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REGIONAL MONITORING PROGRAM FOR WATER QUALITY IN SAN FRANCISCO BAY

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San Francisco Bay Sediment Modeling and Monitoring Workplan

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Preface

This document was prepared with guidance gained through two RMP Sediment Workgroup workshops held in late 2022 and early 2023. Given the variety of participants involved, this Workplan encompasses interests beyond San Francisco Bay RMP funders. We thank the attendees for their contributions.

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1. Introduction and Purpose

In 2020, the Sediment Workgroup (SedWG) of the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) completed a Sediment Monitoring and Modeling Strategy (SMMS) which laid out a conceptual level series of data and information gaps and generally recommended the use of both empirical data collection and modeling tools to answer initial high priority management questions (McKee et al., 2020). At the time, the SMMS promoted the use of surrogates such as time-continuous turbidity measurements for cross-section flux modeling within the Bay without an understanding of existing Bay hydrodynamic models, their strengths, weaknesses, and potential uses for understanding coupled Bay-mudflat-marsh processes. Since then, the Wetland Regional Monitoring Program (WRMP, www.wrmp.org) has generally promoted the use of coupling monitoring and modeling techniques to inform wetlands sediment management decisions. In addition, he completion of the Sediment for Survival report (a RMP-EPA funded collaboration) and the further development of sediment conceptual models has also advanced the need for a coupled dynamic modeling and monitoring program that has the capacity to explore more complex management questions (Dusterhoff et al., 2021; SFEI, 2023). Such a program will take time to develop, but will be more cost-efficient and adaptable and allow for more timely answers to pressing questions.

Monitoring to address sediment management questions has been an RMP priority for 30 years. Suspended sediment monitoring at 15 minute intervals has been ongoing on the “axis” of the Bay since the RMP’s inception (Buchanan and Schoellhamer, 1999) and continues using a combination of RMP funding and a broader multi-agency collaborative (Palm et al., 2022). In addition, monthly sampling on the axis at 37 locations 3-6 km apart was part of the water quality monitoring program that began in 1969, well before the inception of the RMP (Cloern and Schraga, 2016), and was supported by the RMP through to 2016 and then subsequently by the Nutrient Management Strategy (Senn et al., 2012). Beginning in 2001, the RMP switched to sampling using stratified randomization that, over time, has characterized the whole Bay for suspended sediment concentrations (SSC) and bed sediment grain size (SFEI Data Services team, 2023). Over decades, these data have been analyzed and interpreted to answer scores of questions about sediment processes (e.g. David et al., 2009; McKee et al., 2013; Schoellhamer, 2011, 2002, 1996; Schoellhamer et al., 2007, 2005). In addition to these routine programs, a number of sediment special studies have been completed, again too numerous to list except some recent examples (Downing-Kunz et al., 2021; Fregoso et al., 2023; Lacy et al., 2020; Livsey et al., 2021, 2020; McKnight et al., 2020; 2023) and there are field studies planned and underway that include monitoring on marshes for the first time[1].

In addition to ongoing RMP funding and studies, the Bay sediment community has benefited from a large amount of state and federal grant funding. The San Francisco Bay Restoration Authority (SFBRA) is providing $25M per year over twenty years for marsh restoration and other activities[2]. In addition, the EPA-funded Wetland Program Development Grant (WPDG) program provides funding to conduct projects that promote the coordination and acceleration of research, investigations, experiments, training, demonstrations, surveys and studies relating to the causes, effects, extent, prevention, reduction and elimination of water pollution. Annually the EPA Water Quality Improvement Fund (WQIF) has been providing $2-5M for wetlands restoration, improving stormwater quality, and remediating contaminated shorelines. Funding was increased to $25M in 2022 and scope was broadened to include projects on climate change impacts and environmental justice concerns, as well as those that advance landscape-scale watershed restoration. Going forward, up to $50M may be awarded annually by the WQIF. Through a SFBRA and two WPDG grants, the Wetland Regional Monitoring Program (WRMP, www.wrmp.org) is developing a program to monitor representative mature and restored tidal marsh habitats using standardized methodologies (WRMP, 2020).

There is considerable overlap and the need to identify collaboration opportunities between the RMP SedWG and the WRMP, whose geographic scope extends out into the Bay from wetlands to 12 feet below mean lowest lower water (MLLW) and whose mission is to help stakeholders understand how landscape-scale drivers are affecting marshes, support decision-making for wetland management, and facilitate coordinated and standardized monitoring. In early 2023, the WRMP released a Priority Monitoring Site Network Memo that defines and maps Benchmark Sites (historic, minimally modified mature tidal wetlands), Reference Sites (wetlands at late stages of development that may be used to identify a “reference envelope” of feasible conditions for restoration projects), and Project Sites (existing and planned tidal marsh restoration to recover tidal marsh acreages, functions, and values) that form the WRMP’s initial priority near-term monitoring site network (WRMP, 2023). Later in 2023, the WRMP will complete a

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[1]Benicia Bridge flux; South Bay sediment settling velocity; Temporal variability in sediment delivery to a South San Francisco Bay salt marsh; Continuous suspended sediment and wave monitoring in South and Lower South San Francisco Bay; Temporal variability in sediment delivery to a North and a Central San Francisco Bay salt marsh.

[2]Reducing trash, pollution and harmful toxins; improving water quality; restoring habitat for fish, birds, and wildlife; protecting communities from floods; and increasing shoreline public access and recreational areas.

monitoring plans and SOPs that are anticipated to describe where and how a set of approved standard monitoring methods for geospatial, hydrogeomorphic, vegetation, and fish and fish habitat indicators can be used to detect change of living organisms (primarily plants and animals) and their habitats[3].

