Recommendations for Improvement of RMP Sediment Monitoring

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Introduction

The Regional Monitoring Program (RMP) Sediment Workgroup (SWG) met three times in 1997 and 1998 to discuss how to improve RMP sediment monitoring. The workgroup's considerations were guided by the RMP's Objectives and Management Questions. Additionally, conceptual models were developed to guide the discussions and are included. Seven questions pertinent to RMP monitoring design were discussed by the group, and form the basic framework for this report. The recommendations reported below reflect the general agreement of the workgroup based on the discussions at the meeting and follow-up written comments. The written comments of several workgroup participants are also included.

Conceptual Models

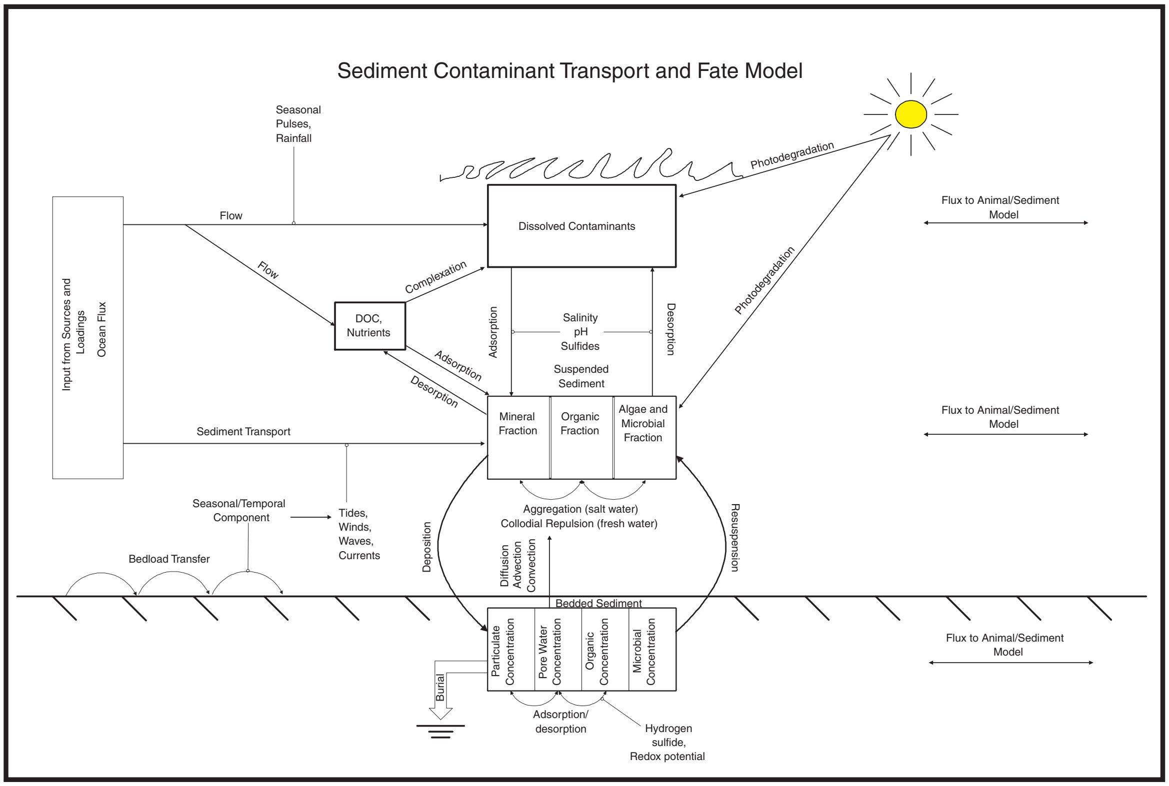
The RMP Reviewers recommended that:

> "Mass balance inventories of contaminants should be developed which can, in turn, lead to models that attempt to account for the distribution, fate, and residence times of contaminants in the Bay…."
>
> (Bernstein and O'Connor, 1998).

The National Research Council's *Managing Troubled Waters* (NRC, 1990) also recommended the use of conceptual models in monitoring design. They defined conceptual models as:

> "descriptions of causes and effects that define how environmental changes are expected to occur. They describe links among the resources at risk, the physical, chemical, and biological attributes of the system, and the human and natural causes of changes. The understanding that results permits testable questions to be clearly stated and ultimately evaluated."

