samples of the desired species to apply the framework correctly. Collaboration with the Bight '18 regional monitoring survey is in progress to provide recent sediment and tissue data from Southern California embayments to facilitate updated calculations of chemical exposure and site linkage. Obtaining recent information on contamination patterns in various water bodies will enable users of the human health exposure assessment tools to increase the accuracy and relevance of consumption risk calculations for specific water bodies or regions.

***Project*: Regional assessment of fish tissue contamination**
A collaborative study between Bight '18 and SWAMP (Surface Water Ambient Monitoring Program) is being conducted to collect samples of fish from multiple species in southern California bays and estuaries. Concentrations of chlorinated hydrocarbons and mercury in the tissue will be measured and compared to update information on potential chemical exposure of humans that consume these fish. These data, in combination with co-located sediment contaminant analyses, will also support updated assessment of sediment quality using the new human health SQO assessment framework.

Priorities for Future Research

SCCWRP will continue to refine and extend chemical exposure thresholds, including application to birds and inclusion of new contaminants of emerging concern. Calculating chemical exposure to wildlife is especially challenging because of the diversity of species of interest and uncertainties/data gaps in key risk parameter values.

***Future focus area*: Seafood and wildlife contamination studies**
Much of the data on fish and bird contaminant concentrations is deficient in terms of sample size, species coverage, or sampling year. Additional water body-specific seafood and bird contamination data are needed for Southern California bays, especially those subject to TMDLs relating to bioaccumulation of toxics (e.g., Los Angeles/Long Beach Harbor, Newport Bay, Marina del Rey).

***Future focus area*: Chemical exposure thresholds for wildlife**
A review and synthesis of information on body size, diet, consumption rate, and sensitivity to contaminants for locally relevant birds and mammals are needed to refine chemical exposure thresholds for wildlife. The highest priority is to determine the critical body residues and toxicity reference values used for assessment, which can vary among species and sample type.