The use of models for answering sediment management questions is not new to the Bay. The RMP Sources, Pathways, and Loading Workgroup (SPLWG) has already completed the development of the Watershed Dynamic Model (WDM), a Loading Simulation Program in C++ (LSPC) based model that simulates 15-minute flows and suspended sediment concentrations (SSC) and loads from the watersheds that surround the Bay for water years (WYs) 1995-2020 (Zi et al., 2022). In addition, the RMP Nutrient Management Strategy (NMS) has been developing a Delft3D-FM (DFM) model, building on the San Francisco Bay-Delta Community Model (Achete et al., 2015; 2017; Martyr-Koller et al., 2017; Nederhoff et al., 2021; Tehranirad et al., 2020; Vroom et al., 2017; 2018). This model uses tides, precipitation, evaporation, winds, salinity, river, creek, and stormwater flows, wastewater flows, and heat exchange to simulate hydrodynamics, salinity, and temperature. DFM is a finite-volume, three-dimensional, unstructured hydrodynamic model that allows for efficient and flexible simulation at spatial scales ranging from small perimeter sloughs and associated mudflats up to a regional representation of the Bay-Delta and coastal ocean. Presently, NMS hydrodynamic simulations cover WYs 2003, 2006, and 2013-2018 but do not yet include a direct simulation of sediment transport (King, 2019; King et al., 2019). However, a number of sediment simulations have been completed for the Bay by others using the DFM platform of models: Delta suspended sediment concentrations (Achete et al., 2015); San Pablo Bay bed sediment morphodynamics (Elmilady et al., 2019; Van der Wegen et al., 2011; Van der Wegen and Jaffe, 2013); sediment exchange at the Golden Gate (Elias and Hansen, 2013; Erikson et al., 2013); and South Bay sediment mudflat morphodynamic evolution (Van der Wegen et al., 2017, 2019). Building upon these previous studies, a master's thesis overseen by M. Van der Wegen was recently completed that quantifies fine sediment fluxes in the southern portion of the Bay (van Gijzen, 2020). A tidally averaged sediment transport model for the whole San Francisco Bay (SFB) subdivided into 50 segments based on the Uncles and Peterson salinity model has also been completed (Lionberger and Schoellhamer, 2009).

[3]This is one of many science priorities for the WRMP; they are listed in the memo (WRMP, 2023) but include tracking where marshes are and are not keeping pace with SLR, and where sediment from watershed and estuarine sources can support wetland resilience.

In addition, a 3-D hydrodynamic, wave, and sediment transport model, UnTRIM, has also been developed for SFB (Bever and MacWilliams, 2013; MacWilliams et al., 2015; MacWilliams and Gross, 2013). It was implemented to evaluate the effects of the observed reduction in wind speed that occurred from 1995-2015 on turbidity in the Bay as a contributing factor for the observed step change in SSC that was related to supply (Schoellhamer, 2011). Although supply was a factor, the model showed that wind speed was the primary factor that caused a decrease in turbidity of 14 to 55% in Suisun Bay from October through January (Bever et al., 2018). UnTRIM was also used to estimate sediment flux through the Golden Gate (Anchor QEA, 2021). Most recently, UnTRIM was used to simulate both suspended and bedload transport to explore questions relating to how sand mining is influencing sand transport with a focus on Suisun Bay and Central Bay (Anchor QEA, 2023). The U.S. Army Corps of Engineers (USACE) is currently exploring strategic sediment placement using a combination of field observations and dynamic modeling - some under subcontract with Anchor QEA using UnTRIM and some done with internal staff and modeling resources; there may be lessons and data sharing opportunities with this effort, and collaboration is already occurring with the RMP providing WDM outputs as boundary conditions for these UnTRIM modeling efforts.

Several marsh models have also been developed and applied in the Bay, including the Coastal Wetland Equilibrium Model (CWEM) (Morris et al., 2022) and the Wetland Accretion Rate Model for Ecosystem Resilience (WARMER) model (Buffington et al., 2021; Swanson et al., 2014). CWEM is a 2D model that incorporates plant growth and sedimentation processes with bulk density profiles to simulate vertical deposition on marsh surfaces without a lateral migration component. An earlier version of the CWEM, the Marsh Equilibrium Model (MEM) has been applied at four historic tidal marshes in the SFB Estuary (Schile et al., 2014; Stralberg et al., 2011). WARMER is a 1D model of elevation that incorporates surface and subsurface biological and physical processes including compaction to simulate vertical marsh accretion. An advantage of WARMER over CWEM is it does allow for march migration. There is existing experience using WARMER in concert with DFM in Southern California (Brand et al., 2022) and MEM in concert with the two-dimensional, depth-integrated ADvanced CIRCulation (ADCIRC) finite element model in Florida (Alizad et al., 2016). Compared to previous models, CWEM has improved parameterizations for below ground organic matter distribution, accumulation, and decomposition, incorporates data on vertical plant distribution, and includes episodic storm sediment pulses. Similarly, WARMER incorporates processes that capture change over event time scales and allows comparisons of the importance of event-scales and annual and longer-term biophysical processes. Based on these models, we have learned the importance of inclusion of these more sophisticated representations of vertical, spatial, and temporal processes for improving the reliability of marsh resilience predictions and related management questions in the face of sea level rise (SLR).

A review of coupled physical and ecological modeling options for exploring future marsh dynamics in relation to SLR highlighted a number of weaknesses in existing modeling approaches (Passeri et al., 2015). These include weaknesses in modeling and monitoring shoreline dynamics; modeling the synergistic impacts of coastal hardening, ports, and harbors; changed sediment supply and other human-related aspects, modeling feedbacks between these human-related developments and soft-restoration options, and integration of the socioeconomics (Passeri et al., 2015). Although not part of this Sediment Modeling and Monitoring Workplan (SMMWP), addressing some of these weaknesses could be considered in future studies.

This brief review illustrates the wealth of information that has been generated by monitoring and modeling sediment dynamics separately, but what has not been done to date is to bring these two tools together in an integrated approach. As mentioned previously, the SFBRA and the EPA WQIF will be spending substantial resources over the coming decades, much of which will be used to restore tidal habitats. This will extend an existing 30-year effort to restore baylands, and since restoration plans have largely been completed for the South Bay, a coupled modeling-monitoring program is not needed as much of the decision-making in the South Bay but could be helpful for North Bay planning. Such a program could also be used to improve restoration designs and will be used to make estimates of the future sediment and vegetation distributions that will likely result from the approach and location of proposed restoration projects (Ganju, 2019). In addition, as SLR continues, and our marshes begin to change more quickly, a coupled modeling-monitoring program would also help determine which marshes may be self-maintaining, be sustained by passive management techniques, require active management techniques to maintain elevation, or need to be abandoned and allowed to downshift to other habitat types such as mudflats or shallow water. The vision of the RMP is to help build the open-source modeling capacity to help address these regional needs.