Two related conceptual models of sediments were developed by the SWG based on examination of several existing models. The sediment transport and fate model and the exposure and effects model are shown in Figure 1. The transport and fate model illustrates how sediments are involved in the conveyance, storage, and transformation of contaminants. The animal exposure and effects model helps understand the linkages between sediment contamination and effects. A brief description of the models follows, and more detailed descriptions are included in the *Atlas of Sediment Contamination, Toxicity, and Benthic Assemblages* (Thompson and Daum, in prep.).



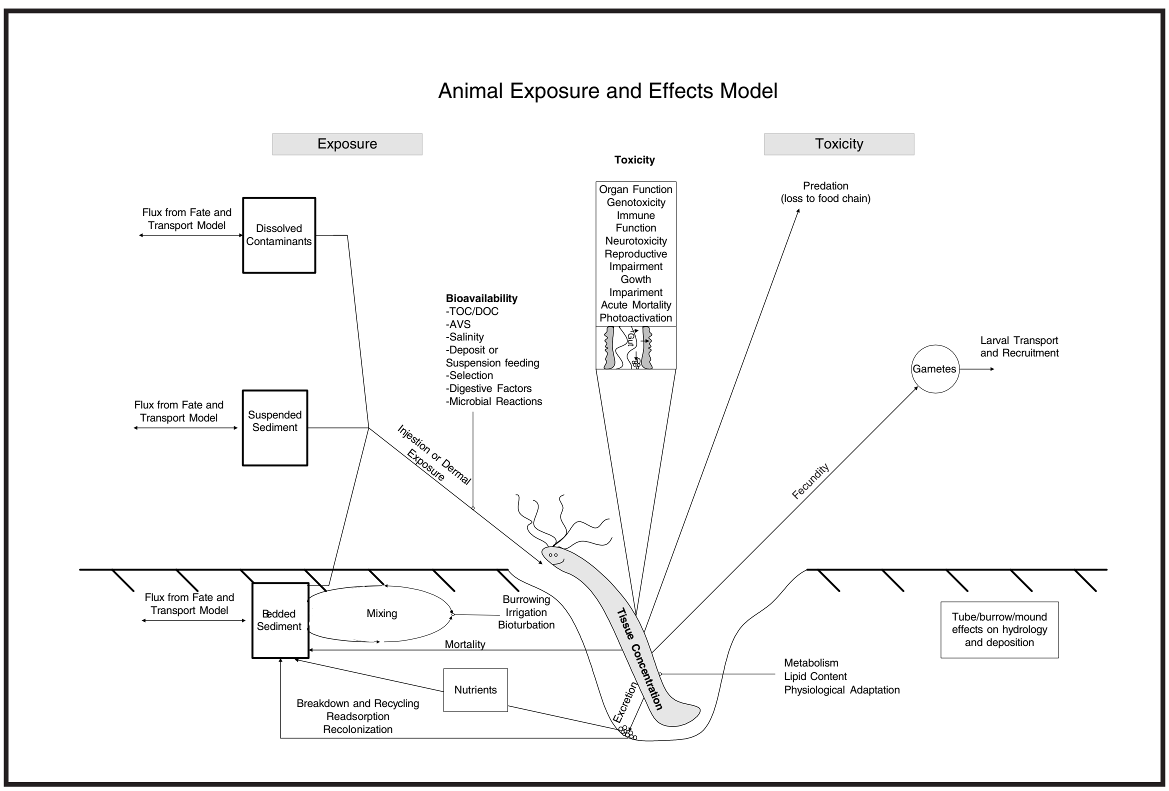


Figure 1. Conceptual models of sediment contaminant transport and fate, and animal exposure and effects. The boxes are compartments (state variables), the arrows are processes (rates), and the attached switches (⊸) denote factors that may influence the processes.