Health Assessment Framework

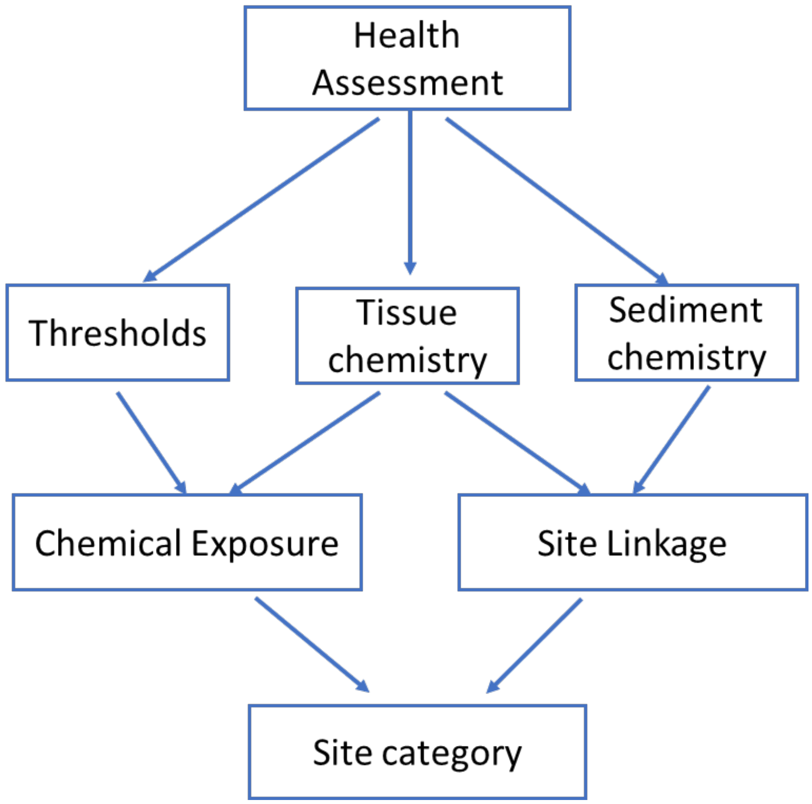
Accomplishments

A conceptual framework and associated methods for assessing contaminated sediment impacts on human health has been developed in coordination with stakeholders and a scientific steering committee (Bay et al. 2017). The framework was incorporated into the Water Board's Water Quality Control Plan for Enclosed Bays and Estuaries in 2018 and received EPA approval for use in regulatory programs in 2019. The framework integrates two independent indicators – chemical exposure and site linkage – to produce a categorical output describing the relative degree of impact associated with sediment contamination within a site (Figure 3). The assessment framework includes three tiers of analysis to address variations in site complexity, data limitations, uncertainty and need for adaptation for site-specific conditions.

- **Tier 1** is a simplified screening assessment that is used to determine whether there is enough potential for impacts to warrant additional assessment (i.e., Tier 2 or 3). The assessment can be conducted with limited chemistry data (either from sediment or tissue).
- **Tier 2** is a standardized assessment based on both site linkage and chemical exposure analyses that also takes into consideration some site-specific conditions. The Tier 2 analysis produces a categorical site assessment outcome that uses a similar five-category system as is used to assess direct exposure effects.
- **Tier 3** is an assessment method intended to provide a highly flexible assessment to accommodate complex site-specific factors that may require the use of alternate analytical approaches or models to evaluate the site.

Selection of the appropriate assessment tier is based on the development of a conceptual site model, consideration of assessment objectives, and consultation with regulatory agencies.

Figure 3. The human health effects SQO assessment framework integrates two independent indicators – chemical exposure and site linkage – to produce a categorical output describing the relative degree of impact associated with sediment contamination within a site.



Ongoing Research

SCCWRP is working to develop guidance, training and data analysis tools to facilitate implementation of the human health SQO assessment framework by environmental managers.

> ***Project*: Human health SQO assessment framework implementation assistance**
> The current SQO assessment technical support manual (Bay et al. 2013b) will be updated to incorporate the new human health assessment framework. New information on study design, monitoring requirements, and data analysis will be included. A short course, based on the manual, will also be developed for use in training new users of the framework. The data analysis tools used for assessment will also be improved as part of this project.

Priorities for Future Research

Future assessment framework development is needed to expand its applicability to different types of contaminants and to other seafood consumers. The highest-priority needs are to extend the assessment framework to other types of contaminants and to develop an assessment framework for wildlife.

***Future focus area*: Extending the human health impact assessment framework to mercury**

Mercury contamination of seafood often constitutes the major driver of human health consumption risk in California's offshore waters, embayments, and inland surface waters. The sources and fate of mercury in coastal environments are more complex than for legacy chlorinated compounds, and it is difficult to determine the linkage of sediment mercury contamination to contamination of local seafood. Research is needed to review new information on mercury biotransformation and cycling in marine/estuarine environments, and to relate it to food web contamination. A mercury bioaccumulation model that can be used to assess site linkage needs to be developed and incorporated into a sediment mercury contamination framework for protecting human health.

***Future focus area*: Developing an assessment framework for wildlife**

Although the State Water Board has adopted a sediment quality objective for the protection of wildlife, it has not developed the guidance needed to implement the objective in a manner that's consistent across the State's water bodies. Research is needed to develop an assessment framework that features an initial emphasis on local fish-consuming birds (e.g., terns, cormorants), which have maximum potential exposure to bioaccumulative contaminants. Activities should include developing guidance for selection of toxicity reference values and health risk calculation parameters, calibration of bioaccumulation models, and development of thresholds and a process for integrating the data to produce a sediment quality assessment.