This report outlines a coupled sediment modeling and monitoring workplan (SMMWP) that aims to lay out how to address a series of priority modeling-monitoring science questions that were derived from the Sediment Workgroup management questions during two workshops held in late 2022 and early 2023. The objective of this SMMWP is to focus the efforts of the RMP SedWG over the next five years and further facilitate and improve our capacity to simulate how sediment transport, accretion, and erosion might vary within and around different Bay habitats and across subregions of the Bay under a range of restoration scenarios at timescales ranging from tides to decades and changing conditions (e.g., future watershed flow and sediment loads, SLR, evolving tidal marsh area, and shifting Bay hydrologic regime). Given that these needs are shared across sediment stakeholders of the Bay, this SMMWP can be seen as a document that identifies monitoring and modeling priorities beyond what the Bay RMP is able to fund. It is therefore intended to highlight key data gaps and help focus sediment monitoring and modeling efforts undertaken outside the auspices of the SedWG.

2. Modeling-Monitoring Approach

Supported by the existing development and application of both monitoring and modeling expertise for the Bay, the RMP, in collaboration with the NMS, is embarking on a multi-year plan to further develop the DFM for dynamically modeling polychlorinated biphenyls (PCBs), contaminants of emerging concern (CECs), and sediment in SFB (Jones et al., 2022). Although it should be noted that there will need to be many implementations of DFM within the Bay, customized for the different management questions, whenever possible, the sediment community should fund DFM development and monitoring together so that the models can be ground-truthed and tuned with field data to build greater confidence in their use.

The current PCB model workplan includes efforts to compile data for the boundary conditions for sediment and comparing bed elevation predictions with measured sediment accumulation rates. The plan is to develop and test the model against field observations initially for two margin areas (San Leandro Bay and Steinberger Slough) in 2023/2024, and then extend the model to the whole Bay (Jones et al., 2022). The whole (Suisun, San Pablo, Central, South, and Lower South Bay) model will include improving a 3D description of Bay sediment bed and Bay-wide sediment transport simulations for dry and wet climatic conditions. Field observations will be needed at both these spatial scales to test and verify the models. The overall objective of the Jones et al. (2020) modeling workplan is to develop sediment modeling capacity to support predicting the transport and fate of PCB and CECs, and sediment limitation of phytoplankton growth, and also answer broad-scale sediment transport-related management questions. Although answering questions about the probability of marsh establishment or successful restoration or marsh persistence in light of SLR will not be answered with current levels of funding, with further development, many of the science questions articulated in this new SMMWP could be answered.

Although there is funding to get started and there are clear efficiencies associated with coordinated modeling to address the questions of the PCB, CEC, nutrients, and sediment management communities, no one model scale, setup, and calibration will address all questions equally well. This will lead to tradeoffs, the need for unique calibration and validation data depending on the specific question, the potential for model convergence and divergence during the timeline of model development, and the need for unique DFM versions. As mentioned previously, there will be the need for customized versions of the DFM and model runs for addressing specific management questions. At present, the PCB projects are focused on understanding the current state and response of the system to loads of sediment and contaminants; answering questions predicting the progression of specific wetland restorations, or speculating on impacts of changes in rates of SLR or other climate impacts are beyond the presently funded scope. Answering these and other sediment management questions will require additional funding to support further DFM model development, coupling the DFM with marsh models (which may be unique for differing marshes and also need funding), and funding to support data acquisition for parameterization and monitoring for calibration. This work will need to be well-coordinated with the WRMP and others and funding may come from the RMP or through other sources or collaborations.

This SMMWP addresses sediment study needs by providing expanded detail about the priority science questions that will help drive a coupled modeling-monitoring program as a funding framework for consideration by the RMP and others over the next five years that will augment the existing (Jones et al., 2022) multi-year plan for developing the DFM. Once the model development reaches suitable maturity to support a sensitivity analysis of parameter inputs and calibration data gaps, the five-year SMMWP will need to be updated to include the monitoring components that the sensitivity analysis shows are needed for further model improvement towards answering management questions. Given the importance of getting as much marsh restoration as possible competed by in the next decade to maximize marsh establishment before the SLR rates are expected to increase, it would be more ideal if the planning efforts could be done earlier.

3. Sediment Workgroup Management Questions

The SedWG has five core management questions (MQs - listed below) to guide modeling and monitoring priorities. The first two questions focus on sediment quality and the effects of dredging and sediment placement on Bay habitats and species. Existing partnerships in the region are advancing numerous studies that pertain to MQ#1 and MQ#2. MQs #3-5 are about the physics of sediment in the Bay—quantity, movement, and deposition, particularly on tidal marshes—and are the focus of this SMMWP. The need for research in relation to these three questions is greater than the presently funded modeling effort or that can be funded in the future by the RMP alone so this SMMWP is envisioned to encourage increasing partnership with other programs.

MQ#1 What are acceptable levels of chemicals in sediment for placement in the Bay, baylands, or restoration projects?

This question will not be addressed here but will be the subject of a future planning effort.

MQ#2 Are there effects on fish, benthic species, or submerged habitats from dredging or placement of sediment?

This question will not be addressed here but will be the subject of a future planning effort.

MQ#3 What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?

In order to inform Bay sediment policy and management actions, increased accuracy and precision of information about the current and potential future sediment budget (and associated contaminants budget) for the Bay and subembayments is needed. The sediment budget consists of sources and sinks (McKee et al., 2020). Sources of sediment to the Bay consist of all Bay-draining watersheds, the Delta, and the Pacific Ocean. Sinks are areas where sediment is stored temporarily or indefinitely, with some of this sediment being removed through dredging and sand mining activities. The bed of the Bay, including the tidal portions of flood control channels (Dusterhoff et al., 2017; Pearce et al., 2021), mudflats, shoals and deep channels (Fregoso et al., 2023; McKnight et al., 2023), may be a source or a sink depending on the time scale, size of sediment particle, and location. The erodible sediment pool (ESP) is defined as any shallow subtidal area within SFB (MLLW to 12 feet below MLLW) containing sediment that can be mobilized and transported (McKnight et al. 2023). Changes occur in these areas as a result of large pulses of sediment deposition and periods of erosion that bring sediment into and out of the pool (Geyer and Ralston 2017). Vertically, the ESP is the upper unconsolidated layer of more recently deposited fine sediment that resuspends under wind wave and tidal forces. The recently completed bathymetric change analysis by Fregoso et al. (2023) could be a good starting point for mapping out a decadal scale average ESP for the Bay; areas eroding over the last decade could be the same as the present ESP. Unfortunately, the gaps in the bathymetric data were all in the shallows thus there is incomplete coverage for the areas closest to many of the wetlands (Fregoso et al., 2023). Similar processes can be considered at larger scales also. Sediment transport through tidal, wind wave, or freshwater advective processes or disposal of dredge material also occurs such that the bed of one subembayment may be a source or sink for another subembayment. However, not all mudflats or sandflats are part of the ESP and can be both a source and sink of sediment.

