San Francisco Bay Sand Budget, Transport, Provenance, and Bathymetric Change Studies and Potential Physical Effects of Sand Mining Activities

Independent Science Panel Findings Report – Best Available Science

June 3, 2024

Prepared for:

California State Coastal Conservancy on behalf of the San Francisco Bay Conservation and Development Commission

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Executive Summary

The San Francisco Bay Conservation and Development Commission (BCDC), in its mission to protect and enhance San Francisco Bay (Bay) resources along with other regulatory agencies, issues permits to companies seeking to commercially harvest sand from specified areas within its jurisdiction. In April 2015, BCDC approved three permits and, for the purpose of informing future permitting decisions in the region, required the permittees to fund certain scientific studies on physical and biological systems in the Bay and San Francisco and Suisun Bay estuary, and the potential impacts of sand mining on those systems. The studies also tried to address the potential effect of sand mining on the supply of sand to the Pacific Ocean.

This report summarizes the findings from the suite of scientific studies on physical systems conducted by researchers and interpreted by an Independent Science Panel (ISP). The studies were commissioned by BCDC and the California State Coastal Conservancy (SCC) with the concurrence of the ISP, the permittees, and the other regulatory agencies with oversight responsibilities on sand mining activities. This ISP Summary Report documents the ISP's determination of the best available science on physical sand systems in the Bay and western Sacramento-San Joaquin Delta (Delta), and the potential impacts of sand mining on that system, as represented by the conclusions of specified physical sand mining studies. These findings are the product of an iterative interpretation process, involving the scientific study teams, regulatory agency representatives, sand mining company representatives, an independent coordinator, and independent scientists with subject matter expertise. The findings referenced in this report do not address all possible effects of sand mining on physical systems, but they do represent the best available science relative to the sand mining management questions that were developed.

The scientific study scopes addressed core sand mining management questions (posed by BCDC Commissioners in 2015 and later refined by a Sand Studies Technical Advisory Committee) to the extent possible with the time and funding available through the permit-funded process. In particular, the sand studies focused on assessing the physical effects of sand mining in Suisun Bay and Central San Francisco Bay (Central Bay) lease areas on sand and sediment transport and supply within the Bay and the outer coast. Areas of study by the scientific teams included: development of a sand budget, conduct of a bedload transport and bathymetric change analysis, application of a sand transport modeling study, and a petrographic analysis of sand sources to determine their provenance in the broader sand system (fingerprinting studies).

Recognizing the existence of key data gaps, the ISP, charged with identifying the best available science, provided an interpretation and synthesis of new insights that were gained from the studies. This ISP Summary Report groups those findings by local observations of bathymetric change in the vicinity of the mining lease areas as well as regional scale findings of how the sediment budget and fingerprinting studies reveal long-term changes on the time scale of decades or longer. Among the key findings from these reports are the following observations.

Key Observations

1. The volume of mined sand is significant relative to the Bay sand budget (it represents the largest outflow of sand from the Bay), including the net sand discharge to the ocean. Additionally, sand is mined faster than it is replenished; therefore, sand is a non-renewable resource over the long term.

2. Suisun Bay sand is not replenished; thus, it is a finite resource, and the bed is being lowered. The bathymetric, modeling, and budget studies all support this. Sand mining effects in lease areas appear to be highly localized, with effects diminishing with distance from the event location. The effect is pronounced in areas of negligible sand transport such as Suisun Bay, where the depressions caused by mining persist in the bed over time.

3. Central Bay sand is relic (i.e., deposited between 20,000 and 6,000 years ago as sea levels rose and the river discharge point migrated through the Bay to its present location in the Delta) and is part of a large bay-ocean reservoir of sand. Sands derived from the watersheds of the Sacramento and San Joaquin Rivers are no longer a significant source to the Bay and ocean, and large volumes of sand do not move through the system during times of high flows (e.g., wet winters), as was previously assumed. Effects of mining to beaches and ecologically important shoals remain unquantified.

4. San Francisco Bay and the Pacific Ocean share a common pool of sand which sand mining reduces. In each tidal cycle, a huge amount of sand is transported between the Bay and the ocean effectively linking the two sand deposits into a shared pool. The size of this shared pool of sand, and thus the significance of the reduction due to mining, is unknown.