Translating Science to Decision-Making

Assessment of the sediment quality at a station or site represents the initial steps in making management decisions or developing a plan to improve quality. Additional data and analysis tools are needed to make program-specific compliance determinations, identify impaired water bodies, and determine effective management responses. The categorical results produced by the direct- and food web exposure assessment frameworks require different statistical methods than the traditional chemical-based tools to determine regulatory compliance. Tools used in the identification of stressors responsible for impairment are needed to identify effective management strategies. In addition, more accurate methodologies for determining clean-up targets and forecast models are needed to evaluate management alternatives. SCCWRP develops data analysis tools and technical support documents for applying sediment quality frameworks that provide detailed guidance regarding monitoring program design and data analysis. Training in these methods is provided through workshops targeted for environmental scientists that feature hands-on experience with data analysis. To increase accessibility, emphasis is on incorporating software and databases into web-based interfaces.

Accomplishments

The technical tools, sediment quality assessment frameworks, and program implementation guidance for assessing both direct exposure effects and food web exposure effects have been incorporated into

California's water quality control plan for bays and estuaries (SWRCB 2018). SCCWRP has developed additional resources to support use of the framework in various programs, including a technical support manual (Bay et al. 2013b), data analysis tools, and training courses for regulators and scientists.

Ongoing Research

The progress on sediment-quality frameworks and incorporation into regulatory programs has generated an ongoing need for SCCWRP to address technical questions about study design and data interpretation, applicability in new habitats, and stressor identification.

Case studies: To support implementation of new sediment-quality evaluation tools in sediment quality programs, a case-study approach is used. SCCWRP develops partnerships to assist local regulatory and management agencies in applying the new methods to address an application need in a specific water body, such as TMDL development. Assisting the local agencies in resolving technical issues associated with using the new methods results in the rapid identification of implementation challenges and development of practical solutions. SCCWRP's partnership with these case studies also supports future implementation activities by providing training to management staff and demonstrating methods for successful implementation in regulatory or monitoring programs. Case studies to support implementation of new sediment quality evaluation tools in these programs were recently completed for Los Angeles and Long Beach harbors and Marina del Rey Harbor. A case study is currently ongoing in San Diego Bay.

> ***Project*: Water column contamination in San Diego Bay and influence on site linkage**
> Extensive application of passive sampling technology and integration with sediment/fish tissue analyses in San Diego Bay is being used to investigate the influence of water column contamination on site linkage determinations using the SQO framework. The results will document spatial and temporal variation in the relationships between sediment contamination, water column contaminants, and fish tissue contamination. The results are expected to lead to improved guidance for implementing and interpreting the human health SQO assessment framework for site remediation planning.

Resources for management action: To facilitate the application of sediment-quality assessment tools to programs, resources for management action are needed. For example, local monitoring and toxicology data play an important role in informing the identification of sediment clean-up targets. The focus of this work is to provide resources for determining sediment clean-up targets that are consistent with the SQO direct-effects approach.

> ***Project*: Alternative methods for determining sediment clean-up targets**
> The chemical targets being used for sediment toxics TMDLs and clean-up actions are usually based on empirical SQGs, such as the NOAA ERM/ERL. These SQGs were not developed for use as clean-up targets, have limited accuracy for such applications, and are not being used in a way that is compliant with SQO policy. SCCWRP is working to develop alternate methods for establishing clean-up targets that are consistent with the methodology and principles of the SQO policy. An update to the SQO technical support manual (Bay et al. 2013b) will include description of alternative approaches for

developing sediment cleanup targets incorporate key elements of the SQO assessment approach.

Priorities for Future Research

Future research in this area will focus on conducting additional case studies to support implementation of the direct- and food web exposure SQO assessment frameworks. A focus of these efforts is likely to be Newport Bay, which has water body impairments related to both types of effects. Guidance documents, training and data analysis tools to support management use of the SQO assessment frameworks are needed.