Tidal marshes that have active edge or surface erosion may be a net source to the Bay, but at present most of our natural wetlands are keeping pace with SLR and are a net sink (Buffington et al., 2021; Callaway et al., 2012; Thorne et al., 2014), which is also empirically/anecdotally true for our restoration project marshes (Dave Halsing, personal communication, August, 2023). Locally, active frontal scarp erosion can be a source depending on the marsh (Dusterhoff et al., 2017; Pearce et al., 2021; Beagle et al., 2015), but at this time, no net trend is evident (SFEI and Baye, 2020). Frontal scarp erosion and retreat may become a broad phenomenon as SLR continues. The Pacific Ocean may be a source or a sink depending on the pathway, time scale, and size of sediment particles (Anchor QEA, 2021; Battalio, 2014; Downing-Kunz et al., 2021).

Monitoring fluxes for short periods coupled with a surrogate measure such as time-series turbidity or flow data can help answer some of the remaining questions about the flux at monthly or shorter timescales between subembayments (Livsey et al., 2021) and at the Golden Gate (Erikson et al., 2013). At average annual timescales, a sediment budget can be used as demonstrated recently (McKee et al., 2023). However, going forward, a coupled modeling-monitoring program would be most cost-efficient where measurements are difficult in cross-sections, and for predicting future changes to the sediment in relation to SLR, changing supply, dredge material fate, changes to sand mining, and evolving wetland area (SFEI, 2023; McKee et al., 2023).

MQ#4 How much sediment is passively reaching tidal marshes and restoration projects, and how could the amounts be increased by management actions?

Maintaining the elevation and health of existing tidal marshes and restoring new functional tidal marshes is integral for building resiliency with SLR and fostering a healthy Bay ecosystem into the future. The Baylands Ecosystem Habitat Goals Update (Goals Project, 2015) laid out a vision of maintaining and restoring tidal marshes around the Bay in the coming decades to reach 100,000 acres of tidal marsh along with a suite of other habitats. Building from this, the SFB Shoreline Adaptation Atlas laid out a shared understanding of which measures used in which places could provide effective, multi-benefit, sustainable sea level rise adaptation for the Bay shore (SFEI and SPUR 2019). The Atlas provided maps of Operational Landscape Units (OLUs), a connected geographic area sharing physical characteristics that would benefit from being managed as a unit to provide particular desired ecosystem functions and services. These 30 OLUs, for example the San Leandro OLU, are connected by the flow of water and sediment, as governed by topography, bathymetry, tidal and wave energy, and the sources of the water and sediment.

The WRMP is presently working on a monitoring plan that will include the development of a set of standardized monitoring methods for assessing tidal marsh accretion and slough channel sediment concentrations and the influence of this sediment on rates of accretion and overall elevation change at the scale of OLUs and individual marshes. In addition, USACE is presently preparing a Regional Dredged Material Management Plan (RDMMP) that also considers the OLU framework (Braud et al., 2022). The vision is to lay out a 20-year plan for dredged material management, building from Sediment for Survival (Dusterhoff et al., 2021) and other resources. The plan will describe alternatives for management across a range of conditions, and include ideas like nearshore placement, water column seeding and other pilot efforts to increase sediment supply to marshes by reusing dredged material. In parallel, USACE is undertaking a pilot project to assess the feasibility of nearshore placement of dredged sediment to bolster sediment delivery to mudflats and marshes.

A central question to the RMP, the WRMP, and USACE is: Is there enough sediment to maintain the current extent of existing marshes and address restoration objectives under accelerating SLR? This question was explored by the recent “Sediment for Survival” report which used runoff estimates from climate models and local sediment rating curves to estimate future sediment loads and compare these to sediment demands from SLR and restoration efforts (Dusterhoff et al., 2021). They found that the projected watershed loads will be insufficient to provide for marsh restoration and to maintain marsh elevation as sea level rises. With that new information, the question has now evolved to: Is there enough sediment actually being deposited in the marshes to address restoration objectives? If not, either more sediment sources need to be found, less marsh area can be restored, or restoration designs need to use less sediment. Ultimately additional questions begin to form such as how we can manage marshes and sediment at a landscape scale to support appropriate functions, priority ecosystem services, and climate resilience while protecting shoreline communities, many of them underserved. To explore these difficult issues, we need an improved understanding of the dynamic processes on mudflats, in feeder channels, in tidal sloughs, and on marshes themselves, and how sediment moves from sources in the watersheds to wetlands, and out into the Bay's ESP and back into wetlands (SFEI, 2023). The aerial extent of the ESP relative to marshes that need sediment is an important remaining data gap. Therefore, in addition to the funding in place to support the sediment model development that primarily will be completed to address PCB, nutrients, and CECs questions (Jones et al., 2022), further funding is needed to map the ESP and support the modeling and monitoring that will help with answering important sediment focused questions like these.

MQ#5 What are the concentrations of suspended sediment in the Estuary and its subembayments?

Suspended sediment concentration (SSC) is controlled by resuspension, settling, flocculation, advection, and mixing. SSC is of interest to managers because it controls light penetration in the water column, limits phytoplankton growth, can impact aquatic life, and can transport hydrophobic contaminants (Cloern et al., 2020; Lacy et al., 2020, 2015; Livsey et al., 2021, 2020; Schoellhamer et al., 2007). Sediment characteristics, like settling velocity or how easily flocs are broken apart, impact sediment transport around the Bay and into wetlands (Livsey et al., 2021; Manning and Schoellhamer, 2013). In 1999 a step decrease in SSC occurred in the Bay (Schoellhamer, 2011) leading to concerns that there may now be less sediment available for supporting restoration. For example, for appreciable net sediment transport to occur into a tidal marsh, there has to be a local ESP that supports a consistent fine sediment concentration in the water column relative to flood tide velocity.