Contamination associated with sediments may derive from contaminants in dissolved form that enter the Estuary in runoff or from the ocean, and adsorb onto the surfaces of mineral particles, or into the organic matrix of particulate organic material (of various origins). Contaminant-laden sediment particles may be directly transported into the Estuary from its tributary watersheds, or from atmospheric deposition directly onto the Estuary surface. As runoff from local rivers and streams brings new mineral particles into the Estuary, they undergo chemical changes that facilitate adsorption of dissolved contaminants (Stumm and Morgan, 1981). This mechanism may explain the generally higher contaminant concentrations observed in sediments at the Southern Slough stations and near the turbidity maximum (entrapment zone) in the Northern Estuary.

Sediments exist as complex and dynamic mixtures of mineral particles, particulate organic material (detritus), microbes, and flocculated chemicals. The exact composition of sediments at any given location depends on proximity to the sources of those materials, and water physics and chemistry. Contaminants in sediments may be associated with any of those sediment fractions. The spatial and temporal variability observed in sediment contaminant concentrations reflects the complexity of estuarine biogeochemical cycles and the varied sources of contamination.

Contaminant distribution is mediated through sediment transport and transformations of sediment-associated contaminants, and includes the processes of suspension, deposition, adsorption, and desorption. Sediment deposition and resuspension is known to be very dynamic in the San Francisco Estuary (Krone, 1979), often removing or depositing large volumes of sediment within short time-periods. Rates of deposition and resuspension are variable over tidal, spring-neap, and annual time-scales. Spatial variability of deposition and resuspension rates also occurs within the Estuary as a result of variation in depth, cohesiveness, and biological activity. The annual recycling of sediments by resuspension and deposition is 10-100 fold greater than sediment inflow or outflow (LTMS, 1996). Therefore, quantifying where and when erosional and depositional areas occur will help understand the sources and sinks of many contaminants associated with sediments. Such dynamic resuspension, transportation, and deposition in sediments may result in sediment measurements that do not necessarily reflect proximity to contaminant sources.

The processes of adsorption and desorption of contaminants from sediment components are fundamental to understanding sediment conveyances. The state of any contaminant is determined by its intrinsic solubility and site-specific conditions. The intrinsic solubility of an inorganic contaminant is primarily determined by its complex solution chemistry, and for organic contaminants, is determined by the polarity of the molecule. Those processes affect not only sediment contaminant concentrations, but dissolved and particulate forms in water as well.

Contaminant transformations are caused directly by biological metabolism and indirectly as a result of diagenic processes in deposited sediments. Mercury methylation is the most obvious example of a deleterious contaminant transformation. Mercury bioaccumulates in the food web as methylmercury, which is produced as a byproduct of bacterial sulfate reduction. Consequently, anaerobic sediments and wetlands can be relatively efficient methylation areas.

Organisms may be exposed to sediment-associated contaminants in several ways. Resuspended sediments may desorb contamination into the dissolved phase exposing plankton and fish to the contaminants. Other organisms may ingest sediment particles directly. Sediment dwelling organisms may be exposed to interstitial water containing elevated concentrations of dissolved contaminants, or may ingest sediment. Contaminant effects are manifested when the exposure (frequency and duration) and dose (concentration) exceed the assimilative capacity of the organism. Effects may be non-lethal bioaccumulation of contaminants at levels below some threshold, to acute mortality if the toxic threshold is exceeded. Predators, production of gametes and offspring, fecal material, and dead organisms all provide pathways of contaminant flux from sediments. Burrowing and tube-building organisms that live in the sediments may mix the deeper layers with more recently deposited material altering sediment and pore water concentrations.

All of the mechanisms described above may affect what is measured by the RMP. Monitoring measurements alone can only provide information on the status of sediments at the time collected. Understanding the variability among the stations, Estuary reaches, and between sampling periods, or over the long-term will require understanding more of the details of the mechanisms summarized above. Such understanding must come from focused special studies. That information is critical to regulatory and management strategies such as the development of total maximum daily loads (TMDLs), toxicity reduction, and reducing human health risks from eating seafood.

Issues and Recommendations for Sediment Monitoring

The sediment workgroups' discussion of current RMP sediment monitoring and considerations for improvement revolved around seven questions. In considering these questions, they referred to the RMP Objectives and Monitoring Questions.