***Future focus area*: Newport Bay TMDL implementation case studies**
Newport Bay's harbor and ecological reserve have 303(d) listings and TMDLs for multiple types of sediment contamination impacts that were established before the State adopted SQOs; thus, the 303(d) listings and TMDLs do not make full use of the assessment frameworks and tools developed to implement SQOs. As part of targeted case studies, research is needed to apply causal assessment methods to help refine sediment cleanup targets that address direct exposure impacts in Newport Bay. Research is also needed to develop site-specific guidance for monitoring program design and data interpretation to support implementation of the direct effects and human health SQO assessment frameworks as part of a revised TMDL.

***Future focus area*: Online methods for sediment quality assessment**
The methods, indices, and assessment frameworks developed to support the SQO program have increased the comparability and effectiveness of sediment quality evaluation. But the data analyses required to apply some of these methods are complex, with variations in computer software and technical background making it sometimes difficult for end users to conduct the data analyses successfully. Thus, research is needed to develop a set of open access online data analysis and reporting tools for applying the direct and human health SQO assessment frameworks. Providing this set of tools on a single web page location with supporting documentation will provide multiple benefits to the user community: (1) easier access to tools and documentation, (2) standardized data submission and reporting formats, and (3) a mechanism to maintain and update the tools.

Literature Citations

Allen, M.J., R.W. Smith, and V. Raco-Rands. 2001. Development of Biointegrity Indices for Marine Demersal Fish and Megabenthic Invertebrate Assemblages of Southern California. 2001. Technical Report 469. Southern California Coastal Water Research Project. Costa Mesa, CA.

Barnett, A.M., S.M. Bay, K.J. Ritter, S.L. Moore, and S.B. Weisberg. 2007. Sediment quality in California bays and estuaries. Technical Report 522. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S., D. Greenstein, and D. Young. 2007a. Evaluation of methods for measuring sediment toxicity in California bays and estuaries. Technical Report 503. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S., W. Berry, P. Chapman, R. Fairey, T. Gries, E. Long, D. MacDonald, and S.B. Weisberg. 2007b. Evaluating consistency of best professional judgment in the application of a multiple lines of evidence sediment quality triad. *Integrated Environmental Assessment and Management* 3:491-497.

Bay, S.M., D.J. Greenstein, M. Jacobe, C. Barton, K. Sakamoto, D. Young, K.J. Ritter, and K.C. Schiff. 2011. Southern California Bight 2008 Regional Monitoring Program: I. Sediment Toxicity. Technical Report 640. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S.M. and S.B. Weisberg. 2012. Framework for interpreting sediment quality triad data. *Integrated Environmental Assessment and Management* 8:589-596.

Bay, S.M., K.J. Ritter, D.E. Vidal-Dorsch, and L.J. Field. 2012a. Comparison of national and regional sediment quality guidelines for classifying sediment toxicity in California. *Integrated Environmental Assessment and Management* 8:597-609.

Bay, S.M., D.E. Vidal-Dorsch, D. Schlenk, K.M. Kelley, K.A. Maruya and J.R. Gully. 2012b. Integrated coastal effects study: Synthesis of findings. *Environmental Toxicology and Chemistry* 31:2711–2722.

Bay, S.M., D.J. Greenstein , S.L. Moore, K. J. Ritter, and J.A. Ranasinghe. 2013a. Evaluation of sediment condition using California's sediment quality objectives assessment framework. Technical Report 764. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bay, S.M., D.J. Greenstein, J.A. Ranasinghe, D.W. Diehl, A.E. Fetscher. 2013b. Sediment quality technical support manual. Technical Report 777. Southern California Coastal Water Research Project. Costa Mesa, CA

Bay, S.M., L. Wiborg, D.J. Greenstein, N. Haring, C. Pottios, C. Stransky, K.C. Schiff. 2015. Southern California Bight 2013 Regional Monitoring Program. Volume I - Sediment Toxicity Report. Technical Report 899. Southern California Coastal Water Research Project Authority. Costa Mesa, CA.