There are decades of data for the Bay on the 15-minute variation in SSC at point locations along the axis of the Bay (Buchanan and Morgan, 2014) and a reasonable understanding of average spatial variation in the near surface in SSC based on RMP data (SFEI Data Services Team, 2023). There is less information about the vertical profile of sediment in the water column, flocculation processes and floc size, temporal variability in SSC, and relationships between these water column variables and the ESP, bulk density, and bed erodibility, yet these properties strongly influence sediment transport (Allen et al.,2019; Livsey et al., 2021, 2020). Flocculation is influenced by gradients in physical, chemical, and biologic processes, and in the Bay the primary control appears to be turbulence-induced particle collisions, with sand and biological processes exhibiting secondary controls. As a result, floc size tends to be larger in the South Bay and smaller in Central and San Pablo Bay (Livsey et al., 2020; Manning and Schoellhamer, 2013) although this spatial gradient may have been influenced by the use of floc-cam which does not measure the smaller particles. Earlier work suggested a consistency between floc size and density and consistent floc sizes across the estuary (Ganju et al., 2007). Further work is needed to better resolve uncertainties.

Erodibility, a key control on SSC in the water column, is a poorly quantified variable for the Bay. Yet it is a key model parameter that varies in relation to factors including wave stress, sediment grain size (% sand and % clay), organic matter content, sediment layering, bioturbation, salinity variation and gradients, recent deposition, bed disturbance, cohesion/consolidation, and erosion/winnowing of fines (Allen et al., 2019; Brennan et al., 2002; Egan et al., 2022; Wright et al., 2022). The USGS is presently developing a regression model between grain size and organic carbon using locally available data, which will likely also identify data gaps. A spatial estimate of dry bulk density based on texture and organic carbon may be a suitable proxy for erodibility until better information becomes available although such a proxy has been allusive even after decades of research (Earl Hayter, personal communication, August, 2023). A nimble monitoring program that can provide data at multiple spatial and temporal scales coupled with a flexible grid modeling platform is needed to further resolve Bay physics at the temporal and spatial scales of interest to sediment managers.

4. Sediment Workgroup Science Questions, Priorities, and Collaboration

Since SedWG inception, a number of studies have been completed at the regional scale that help answer the SedWG MQs (McKnight et al., 2020; 2023; Schoellhamer et al., 2018; SFEI, 2023) and the local scale (Anchor QEA, 2021; Downing-Kunz et al., 2021; Hart and Work, 2023;

Livsey et al., 2021, 2020). Going forward, as the needs of the SedWG become more specific in both temporal and spatial scales and more forward-looking, we need a series of modeling and monitoring science questions that translate the MQs into a set of actionable studies that drive a body of progressive information development. Table 1 presents the set of SedWG monitoring/modeling science questions (SQs) that stakeholders and advisors see as the priorities over the next five years. The ranking reflects the opinions of those in attendance at the workgroup meetings in late 2022 and early 2023 and are reflective of diverse interests not just those of the RMP. In addition, the ranking in some cases does not reflect the logical efficient order of scientific investigation; a lower ranked or subordinate question may need to be answered before a higher ranked more central question. The coordination needs column (Table 1) reflects the primary group(s) that share an interest in a similar question and possible funding sources or opportunities to collaborate on funding proposals to granting agencies. Although the priorities will evolve as our understanding of the system improves, this set of science questions provides an important framework for supporting resource allocation decisions, and building stronger collaborations (although collaboration may require additional funds) over the next five years. Although there is some inevitable overlap, the following paragraphs provide more detail on what is intended to be covered under each question.

SQ3.1 How will watershed sediment load to the Bay change?

This question addresses the two main pathways that supply sediment to the Bay: the Sacramento and San Joaquin Rivers via the Delta (154,000 km^2 upstream of Mallard Island) and the local tributaries that drain to the Bay from the nine counties that surround the Bay (8,145 km^2 downstream of Mallard Island). Restoration decisions and water quality are directly linked to estimates of watershed sediment load which is expected to change in the future in relation to changing climate, changes to dams and reservoirs, vegetation cover, and land use. Although regional and subembayment scale sediment loads are needed to support reevaluation of the gross sediment budget for the Bay, loads information is also needed at the scales of priority margin units (PMUs), OLUs, and individual wetland complexes. Given the large sand and mud sediment supply contribution and the lack of recent and suitable sediment loading information for Napa River and Sonoma Creek, a project to address those weaknesses has been added to the Supplemental Environmental Project (SEP) list maintained by the RMP.

Table 1. RMP Sediment Workgroup management questions and priorities.

RMP Sediment workgroup Management Question		Modeling/monitoring science questions (SQ)	Rank	Coordination needs?
MQ#3: What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?	#3.1	How will watershed sediment load to the Bay change in relation to changing watershed and channel management, climate, vegetation cover, and land use??	High	WRMP
	#3.2	What is the flux of sediment through the Golden Gate and other Bay cross-sections and how will this change with estuarine dynamics linked to climate change, changing watershed supply, dredge material fate, sand mining, sea level rise, and wetland restoration?	High	BCDC
	#3.3	What are the main sediment transport processes and pathways within subembayments, including from deep Bay channels to marsh edges?	High	BCDC
	#3.4	Are marsh edges and shorelines undergoing net erosion or progradation in relation to wave energy (wind direction and fetch), mudflat morphology, or other factors and how will erosional dynamics change with changing supply and sea level?	Med	WRMP
	#3.5	What is the current sediment budget and how is the sediment budget changing for each subembayment with climate, land use and sediment management?	Med	BCDC
	#3.6	What are the sources and pathways of coarse sediment to beaches around the Bay, and is there adequate supply under changing conditions?	Low	WRMP/BCDC
MQ#4: How much sediment is passively reaching tidal marshes and restoration projects, and how could the amounts be increased by management actions?	#4.1	What are the best tools to evaluate restoration goals and inform restoration investments considering sediment availability?	High	WRMP
	#4.2	What actions can we undertake to increase deposition rates in restoration sites, and how are these influenced by the main variables that determine sediment deposition rates (SSC, elevation, inundation, wind waves, and others)?	High	WRMP
	#4.3	Is large-scale marsh restoration likely to erode mudflats? What are the potential trade-offs between marshes and mudflats and are any trade-offs consistent around Bay and how will it change through time?	Low	USACE/WRMP
	#4.4	What are the accretion/erosion rates and fluxes between individual marshes, mudflats, and shallow subtidal shoals (locally and regionally) in relation to wave exposure, local sediment supply and other factors, and how is it expected to change with deeper water and other factors associated with sea level rise?	High	WRMP/BCDC
	#4.5	What is the design an integrated monitoring program that will inform future restoration designs (i.e., water	Med	WRMP