These conclusions represent a significant advancement in the understanding of sand in the Bay. Nevertheless, the ISP noted that some impacts of sand mining were not sufficiently investigated by the studies to draw conclusions and represent key study limitations. The ISP and the study scientists suggested that resolving key information gaps could reduce uncertainty in the assessment of the physical effects of sand mining. The unquantified bi-directional exchange of sand between the Bay and Pacific Ocean; the source and trajectory of sand supplies to Bay beaches and shallow environments; contributions of wave-induced and density-driven sand transport to the overall budget; and the uncharacterized variation of sand transport due to grain size differences are all key information gaps. Continued data collection, surveys, monitoring, and analysis in the lease areas can also inform managers of the evolving response of the Bay floor to sand mining.

This ISP Summary Report is organized in four sections with supplemental Appendices.

- Section 1, Introduction – provides background information on sand mining in the Bay and the western Delta and describes the Report’s purpose.

- Section 2, Study Design and Methodology – describes the development of the sand mining management questions, the selection process for the sand mining study research teams, the research study approaches, key study limitations, and the iterative process to interpret findings.

- Section 3, Synthesis of Findings – presents the local and regional scale findings of the studies, as well as high level responses to the first-tier management questions.
- Section 4, Recommendations for Future Studies and Monitoring – summarizes the remaining key information gaps and study contractors' suggestions for further monitoring, data analysis, and studies to fill in information gaps.
- Appendices include information on the Independent Science Panel, Sand Studies Technical Advisory Committee, study scopes and supporting organizational documents, scientific study deliverables and key finding memos, and discussion summaries from the iterative review process.

The findings presented in this ISP Summary Report are representative of the best available science regarding Bay sand budget, transport, and provenance to date. Best available science is not comprehensive of all possible conditions; instead, it represents the most accurate, reliable, legitimate, and relevant information on the topics listed above and is responsive to new science and changes over time. Best available science is the foundation from which resource managers make planning and policy decisions.

Abbreviations

Bay	San Francisco Bay
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin Delta
BCDC	San Francisco Bay Conservation and Development Commission
Central Bay	Central San Francisco Bay
CSLC	California State Lands Commission
cy	cubic yard
Delta	Sacramento-San Joaquin Delta
ESA	Environmental Science Associates
ISP	Independent Science Panel
Lind	Lind Marine Incorporated
Martin Marietta	Martin Marietta Materials
mcy	million cubic yard
PRC	Public Resources Code
RWQCB	Regional Water Quality Control Board
SCC	California State Coastal Conservancy
SFEI	San Francisco Estuary Institute
South Bay	South San Francisco Bay
STAC	Sand Studies Technical Advisory Committee
UC Davis	University of California, Davis
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTA	University of Texas at Austin

1.0 Introduction

The mission of the San Francisco Bay Conservation and Development Commission (BCDC) is to protect and enhance San Francisco Bay (Bay) and advance the Bay's responsible, productive, and equitable uses for this and future generations (BCDC 2024a). In its role as manager of Bay resources, inclusive of Suisun Marsh and the Bay shoreline (BCDC 2024b), BCDC issues permits within its jurisdiction to sand mining firms to commercially harvest sand for use in the construction industry from specified areas leased from the California State Lands Commission (CSLC) and from one private lease area within the Bay and a portion of the western Sacramento-San Joaquin Delta (Delta). In April 2015, BCDC approved three permits to the sand mining firms Lind Marine Incorporated (Lind) and Lehigh Hanson, Inc. (since acquired by Martin Marietta Materials and hereafter referred to as Martin Marietta), and the two firms operating together as Suisun Associates. The permits together authorized 1.426 million cubic yards of mining annually through 2025. The permits included a condition that required the permittees fund certain scientific studies to increase the understanding of physical and biological systems in the Bay and San Francisco Bay/Sacramento-San Joaquin Delta (Bay-Delta) estuary, and the potential impacts of sand mining on those systems.

This document reports on the preparation of priority sand mining management questions, the design and results of the physical system studies, and an iterative synthesis process that was applied by an Independent Science Panel (ISP) to understand how the study findings answer the priority questions articulated during the studies' design. A roster of ISP members (Bob Battalio, PE; Craig Jones, PhD; John Largier, PhD; David Schoellhamer, PhD; and Paul Work, PhD, PE) and their curriculum vitae are contained in **Appendix A**.