1. Where should sediment contamination be monitored?

RMP management questions (numbers in parentheses reference specific management questions) refer to "Estuary reaches" (1c) and to "shallower margins" (2c). Characterization of reaches and shallows may be best accomplished using probabilistic sampling (Stevens and Olsen, 1991). However, an RMP study by Jassby (1997) recommended systematic sampling for water. A major question for redesign is, should RMP change its basic design, gaining representativeness, but losing information about site-specific trends collected since 1991? Management question 3a refers to a variety of locations to document sources and loadings. Management question 2d suggests relating spatial patterns and trends to estuarine processes. Addressing those questions suggests sampling specific locations, perhaps best done through Pilot or Special Studies.

Recommendations

Both probabilistic and fixed-site sampling will be necessary to address the RMP management questions. The RMP probably cannot afford to conduct adequate random stratified probabilistic (by reach or depth) sampling because of the large sample sizes needed. A "test" of this concept may be conducted in collaboration with the U.S. Environmental Protection Agency's (U.S. EPA) Environmental Monitoring and Assessment Program (EMAP) in 2000 when they plan to sample San Francisco Bay using random stratified sampling.

- The RMP status and trends program should continue to conduct fixed-site sampling at several "representative" sites in each reach in order to continue tracking the established long-term trends. This will require some testing of "representativeness", perhaps in collaboration with EMAP. A Special Study to determine the optimal (cost:power) number of samples per reach necessary to be "representative", should be conducted.
- To address management question about sources and shallow water, the RMP should begin Pilot Studies to establish additional base program sites:
- At the mouths of major tributaries to begin to learn more about potential sources of contaminated sediments (coordinate with Pathways and Loadings Program),
- In the shallower margins of the Estuary to learn more about gradients of sediment concentration from shallow to deep, and
- Near selected "hotspots" to understand timescales of recovery.

Special Studies on sediment processes were given a high priority by the SWG to address management questions. Special Studies should be conducted in specific areas, on specific questions, particularly in areas where there are important human or ecological resources that may be impacted by sediment contamination, and to address questions about sediment processes that affect concentrations. Such studies could be "piggy-backed" with the Pilot Study gradients monitored above in order to provide information needed to understand sediment transport and fate processes on time scales related to estuarine events such as flood flows or El Niño. More frequent sampling (than trends monitoring) along several selected gradients of inflow, sediment supply, or contamination would elucidate sources, residence times, and fates of sediment contamination. That information is crucial to making sound regulatory and management decisions about sediments.

The subjects of such studies may come from Regional Board needs for information for regulatory purposes (e.g., methylmercury processes), or as identified by the Technical Review Committee as priority information needs.

2. How frequently should sediments be monitored?

RMP management question 2a refers to "long-term" changes, questions 2b and 3c refer to monitoring changes in inputs or sources, and questions 2d, 3b, and 3d address monitoring sediment changes at time scales related to processes such as sediment transport and transformations.

Recommendations

As with the spatial question, addressing the RMP management questions about temporal changes will require different sampling regimes. For tracking long-term trends, several data sets were examined. Analysis of RMP sediment contaminant trends showed that only about 7.5% of the sites exhibited significant upward or downward trends for some contaminant between 1991 and 1997 (Daum and Thompson, in prep). Neither RMP or U.S. Geological Survey (USGS) sediment data collected monthly at several locations (USGS, unpublished), showed consistent evidence of seasonal trends in concentrations, although changes in some metals were observed in conjunction with the January 1997 floods.

Based on the above, the work group recommended that the RMP reduce its sediment trends monitoring. Although there was general agreement that the RMP could reduce the sampling frequency at base program sites, exactly when and how frequent was not determined. In order to address long-term trends, annual sampling at a fixed "index sampling period", probably in the Fall, would be adequate. However, some participants suggested monitoring every three or five years.

Addressing the "process" questions, will require Special Studies. Studies that sampling at time scales related to flow and transport events could provide the necessary understanding of how these processes influence sediment concentrations. For example, if there is a need to understand loadings from tributaries related to sediment pulses, then frequent sampling associated with flow events would be necessary. Special Studies will be needed to understand time scales of change related to specific contaminants of concern. Time scales may differ between contaminants. For example, copper appears to be diluted following high flows, whereas mercury appears to be enriched.