Bay, S.M., D.J. Greenstein, A.N. Parks, C.Q.T. Zeeman. 2016. Assessment of Bioaccumulation in San Diego Bay. Technical Report 953. Southern California Coastal Water Research Project Authority. Costa Mesa, CA

Bay, S.M., A.N. Parks, A.R. Melwani, B.K. Greenfield. 2017. Development of a Sediment Quality Assessment Framework for Human Health Effects. Technical Report 1000. Southern California Coastal Water Research Project. Costa Mesa, CA.

Greenstein, D., S. Bay, B. Anderson, G.T. Chandler, J.D. Farrar, C. Keppler, B. Phillips, A. Ringwood, and D. Young. 2008. Comparison of Methods for Evaluating Acute and Chronic Toxicity in Marine Sediments. *Environmental Toxicology and Chemistry* 27:933-944.

Greenstein, D., S. Bay, and D. Young. 2011. Sediment toxicity identification evaluation for the mouths of Chollas and Paleta Creek, San Diego. Technical Report 669. Southern California Coastal Water Research Project. Costa Mesa, CA.

Greenstein, D., S. Bay, M. Jacobe, C. Barton, K. Sakamoto, D. Young, K. Ritter, and K. Schiff. 2013. Regional Assessment of Marine and Estuarine Sediment Toxicity in Southern California, USA. *Environmental Monitoring and Assessment* 185:2055–2065.

Greenstein, D., S. Bay, D. Young, S. Asato, K. Maruya, W. Lao. 2014. The use of sediment toxicity identification evaluation methods to evaluate cleanup targets in an urban estuary. *Integrated Environmental Assessment and Management 10:260-268.*

Ranasinghe, J.A., S.B. Weisberg, R.W. Smith, D.E. Montagne, B. Thompson, J.M. Oakden, D.D. Huff, D.B. Cadien, and R.G. Velarde. 2009. Calibration and evaluation of five indicators of benthic community condition in two California bay and estuary habitats. *Marine Pollution Bulletin* 59:5-13.

Ranasinghe, J.A., K.I. Welch, P.N. Slattery, D.E. Montagne, D.D. Huff, H. Lee, J.L. Hyland, B. Thompson, S.B. Weisberg, J.M. Oakden, D.B. Cadien, and R.G. Velarde. 2012. Habitat-related benthic macrofaunal assemblages of bays and estuaries of the western United States. *Integrated Environmental Assessment and Management* 8:638-648.

Ritter, K.J., S.M. Bay, R.W. Smith, D.E. Vidal-Dorsch, and L.J. Field. 2012. Development and evaluation of sediment quality guidelines based on benthic macrofauna responses. *Integrated Environmental Assessment and Management* 8:610-624.

Schiff, K.C., D.J. Greenstein, N. Dodder, D.J. Gillett. 2015. Southern California Bight regional monitoring. *Regional Studies in Marine Science* 4:34-46.

State Water Resources Control Board (SWRCB). 2018. Amendments to the Water Quality Control Plan For Enclosed Bays And Estuaries Of California - Sediment Quality Provisions. State Water Resources Control Board. Sacramento, CA.

Steinberg, S.J., S.L. Moore. 2017. San Diego Bay Fish Consumption Study. Technical Report 976. Southern California Coastal Water Research Project. Costa Mesa, CA.

Teixeira, H., S.B. Weisberg, A. Borja, J.A. Ranasinghe, D.B. Cadien, R.G. Velarde, L.L. Lovell, D. Pasko, C.A. Phillips, D.E. Montagne, F. Salas, and J.C. Marques. 2012. Calibration and validation of the AZTI's Marine Biotic Index (AMBI) for southern California marine bays. *Ecological Indicators* 12:84-95.

Thompson B., D. Tsukada, and J. Laughlin. 1993. Megabenthic assemblages of coastal shelves, slopes, and basins off southern California. *Bulletin of the Southern California Academy of Sciences* 92:25-42.

Vidal, D.E. and S.M. Bay. 2005. Comparative sediment quality guideline performance for predicting sediment toxicity in southern California, USA. *Environmental Toxicology and Chemistry*, 24:3173-3182.