The findings referenced in this report do not address all possible effects of sand mining on physical systems, but they do represent the best available science relative to the sand mining management questions that were addressed.

1.1 Report Purpose

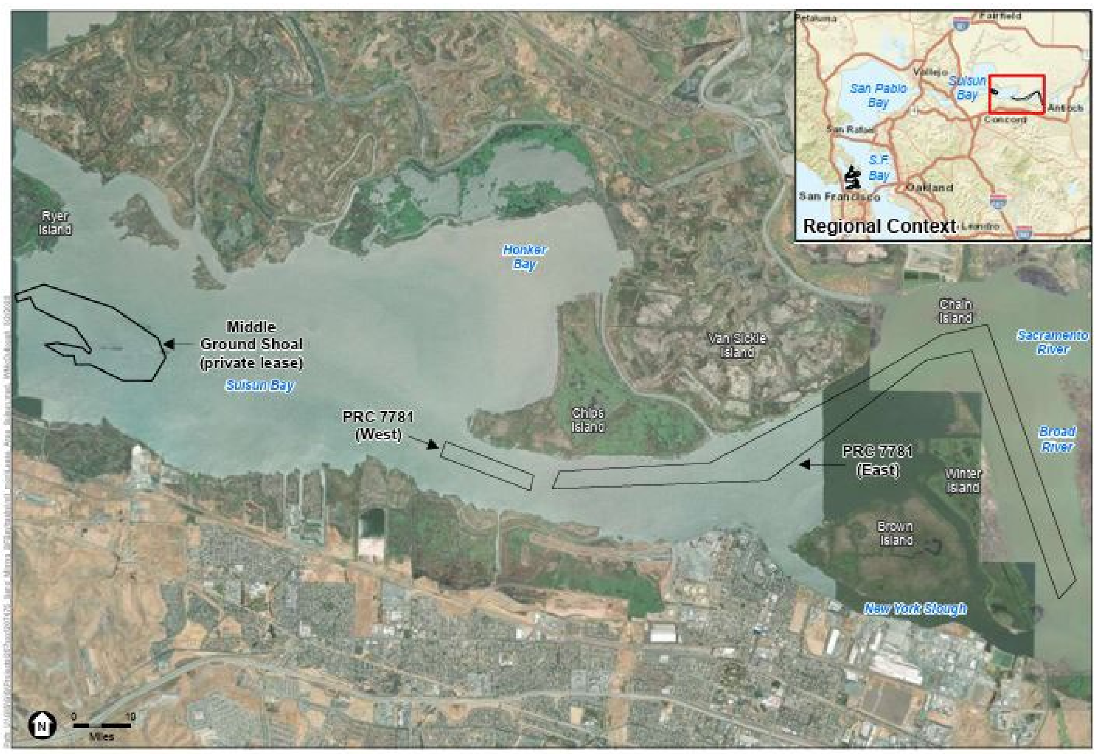
This ISP Summary Report documents the ISP's determination of the best available science on physical sand systems in the Bay and western Delta, and the potential impacts of sand mining on that system, as represented by the conclusions of specified physical sand mining studies. This is one among other relevant documents for use by BCDC in their review of future sand mining activities and permit applications. Appendices to this ISP Summary Report include reports from the physical system studies and more detailed analysis and findings.

1.2 Sand Mining in San Francisco Bay and Western Sacramento-San Joaquin-Delta

Although sand mining in the Bay has occurred for over one hundred years, it has recently increased significantly, starting in the 1990's. The majority of these hydraulically mined sands range 0.0625 – 2.0 millimeters in diameter, with a small percentage that are larger (up to 9.0 millimeters in diameter). These sands are used to supply the Bay Area construction industry, as a component of concrete, asphalt, roads, bridges, and buildings, and as general fill, backfill for utility trenches, or for other construction purposes. Mined sand and gravel have been occasionally used in local beach enhancement projects.

Sand mining currently occurs in the Central San Francisco Bay (Central Bay) and in the Suisun Bay of the western Delta. The Suisun Bay lease area consists of two parcels of submerged lands within a single CSLC-issued lease totaling 938 acres. An additional sand mining lease area of 367 acres (not under the jurisdiction of CSLC) is in the Middle Ground Shoal of Suisun Bay and in the eastern portion of Suisun Channel (Figure 1). The Central Bay lease areas lie between the Golden Gate Bridge, Angel Island, Alcatraz Island, and Crissy Field and encompass 2,601 acres. They consist of nine parcels of submerged lands within four leases currently issued by CSLC (Figure 2).