RMP Sediment workgroup Management Question		**Modeling/monitoring science questions (SQ)**	**Rank**	**Coordination needs?**
		levels, accretion rates, sediment supply) of both natural and restored marshes?		
MQ#5: What are the concentrations of suspended sediment in the Estuary and its subembayments?	#5.1	What are the predicted trends for suspended sediment concentrations, and how does it vary spatially and temporally around the Bay?	High	WRMP/BCDC
	#5.2	How does bed erodibility vary around the Bay in relation to physical factors such as texture, tides, and waves, and biotic factors such as phytobenthos and bioturbation?	Med	BCDC/USACE
	#5.3	How do flocculation processes and floc sizes vary throughout the Bay in relation to SSC, water column depth, tides, wind, and other drivers, and how do these influences settling velocity?	Med	USACE
	#5.4	What are the concentrations and fluxes of suspended sediment in nearshore areas over tidal cycles, spring and neap tides, and seasonally?	High	WRMP/USACE

SQ3.2 What is the flux of sediment through the Golden Gate and other cross-sections?

Sediment moves around the Bay dynamically in relation to watershed supply, human activities (dredging and disposal, sand mining, wetland restoration), and drivers of estuarine circulation (freshwater inflows, salinity, density gradients, tides, wind, rivers). These movements are only partially understood at this time. Moreover, the effects of climate change—particularly SLR, shifts in salinity patterns, changes in frequency of large pulses of flow and sediment, and increased water temperatures—will likely alter estuarine circulation in the future. Knowledge about flux through key cross-sections is necessary to constrain fluxes between subembayments and at the Golden Gate, which can help constrain subembayment sediment and contaminant budgets and directly link to the sustainability of mudflats and marshes and primary productivity through light attenuation. Given the plan to develop a detailed PCB model based on sediment in San Leandro Bay PMU (Jones et al., 2022), there is an immediate need to complete field-based flux studies in selected cross-sections of San Leandro Bay.

SQ3.3 What are the main sediment transport processes and pathways within subembayments?

Sediment transport to marsh edges directly influences the concentration in the water column during flood tides yet transport pathways (estuarine sediment transport vectors) within each subembayment are not well described. The ESP, the unconsolidated sediment that can be easily resuspended by wind waves, tides, and currents is conceived as the immediately available source of sediment to wetlands. This question aims to support management decisions by mapping out the ESP in the mudflats and sandflats and better defining the circulation patterns for sand and mud sediment both within each subembayment and at the scales of marsh-mudflat complexes, which will help with understanding how sediment is supplied to marsh edges and for predicting which marshes may be more sustainable. Given the complexities of these processes, a project to advance our conceptual models for Bay segments and subembayments has been added to the SEP list. In addition, there is an immediate need for improving our understanding of the erodible sediment pool in the San Leandro Bay OLU and at the subembayment scale more generally; once completed, future versions of the sediment budget can identify the contribution of the ESP in relation to other budget terms.

SQ3.4 Are marsh edges and shorelines undergoing net erosion or progradation?

Marshes can be a large net supply of sediment to an estuary yet there is not a full understanding of the current status of marsh frontal scarps around the Bay. Regardless of the current status, as sea level continues to rise, the energy transfer to frontal marsh scarps will likely increase, potentially causing lateral shifts in the planform position of the marsh. Change can be mapped by comparing repeated aerial and satellite images. The WRMP is planning to do this but if this information could be combined with estimates of height and sediment dry bulk density, estimates of change in marsh sediment volume and mass can be made that would interest the RMP. This question aims to explore shoreline location, volume change and associated mass change, and the driving processes including wave energy (wind direction and fetch), mudflat morphology, sediment supply, and other factors. The question also aims to help predict, at the subembayment scale, which marsh edges will likely erode at thus support an improved understanding of the sediment budget. The information will also support analyses at the OLU scale (SQ 4.4).

SQ3.5 What is the current sediment budget and how is the sediment budget changing?
The Bay sediment budget changes dynamically in relation to changing watershed supply, dredging and dredge disposal, sand mining, SLR, and the increasing tidal prism with wetland restoration. A sediment budget was recently developed for a 20-year average period at a subembayment scale (McKee et al. 2023). Although providing a lot of new information of about the relative magnitudes of each of the budget terms, the budget does not support an understanding of cause and effect; the information needed for management decisions. In addition, the currently available sediment budget does not contain a separate term for the ESP and there are gaps the bathymetric data on the Bay margin that presently preclude this analysis (although there is a project currently on the SEP list to address bathymetric data gaps). This question aims to facilitate collection of additional data to support sediment budgeting and provide managers not only with a gross understanding of the relative size of sources and sinks and if the Bay is a net source or sink to the Pacific Ocean but also how those sources and sinks change spatially at OLU scales and dynamically in relation to climate and anthropogenic drivers.

SQ3.6 What are the sources and pathways of coarse sediment to beaches?
Stable beaches are ones where supplies (from estuarine circulation or augmentation) exceed or nearly equal erosion from wave energy. Coarse sediment supply to beaches is a fundamental knowledge gap for understanding which beaches might be sustained under changing SLR and sand budget elements that might need augmentation in the future. This question aims to explore beach sand sediment budgets and the sources and pathways that sustain sandy beaches,

including the influence of sand mining, dredging and beach proximity to watershed, headland, and ocean sources.

SQ4.1 What are the best tools to evaluate restoration goals and inform restoration investments considering sediment availability?