These studies could be "piggy-backed" with the gradient studies recommended under question 1. Additionally, the RMP should investigate the possibility of closer collaboration and support for ongoing USGS efforts where sampling is conducted at sites near the major tributaries in the Northern Estuary and South Bay.

3. Which sediment variables should be monitored?

The RMP currently monitors a wide variety of sediment contaminants, as listed in the *Quality Assurance Project Plan* (Lowe *et al.,* 1999). Additionally, non-contaminant sediment variables (e.g., grain-size, organic material, ammonia, sulfide) that facilitate the understanding and interpretation of other RMP components (sediment toxicity, benthic sampling) are measured.

RMP management question 1b refers to comparisons of monitoring results to relevant guidelines, suggesting that it is important to at least monitor those contaminants for which guidelines exist. Monitoring "contaminants of concern" identified by the Regional Board and other research on contaminant effects in the Estuary should also be considered.

Recommendations

There was general agreement that monitoring a of a suite of contaminants should be continued. The RMP should be adaptive and responsive to new information and the Regional Board's identification of "contaminants of concern". The appropriate pesticides to monitor in sediments should be evaluated based on use patterns through consultation with the Central Valley Regional Board. In particular, measurements of chlorpyrifos and diazinon in sediments should be investigated.

Pilot Studies on the expanded use of ELISA or the Reporter Gene System (RGS) should be conducted, particularly for use in future Pilot and Special Studies. Both methods are quicker and less expensive than conventional chemistry.

Special Studies on refining the relationships between sediment grain-size fractions (phi or size frequency distributions), total organic carbon, and aluminum vs. metals may help understand and develop predictive tools that could be used to estimate sediment contaminant concentrations.

Most SWG participants felt that the ratio of acid-volatile sulfides:sumultaneously extracted metals (AVS:SEM) would not be useful as a routine monitoring tool. However, Pilot Study sampling at some sites may be useful to see if it helps better explain either sediment toxicity or benthic results. The SWG also discussed the possibility of measuring metals in pore water as an alternative approach to determining bioavailability of metals in sediments. This measurement may also be appropriate for a Special Study comparison to bulk phase and AVS-SEM analyses.

4. To what depth should sediment contaminants be measured?

Since the RMP began, the top 5 cm of sediment has been sampled. The use of that depth was agreed to in an early project scoping session as an alternative to the widely used 2 cm depth in other monitoring programs. Since then, the question of "why 5 cm?", has arisen many times. The RMP external review panel addressed this question in its explicit recommendation (3j):

> "The RMP should use data from the USGS on the chemical concentrations in dated sediment cores to determine the time required for particles to be buried so deeply that they no longer contribute trace substances to surface sediments or to total suspended solids (TSS). This needs to be known to gauge the number of years required for surface sediments and TSS to respond to changes in contaminant inputs. This in turn is needed to properly scope the RMP's trend monitoring design."

The bottom of the Bay is of variable substrate and composition, and changes over time. Recent USGS imagery of the Bay floor between the Golden Gate and Central Bay shows a variety of bottom features including large sand waves, rubble fields, sedimented channels, and rock outcrops. Previous studies have shown that parts of the Bay may be alternately depositional or erosional over various time scales. USGS sediment cores in San Pablo Bay indicated much higher deposition rates than those in Richardson Bay, and had quite different active sediment layers. The active layer for Richardson Bay was 33 cm (Fuller *et al.,* 1999). USGS also estimated that about half of the contaminants deposited 35 years ago would remain in that mixed layer. Jaffe *et al.* (1998) showed that San Pablo Bay is a net erosional area as a result of sediment starvation from dams constructed in the Central Valley and Sierra Nevada foothills. They predict that this erosion will gradually expose mercury-laden sediments deposited after the hydraulic mining era of the late

1800s. Such quantitative understanding of current and future mercury input rates from sediments is a vital piece of information for development of the mercury total maximum daily loads. The above information indicates that erosion and deposition, thus burial rates in the Bay are very complex and that no standard sampling regime can be used for monitoring.