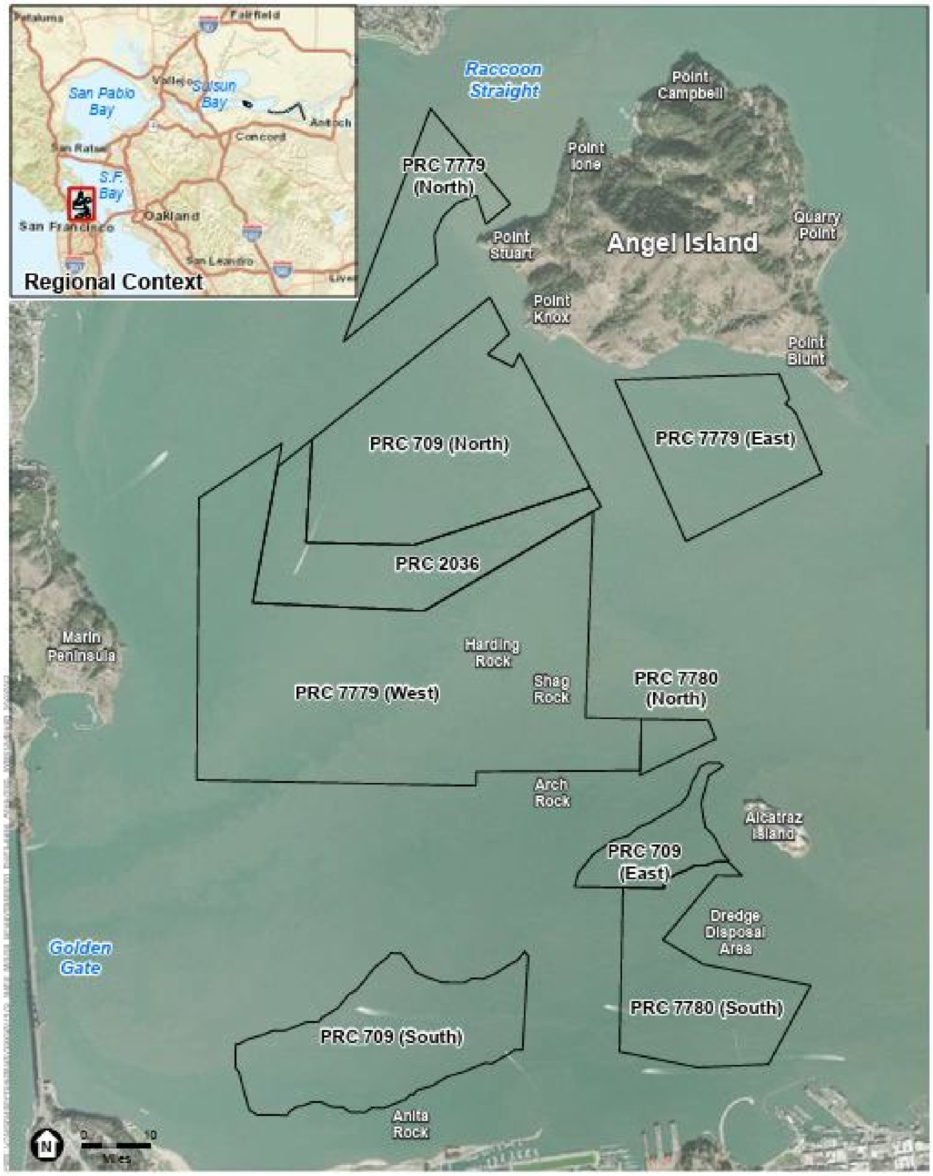
Historically, sand mining occurred in areas outside those that are depicted in Figures 1 and 2, including several lease areas that were active near Carquinez Strait and Alcatraz during the period of analysis used for the physical science studies.[1] Mining companies selectively target shoals that contain sands of certain grain sizes and mine those same areas multiple times in a given season or year. Some lease areas are mined more extensively whereas others have more limited activity.