Presently available information suggests that there is not enough sediment to maintain marsh elevations above rising sea level later this century, which is largely dependent on the rate of SLR yet restoring tidal marshes is forging ahead. This leads to the challenge of either (1) greatly accelerating changes in sediment management, including watershed approaches, to deliver more sediment to marshes and mudflats, (2) reducing expectations of marsh acreage that will persist over time in place and supporting the transition of some marsh areas to mudflats and subtidal habitat, or (3) doing more analysis on the tradeoffs between managing sediment at the scale of an individual marsh-mudflat versus OLU or larger scales. In addition, some marshes have room to migrate inland. Further analysis on how to facilitate this in SFB is needed; for example, is land acquisition needed and where. SQ4.1 aims to explore how restoration decisions will be made and by whom and what information and tools will be needed to support such decisions; ultimately, we need to decide how to balance the use of resources between maintenance of existing marshes, marsh migration, or restoring new marshes.

SQ4.2 What actions can we undertake to increase deposition rates in restoration sites?

Sediment deposition at restoration sites is influenced by a number of variables including the configuration of levee breaches, water column SSC, elevation, tides, inundation, wind waves and resuspension, edge erosion, proximity and connection to local tributary sources, and vegetation type. Understanding the relative importance of these variables at different sites will enable robust model predictions of deposition and enable management of marshes to maximize deposition.

SQ4.3 Is large-scale marsh restoration likely to erode mudflats?

Under limited sediment supply conditions, sediment transport to marshes may cause erosion on nearby mudflats. Experience in the South Bay Salt Pond Restoration Project suggests that this is not occurring. However, this may not be true for all subembayments and all mudflat-marsh complexes and may not remain true with SLR and sediment budget conditions in South Bay. This question aims to provide managers with information about the potential trade-offs between marshes and mudflats and how that may change through time.

SQ4.4 What are the accretion/erosion rates and fluxes between individual marshes, mudflats, and shallow subtidal shoals?

Net accretion or erosion rates and fluxes between the marshes, mudflats, and shallow subtidal shoals of the Bay system vary in relation to wave exposure, local sediment supply, and the ESP. Understanding the morphodynamics (energy and fluxes between these elements) and predicting the sustainability and variability of the existing marsh-mudflat complexes under a changing sea levels and sediment budgets will provide managers with information about the needed supply of sediment between the ESP and marshes of interest.

SQ4.5 What is the design an integrated monitoring program that will inform future restoration designs?

Monitoring is an important component of any adaptive management system. Each tidal marsh is supplied by a unique balance of watershed and Bay sediment that may change over time. An integrated monitoring program is needed to track a representative set of wetlands over a range of temporal and spatial scales and compare marsh change to important thresholds that may trigger a management response to prevent loss or damage, or to enhance recovery. As discussed previously, the WRMP has completed a list of priority monitoring sites and, by late 2023, will have a monitoring plan supported by a set of approved standard monitoring methods for numerous physical and ecological indicators in natural and restored marshes. Although the WRMP is mainly focused on existing marshes, the standard methods should be applicable to newly restored marshes that may not be vegetated and thus if applied will provide the needed data for learning and management adaptation and for improving subsequent designs.

SQ5.1 What are the predicted trends for suspended sediment concentrations?

The spatial distribution of SSC is a critical driver for influencing most other aspects of the physics and biology of the Bay; for example, driving sediment and pollutant transport, influencing food web pollutant exposure, controlling light attenuation, and predicting marsh accretion rates and subtidal vegetation distributions. As discussed earlier, there was a step decrease in SSC in the Bay water column in 1999 in response to a downward trend in sediment loads from the Central Valley. Changing climate and watershed and water management is anticipated to continue to modify sediment loads to the Bay. How this will affect the SSC water column profile remains unclear. This question aims to quantify how SSC varies around the Bay at the subembayment scale and vertically in the water column and how SSC is likely to change in the future. Satellite imagery-based estimates of SSC in combination with hydrodynamic modeling could be used to estimate fluxes and long-term trends (Oliver Fringer, Stanford University, personal communication, August, 2023). A proposal could be developed to pilot this work.

SQ5.2 How does bed erodibility vary around the Bay?

The erodibility of the bed is a key parameter in the in-Bay dynamic sediment transport models, yet at this time it is not well characterized. There are a number of methods for measuring erodibility which, as discussed earlier, is influenced by a number of textural and hydrodynamic factors. A review of methods of measurement and on the likely influential factors to consider for Bay site selection is needed to design a locally relevant field study. This question aims to support the development of improved information on bed erodibility and how it relates to other more easily measured and modeled properties.

SQ5.3 How do flocculation processes and floc sizes vary throughout the Bay?

The concentration of suspended sediment and time that suspended sediment spends in the water column have strong influences on direction and magnitude of transport in relation to tidal oscillation. Disaggregation of macroflocs and flocculation of small primary particles and microflocs strongly influence SSC. Flocculation is influenced by salinity, turbulence, grain size, suspended sediment concentration, organic matter, and biological processes. This question aims to continue to improve our understanding of flocculation processes and size in relation to SSC, water column depth, tides, wind, and other drivers and how these influences settling velocity. This question has direct linkage to estimates of sediment flux between and within subembayments and from deeper channels onto marshes.

SQ5.4 What are the concentrations and fluxes of suspended sediment in nearshore areas?

Sediment transport on and off marshes is strongly influenced by the concentration of suspended sediment in the water column. Concentrations vary over daily, weekly, and monthly tidal cycles, and seasonally in relation to biological cycles, winter season storms, wind, and earth-moon-sun cycles. This question calls for the deployment and maintenance of a network of monitoring equipment strategically placed in nearshore environments in relation to marsh investigations and model calibration needs. Monitoring arrays would likely include turbidity, velocity, water level, and wave height sensors.

5. SMMWP and Preliminary Budget Estimates

Table 2 provides the proposed SMMWP SQs and associated study ideas to address the questions organized in chronological order. A primary factor influencing the order is the timing of the in-Bay sediment dynamic model being developed by the RMP and NMS to quantify current processes in the Bay, with funding from the RMP ($75k), USEPA WQIF ($960k), Supplemental Environmental Project funds ($408k), and additional and funds from the NMS. Both the timeline and budget amounts are estimates shown in Table 2 and subject to change. The SedWG five-year plan and the RMP five-year plan will augment the SMMWP presented here. It should be noted that these are not projects per se but rather questions that will allow RMP scientists and external researchers and modelers to formulate proposals each year. For example, the SEP list maintained by the RMP presently has three SedWG projects; Napa and Sonoma sediment loads, advancement of conceptual models for Bay segments and subembayments, and filling bathymetry data gaps. These are examples of specific projects that fit under the rubric of SQs 3.1, 3.3, and 3.5 respectively. As mentioned above, once it is possible to perform sensitivity analysis with the dynamic in-Bay model (i-BM), this five-year plan may need to be revised to reflect a better understanding of how to continue to develop an integrated modeling-monitoring tool. This might be timely in 2025 or 2026, but in the meantime, the order and costs tabulated below are the best planning estimates.