Sediment types at the RMP sites range from fine muddy sediments in the shallower areas of the Bay (Grizzly Bay, Redwood Creek) to coarse sandy sediments at sites in the main channel of the Sacramento River, at Davis Point and Red Rock. The depositional regimes are probably quite different among the RMP sites.

Another consideration is how to deal with sediments that have an anoxic layer. Anoxic sediments bind differently with trace metals than oxidized sediments (Stumm and Morgan, 1981). In practice, the anoxic layer at most RMP sites is below the currently collected 5 cm depth. However, if the RMP establishes new sites in shallower areas, this could become a problem. Currently, the USGS samples the top 2-3 cm, sampling only the oxic layer.

Recommendations

The SWG concluded that there is no uniform active sediment layer or uniform burial depth in the Bay that could be used for sediment monitoring. Sampling the entire active sediment layer is not practical because of the volume of sediment that would need to be collected at many sites which would yield long term average concentrations. The RMP appears to be more interested in monitoring changes in the most recently deposited material in order to assess changing sediment inputs on at least annual time scales.

The RMP should continue to sample the top 5 cm when it is oxidized. If the anoxic layer is less than 5 cm deep, only the oxic layer should be collected. The rationale for that recommendation is that the top 5 cm provides a reasonable *estimate* of the most recently deposited material and is the layer to which most organisms are exposed.

There are other coring data available and perhaps a Special Study to assess that information would shed further light on this question.

Pilot sampling in new areas (tributaries, shallow margins) should be conducted to determine adequate sampling depths.

The SWG generally endorsed the CHC SWG's recommendations of Special Studies to determine the "active sediment layer" at various locations in the Estuary.

5. Is sediment toxicity testing using *Eohaustorius* and bivalve larvae adequate?

Although not specifically referred to by the RMP external review, their recommendation to rationalize all RMP components (3a) is the basis for the SWG addressing this question. Sediment bioassays are used in the RMP to address Objective 3: Measure contaminant effects on the selected parts of the Estuary ecosystem, and Objective 4: Compare monitoring information to relevant water quality objectives and other guidelines. The latter refers to the Basin Plan narrative for no toxicity.

Currently, sediment bioassays have been used since 1991 as part of the BPTCP Pilot Studies and were adopted when the RMP began in 1993. The RMP currently conducts sediment toxicity tests twice a year using *Eohaustorius* (amphipod) exposed to bulk sediments and bivalve embryos exposed to sediment elutriates. Questions have arisen about the interpretation of toxicity to non-resident organisms, and the use of sediment elutriates to evaluate toxicity. Samples from RMP freshwater sites are "salted-up" during the bioassays raising questions of applicability.

Another amphipod *Ampelisca abdita* is a resident (not native) that dominates many of the Central Bay and estuarine benthic samples. Like *Eohaustorius* it has well developed protocols and is widely used in sediment bioassays by other monitoring programs (e.g., EMAP). The RMP sponsored Special Studies in 1994-1996 to develop the use of *A. abdita*, including a chronic endpoint (Weston, 1996). However, almost all testing to date in the Estuary has used *Eohaustorius* providing important information about long-term trends in toxicity that would be lost if testing using that species were to be discontinued. Sediment or other environmental factors that cause sediment toxicity are poorly understood.

The currently used amphipod, *Eohoustorius estuarius* is a well established bioassay species and provides reliable indications of sediment toxicity. However, it is not a resident species, and preliminary estimates of how well sediment bioassays actually predict benthic impacts have shown little relationship (SFEI, unpubl.). Sites with *Eohaustorius* toxicity often have high abundances of *Ampelisca*, although it is recognized that these species might respond differently to different contaminants and environmental variables. Using A. abdita in laboratory biaossays, as well as studying their relationships to contamination in benthic samples from the same sites could provide a better understanding of environmental effects of contaminants on the benthic resources of the Bay (Objective 3).

Sediment elutriates were used by the RMP as a different type of test and are also used in dredged material testing. However, exposures to elutriates is not considered to be a realistic exposure of the embryos. Newer methods that provide more realistic exposures to dissolved contaminants at the sediment water interface have been tested (Anderson *et al.,* 1996) and may be more suitable for the RMP.