Source: CSLC 2023

Figure 1. Contemporary Suisun Bay Lease Areas

[1] Lease area sizes, shapes, and configurations are a result of nominations for mining activities at those locations from mining companies that occurred in the distant past. The lease areas have remained fixed in the region even though the mining companies have purchased the rights to them over the years. The exception to this is a change to the lease around Alcatraz due to exclusion of federal lands from the lease area in 2012.



Source: CSLC 2023.

Figure 2. Contemporary Central Bay Lease Areas

Mining operations in the Central Bay lease areas use a hydraulic drag head technique,[2] occurs at water depths ranging from 30 to 90 feet, lasts 3 to 5.5 hours, and results in the removal of an average of 2,100 cy

[2] This technique involves positioning and lowering a hydraulic drag arm into the selected mining area, and once the drag head is within approximately three feet of the sand shoal, the pump is primed, and the drag head is lowered six to 18 inches into the sand shoal. As the sand is mined, a pothole is created around the drag head and as the drag head is pushed further into the substrate, the pothole widens and sand slumps in from the sides of the hole. If there is a sufficient volume of sand in the area, the drag head remains relatively stationary, adjusting as needed over the shoal. If/when the desired grain size of sand is depleted in that area, the barge is moved along with the drag head on the Bay bottom while pumping sand and water, until another pocket of appropriately sized sand is found. The mining continues in this way until the barge is filled.

per event. Mining in the Middle Ground Shoal and Suisun Bay leases uses a pipe dredge technique[3] (e.g., potholing method), occurs at water depths ranging from 15 to 45 feet, lasts 5 to 7.5 hours, and results in the removal of approximately 1,400 cy per event (CSLC 2023).

The McAteer-Petris Act requires any entity that wishes to place or extract materials exceeding $20 in value or substantially change the use of land, water, or structures within BCDC's jurisdiction must secure a permit from the Commission (in addition to any permit required by other relevant jurisdictional authorities). The Act provides that the Commission will grant a permit if it finds the project is consistent with the provision of Act and with the applicable provisions of the San Francisco Bay Plan, or if it is necessary to the health, safety, or welfare of the public in the entire Bay Area (BCDC 2024b.).

On April 16, 2015, BCDC approved three permits, included in **Appendix B**:

- 2013.003.00 for Lind to mine up to 100,000 cy of sand annually from Middle Ground Shoal (Figure 1)
- 2013.004.00 for Martin Marietta to mine up to 1.141 million cubic yards (mcy) of sand annually from Central Bay (Figure 2)
- 2013.005.00 for Suisun Associates (a joint venture between Lind and Martin Marietta) to mine up to 185,000 cy of sand annually from Suisun Channel (Figure 1)

The BCDC permits authorized Lind, Martin Marietta, and Suisun Associates to cumulatively mine 1.426 mcy annually, with a peak of 1.75 mcy of sand in any year if the full volume was not mined in previous years, for a total of up to 14.26 mcy over a ten-year period ending in 2025. Permitted sand mining volumes for each lease area are provided in Table 1.

Table 1. 2015-2025 Permitted Sand Mining Volumes

Lease Area	Lease/Location No.	2015-2025 Annual Permitted Volumes (cy)	Peak Annual Volume (cy)
Central San Francisco Bay	PRC 709: Presidio (South), Point Knox (North), Alcatraz (East) Shoals (Martin Marietta)	170,000	235,000
	PRC 2036 Point Knox Shoal (Martin Marietta)	360,000	450,000
	PRC 7779: Point Knox North, West, and East Shoals (Martin Marietta)	484,000	550,000
	PRC 7780: Alcatraz North and South Shoals (Martin Marietta)	127,000	160,000
	Central San Francisco Bay Total	**1,141,000**	**1,395,000**
Suisun Bay	PRC 7781: Suisun Bay/Western Sacramento-San Joaquin Delta (Lind)	185,000	235,000
	Grossi Middle Ground: BCDC Permit 16-78 (Lind)	100,000	120,000
	Suisun Bay Total	**285,000**	**355,000**
Total Annual Permitted Volume		**1,426,000**	**1,750,000**

Source: BCDC Permits 2013.003.00, 2013.004.00, and 2013.005.00

[3] This technique involves lowering a pipe dredge into the selected sand shoal and inserting it into the sand approximately 18-36 inches. Water is injected to slurry the sand, which is pumped up into the barge. The pipe dredge remains stationary for the full mining event.