6. Conclusions

The RMP Sediment Workgroup is transitioning from a primarily field-based program to a coupled modeling and monitoring approach that has the capacity to explore complex questions about the present and future sediment dynamics of the Bay and wetlands. Given the existing modeling and monitoring experience, the DFM model will be used as the initial basis of the approach. MQs 1 and 2 will be the focus of a future planning effort, and so here we focused on MQs 3, 4, and 5, and lay out a series of high priority science questions and provide a proposed order and funding level for a five-year pilot level program. As the program progresses and the coupled modeling and monitoring matures, the findings from studies initiated under the rubric of each of the SQs will feed back into decisions on how to improve aspects of the model with the likelihood that this work plan will need refinement.

Given the commonality of these questions among Bay sediment practitioners and the limitations of RMP funds, this SMMWP was written with the intent of promoting collaboration and

Table 2. Proposed timeline and preliminary budget ($k) estimates for modeling and monitoring elements to address management questions of interest to the wider Bay sediment community. C indicates currently funded by the RMP or grants to the RMP or SFEI/ASC. As time progresses, future iterations will include clarity on how data collected is informing and improving model predictions and how this then drives further data collection.

Modeling/monitoring questions		**Explanation**	**Cost (x $1,000)**				
			2024	**2025**	**2026**	**2027**	**2028**
#3.1	How will watershed load to the Bay change?	Napa and Sonoma field sediment loads ($140k). Watershed modeling ($232k) starting in 2025 done out in front of using the i-BM to predict future sediment dynamics.		82 140	100	50	
#3.2	What is the flux of sediment through the Golden Gate and other Bay cross-sections?	San Leandro Bay flus estimated needed ($100k+); $50k placeholder to model GG flux estimates if further empirical observations are made.	C*	C* 100+	C*	50	
#3.3	What are the main sediment transport processes and pathways within subembayments?	Further conceptual model development has been proposed through a SEP ($50k/subembayment). There is an immediate need for mapping out the ESP in San Leandro Bay ($50k/subembayment).	C**	C** 50+ 50+	C**		
#3.4	Are our marsh edges and shorelines undergoing net erosion or progradation?	Needed periodically to learn when we pass a threshold. To get mass, we need vertical and bulk density.		75	75		
#3.5	What is the current sediment budget and how is the sediment budget changing?	Update and address gaps in bathymetric data ($50-250k). Use i-BM to explore sediment budgets for selected areas.	C	C 50-250	C	50	
#3.6	What is the source and pathway of coarse grain material to beaches?	Explore the sources and pathways of sediment supply to selected beaches.				75	125
#4.1	What is the best tool to evaluate restoration goals and inform restoration investments?	Use the i-BM to explore future tradeoffs.					125
#4.2	What actions can we undertake to increase deposition rates in restoration sites?	Learn more about lessons from existing restoration efforts. Use i-BM to predict future conditions. ***	204			>150	
#4.3	Is large-scale marsh restoration likely to erode mudflats?	Use i-BM to explore future mudflat-marsh sediment budgets in relation to restoration goals. ****				>150	>75

Modeling/monitoring questions		Explanation	Cost (x $1,000)				
			2024	2025	2026	2027	2028
#4.4	What are the accretion/erosion rates and fluxes between individual existing marshes, mudflats, and shallow subtidal shoals?	Further empirical study in 2025/2026 followed by i-BM and marsh modeling. ****		120	140	>150*****	200*****
#4.5	What is the design an integrated monitoring program that will inform future restoration?	This is a charge of the WRMP. Need for additional funding is unknown at this time.	WRMP				
#5.1	What are the predicted trends for suspended sediment concentrations?	Work with Oliver Fringer, Stanford University to apply for funding to pilot the use of satellite data coupled with i-BM then expand in 2028 using the i-BM.		?	?	?	150
#5.2	How does bed erodibility vary around the Bay?	Literature review in 2025 to select methodology. and develop a detailed work plan. Field study in 2026 and 2027 at locations directed by the modeling team.		50	100	100	
#5.3	How do flocculation processes and floc sizes vary throughout the Bay?	Literature review in 2025 to select methodology and develop a detailed work plan. Field study in 2026 and 2027 at locations directed by the modeling team.		50	100	100	
#5.4	What are the concentrations and fluxes of suspended sediment in nearshore areas?	Continued monitoring of nearshore areas as directed by the modeling team.	79	75	75		
		Total	283	>842-1042	>590	>875	>675

* In-Bay modeling project will include fluxes at internal cross-sections on an event and multi-year scale, but climate change time scales and explicit study of the GG are not included.

** In-Bay modeling project. Sediment pathways at the larger embayment scale are included; however, transport to individual marshes edges may not be included at the present resolution.

*** Will require special scenario studies which may take staff resources beyond the current estimates

**** Will require significant changes to the model grid to include marshes and likely additional resources

***** Development of the marsh model (WARMER).

facilitating application for additional grant money. Therefore, purposefully, the SMMWP aims to strike a balance between enough detail to provide a coherent vision while providing enough flexibility to adapt to new priorities and information and to be able to invite in new expertise or utilize new methods as they emerge. In addition, the balance between modeling and monitoring proposed may evolve due to funding limitations or if the models fail to adequately reproduce the complexity and diversity of our Bay-mudflat-marsh environments. This may be somewhat resolved by the SMMWP helping to facilitate improved collaboration between the RMP, NMS, WRMP, BCDC and USACE with additional grant funding support. In some instances, governance and review may need to be reconsidered. Over the short and medium term, we anticipate a need for minor adjustments to this SMMWP each year and a more major update in 2025 or 2026 is anticipated. Input from National Marine Fisheries Service and the State Coastal Conservancy given their interest in Bay sediment management, may be important in near future updates and may help to ensure this planning document is suitable for supporting grant applications to each of these entities.

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