Recommendations

The SWG did not reach any agreement on whether the RMP should use *Eohaustorius* or *Ampelisca*. The Army Corps of Engineers representative suggested using several species to conform with recommendations of the *Inland Testing Manual*. The SWG agreed that side-by-side testing was necessary, therefore Pilot Studies are recommended to test the use and application of both species before any decisions are made about replacement or additions. The proposed EMAP sampling in 2000 would help accomplish that testing.

Studies comparing resident and non-resident *Ampelisca* should be conducted to determine if there is a contaminant acclimation effect by resident organisms.

Continue to use the bivalve embryo test, but switch to the Sediment-Water Interface exposures method rather than elutriates. Side-by-side testing at a few locations would help transition, but we should not expect directly comparable results. Conduct TIEs to understand causes of toxicity.

At the freshwater locations develop and implement more appropriate tests. Possibly *Ceriodaphnia* or larval *Corbicula*, in lieu of bivalve embryos, and a freshwater amphipod such as *Hyallela* or *Gammarus* instead of *Eohaustorius*. Such development could occur through a Pilot Study.

Continued Special Studies to determine causes of sediment toxicity should be a high priority as suggested by the RMP Program reviewers and RMP Management Question 4c. It is not possible to make management decisions about how to reduce toxicity until the causitive agents are known.

6. Should the RMP initiate a sediment bioaccumulation component?

The RMP currently monitors bioaccumulation in transplanted bivalves suspended in the water column, and in fish tissue. However, no monitoring of bioaccumulation from exposure to sediments is conducted, leaving an information gap about the transfer of contaminants from sediments to organisms. Sediment testing for dredging includes a laboratory bivalve bioaccumulation test. An RMP sediment bioaccumulation component could provide a background data base to which dredge testing could be compared. It would also provide information about the link between sediments and uptake by organisms (RMP Management Question 4a). Which species to use, locations, and times to monitor should be considered.

The USGS currently samples the introduced Asian clam *Potamocorbula* amurensis at several sites in the northern Estuary. They have found it to be a sensitive and useful indicator of contamination (e.g., Pereira *et al.,* 1992; Parcheso *et al.,* 1997). Similarly, *Corbicula fluminea* has been sampled by the State's Toxic Substance Monitoring Program in the Delta and provides useful information about bioaccumulation by a resident species (SWRCB, 1996). However, both *P. amurensis* and *C. fluminea* are filter feeders and their bioaccumulation patterns more closely resemble suspended sediments than bedded sediments.

Recommendations

The RMP should begin a Pilot Study of resident benthic bivalve bioaccumulation in order to address several RMP management questions. Using resident bivalves would provide an easily interpretable measure of exposure, bioavailability, and accumulation of many persistent sediment contaminants, and their impact on the condition of resident bivalves as diagrammed on Figure 1. The use of a deposit-feeding clam was recommended. *Macoma* or *Tapes* could be used at some locations but their availability may be limited to a few locations and times. The choice of species, locations, and times should be investigated in the recommended Pilot Study. The Corps of Engineers representative suggested that two species be used, and requested that at least one be from the Inland Testing Manual. The RMP should explore closer collaboration and support of ongoing USGS bivalve monitoring programs. Such collaboration would strengthen the RMP by building upon an existing and successful sampling program and encouraging further participation in the RMP by the USGS.

There was no agreement on the use of laboratory measurements of bioaccumulation using field sediment. However, Special Studies could be useful in understanding the relationships between laboratory bioaccumulation measurements as used by the dredgers and field bioaccumulation measurements.

7. Should benthic macrofauna be monitored?

A summary of the RMP Benthic Pilot Study was presented to the SWG. The recommendation at that time was to continue the Pilot Study with the goal of better documenting how different water years affect benthos, and linking sediment contamination with benthic effects (RMP Management Question 4c). A Technical Report of the findings from the Benthic Pilot Study is being prepared by SFEI staff. That report will be sent out for external review and comment on the usefulness of benthic monitoring for the RMP.

The SWG did not discuss this question further. They encouraged the completion of the Benthic Pilot Study Technical Report and its subsequent external review and recommendations.

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Appendix 1
Table of Contents from the Atlas of Sediment Contamination, Toxicity, and Benthic Assemblages in San Francisco Bay (Thompson and Daum, 1999)