In addition to BCDC, the sand mining companies received a lease from CSLC and permits from the San Francisco Bay Regional Water Quality Control Board (RWQCB), and United States Army Corps of Engineers (USACE). CSLC's lease authorized 2.039 mcy of sand mining annually whereas the RWQCB, USACE, and BCDC permits together limit peak and average annual mining volumes to 1.75 mcy and 1.426 mcy respectively, as described above.

2.0 Study Design and Methodology

The management questions informing this report were designed to determine the best available science on potential impacts of sand mining on the physical systems in the Bay and Suisun Bay. Biological and ecological effects were not investigated. BCDC utilizes the best available science as part of their deliberative decision-making processes. They seek objective, accessible, good quality scientific information and data using recognized practices, standards, technologies, and methodologies. For the purposes of the sand mining studies, BCDC's Executive Director, in consultation with the permittees and others, appointed an ISP. The ISP consists of five independent scientists with relevant expertise to guide scientific studies to completion. **Appendix A** includes their curricula vitae.

In addition to the ISP, BCDC's Executive Director also selected a Sand Studies Technical Advisory Committee (STAC) consisting of representatives of the permittees and regulatory and resource agencies as appropriate, and two key stakeholders who expressed an interest in participating. The mining companies requested that two consulting firms also attend the meetings to assist them in understanding the scientific content of the work. **Appendix C** includes the STAC Member Roster. The process by which the STAC and ISP, together, informed the design and methodology of the physical sand mining studies follows in this section.

Lastly, the sand miners provided additional funds to hire a third-party Study Coordinator to support the development of this ISP Summary Report. Stantec Consulting Inc. (Stantec) was selected and has supported the ISP and STAC in facilitating and documenting discussions following completion of studies (described in Section 2.6) using their technical understanding of subject matter and facilitation expertise. Stantec is co-managed by a subset of the STAC that includes BCDC, State Coastal Conservancy (SCC), Lind, and Martin Marietta (formerly Lehigh Hanson, Inc.). The Memorandum of Understanding for co-management between the four parties is attached in **Appendix D**.

2.1 Best Available Science

For these studies, the best available science is not definitive or comprehensive of all possible conditions that affect a particular land use or natural resource management decision. Instead, agencies like BCDC use the best scientific information that is available at a given time to inform related decisions. The best available science changes over time and is responsive to new science. In all cases, the best available science must be accurate and credible, reliable, and legitimate, and relevant or salient for making natural resource and land-use planning, policy, or management decisions.

2.2 Sand Mining Management Questions

In July 2018, the STAC identified a set of management questions regarding sand mining activities and their potential impacts to the Bay and outer coast sand transport (see **Appendix D**). At an over-arching level, the first-tier management questions ask:

1. Is sand mining at existing lease areas, at permitted levels, having a measurable or demonstrable impact on sediment transport and supply within San Francisco Bay?
2. What are the anticipated physical effects of sand mining at permitted levels on sand transport and supply within San Francisco Bay and the outer coast? and
3. Are there other feasible sand mining approaches to consider in San Francisco Bay?

The STAC identified second tier questions (**Appendix D**) that addressed specific elements of the first-tier questions and that, taken together, would build the foundational knowledge bases needed to cumulatively answer the first-tier questions. These questions were developed with the intent of guiding the ISP in recommending appropriate studies or research that would inform future management of mining activities. The questions were not meant to be exhaustive, and the STAC recognized that not all the questions could be researched or addressed with the available time and funds.

ISP discussions of the sand mining management questions are included in **Appendix E**, and their over-arching responses to the first-tier questions are included in Section 3.3 of this report.

2.3 Sand Mining Studies' Researcher Selection

The ISP, with support from the STAC, developed the scopes of work for a suite of physical science studies to address key management questions fundamental to understanding sand mining effects on sand supply and transport. The ISP developed three scopes that outlined the objectives of the studies, management questions to be addressed, and anticipated necessary tasks and deliverables to meet the study objectives:

1. San Francisco Bay Sand Budget, Information Collection, and Synthesis: Review and summarize existing sand-transport and related geophysical literature and bathymetric data for the sand mining lease areas and surrounding areas in Central Bay and within Suisun Channel to update and refine an existing draft sand budget and database for the Bay and adjacent outer coast.
2. Fingerprinting Sand Sources: Conduct petrographic sampling in multiple sand mining lease areas covering approximately 2,061 acres of Central Bay and 1,303 acres of Suisun Bay to identify their provenance in the broader system and determine sand resource availability. Analyze other available sediment samples within the study vicinity to support interpretation of sand sources and deposition patterns over time.
3. Sand Transport Study: Review and interpret recently collected bathymetry data to evaluate bed elevation changes relative to sand mining data, characterize bedforms that imply directions of sand transport in the Bay and the adjacent outer coast, and provide insights as to whether sand mining is influencing sand transport.

Applicants were invited to submit proposals for one or more of the scopes outlined in the request for proposals with a methodology that would achieve the associated scope's objectives.

Following the collaborative development and review process between the STAC and ISP, the study scopes of work were authorized by BCDC and SCC. From July – August of 2020, requests for proposals and qualifications were solicited to the public by the SCC, the agency managing BCDC's permit mitigation funds via a memorandum of understanding. From August to December 2020, proposals were reviewed and scored by the ISP and volunteers from the STAC (SLC, National Oceanic and Atmospheric Administration, California Coastal Commission, Martin Marietta, SCC, and BCDC) based on their qualifications, experience, and proposed methodology. Of those that applied, three study teams were selected for interviews and discussion of their methodology with the ISP and volunteers from the STAC. To best meet the objectives of the studies and the remaining budget, the ISP negotiated each study team's scope of work based on what they determined to be the best methodology to accomplish the necessary objectives. That negotiation resulted in rescoping the proposals to create a set of studies most aligned with the management questions. The study teams adjusted the proposals and agreed to work collaboratively between teams as each study had inter-related components that provided building blocks supporting the other studies.

In Spring of 2021, three study teams were retained to conduct studies funded by the permittees under the terms of their agreements, responsive to the Management Questions. Table 2 lists the researchers by study team.

Table 2. Sand Mining Studies Research Teams

Sand Mining Study Topic	Research Team (Affiliation)
Sand Budget and Bedload Transport	Lester McKee, Tan Zi, Sarah Pearce, Cristina Grosso, Adam Wong, Michael Weaver, Scott Dusterhoff, and Jeremy Lowe (SFEI) Edwin Elias and Floortje Roelvink (Deltares) Bruce Jaffe, Theresa Fregoso, Mathieu Marineau, Christopher Ely, and David Hart (USGS)
Sand Transport Modeling	Aaron Bever and Michael MacWilliams (Anchor QEA)
Fingerprinting Sand Sources	Matthew Malkowski (University of Texas at Austin, previously Stanford) and Zack Sickmann (University of Texas at Austin and Dallas) Bruce Jaffe and Theresa Fregoso (USGS)

Key:
SFEI = San Francisco Estuary Institute
USGS = United States Geological Survey

Additionally, USGS and Deltares collaborated on related work during the period of these studies. While that work was not funded through this effort, the ISP, STAC, and study teams received informational presentations on the SedTRAILS[4] study (Floortje et al. 2023) to visualize sand transport pathways at the Quarterly Research Update Meetings (summaries from which are included in **Appendix F**).

The studies' geographic boundaries were limited to the San Francisco Bay and Suisun Bay areas, between the Delta and Pacific Ocean and including the sand mining areas. The Delta and Pacific Ocean serve as useful traditional boundaries due to the historical information available. The outer coast was excluded from the study area because the complexity of sand transport study required resources beyond those available, and transport dynamics are so active that the effects of sand mining are likely to be obscured. Hence, the

[4] The SedTRAILS study used an existing Delft3D 4 model schematization for the Bay to operate simulations that were then intensively calibrated and validated to model sediment transport pathways by tracking sand waves. Through this process, Deltares assesses the connectivity between the mining areas and the greater West-Central Bay.

focus was inside the Bay closer to the sand mining areas. Note: more on this topic is provided in the Findings section. An exception to these geographic extents is in the fingerprinting study, which extended offshore to include the San Francisco Bar.[5] This exception was made to establish the historical sand supply.

2.4 Researcher Study Approach

The research teams' overarching approach to accomplishing the goals of their respective study scopes are described at a in the subsections to follow. Their detailed scopes of work are included in **Appendix D** and referenced deliverables are in **Appendix G**.

Table 3 describes the referenced deliverables and the naming convention applied for citing each in this report.

Table 3. Deliverable Names and Convention for Referencing in Report

Attachment No. in Appendix G	Full Deliverable/Document Name	Abbreviated Reference Name
1	Research to Understand Impacts of Bay Sand Mining on Sand Transport in San Francisco Bay and the Outer Coast: **Sand Budget and Transport in San Francisco Bay**	McKee et al. 2023
2	Understanding Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Part 3: **Synthesis**	Elias and Roelvink 2023
3	Modeling Sand Transport and the Effect of Sand Mining in San Francisco Bay	Anchor QEA 2023
4	Fingerprinting sand and its transport history through San Francisco Bay: Implications for sand mining and its environmental effects	Malkowski et al. 2023
5.1	Research to Understand Impacts of Bay Sand Mining on Sand Transport in San Francisco Bay and the Outer Coast. Task 1: San Francisco Bay Sand Budget, Information Collection and Synthesis. Subtask 1.1: **Literature review and synthesis**	SFEI 1.1
5.2	Research to Understand Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Subtask 1.2: **Sand supply to San Francisco Bay from the Sacramento and San Joaquin Rivers of the Central Valley, California.**	SFEI 1.2
5.3	Research to Understand Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Task 1: San Francisco Bay Sand Budget, Information Collection and Synthesis. Subtask 1.3: **Sand supply to San Francisco Bay from the local tributaries in the nine urbanized countries that ring the Bay**.	SFEI 1.3
5.4	Research to Understand Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Task 1: San Francisco Bay Sand Budget, Information Collection and Synthesis. Subtask 1.4: **Net sand storage/removal from local tributary flood control channels in the nine county Bay Area**.	SFEI 1.4
N/A[1]	Contributions of erosion, deposition, and human activities to a change in sand storage in the bed of San Francisco Bay, California	USGS 1.5
5.5	Memo: Draft whole Bay mud and sand budgets for San Francisco Bay	SFEI 1.6

[5] The San Francisco Bar refers to a crescentic shoal found several miles seaward of Golden Gate. Sand that is transported seaward by strong tidal currents through Golden Gate is subsequently deposited where these tidal currents slow down. This tidal bar is also modified by wave action and in turn it influences wave energy inshore of the bar and their role in wave-driven transport of sand along the shoreline outside the Bay.

Attachment No. in Appendix G	Full Deliverable/Document Name	Abbreviated Reference Name
5.6	Understanding Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Part 1: **Morphodynamic change and bedform dynamics**	Deltares 2.1
5.7	Understanding Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast. Part 2: **Mining volume area analysis**	Deltares 2.2
6.1	San Francisco Bay Sand Budget Report: Summary Bullets	Key Findings – Sand Budget
6.2	Memo: Understanding Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast	Key Findings - Bedload Transport
6.3	Main Findings from Hydrodynamic and Sediment Transport Modeling of Sand Transport in San Francisco Bay	Key Findings – Sediment Transport Modeling
6.4	Stratigraphy Report – Summary of Key Findings	Key Findings – Fingerprinting

Note:
[1] The USGS report, “Contributions of erosion, deposition, and human activities to a change in sand storage in the bed of San Francisco Bay, California,” was reviewed by the ISP and STAC as a final draft but has not been finalized within USGS’s internal review processes which extend beyond the time frame of this report. The draft is not approved to be included as an attachment.

2.4.1 SAND BUDGET AND BEDLOAD TRANSPORT STUDY

The Sand Budget and Bedload Transport team’s research addressed questions pertaining to the sand budget and the anticipated physical effects of sand mining on sand bedload transport and deposition within the Bay.

2.4.1.1 Sand Budget

A sand budget is a traditional and fundamental means of assessing interventions in sand supply, such as sand mining. The sand budget considers the magnitude of sand mining relative to other loss and gain terms in the budget. By considering the sand budget for different sized areas, it can also quantify the spatial extent (zone of influence) of the intervention. Although this budget is for sand (i.e., coarse sediment), it benefited from prior work on a fine sediment (e.g., silt) budget conducted for the Bay, as well as from recent assessments of sediment yield from local tributaries. A notable summary and list of abstracts for literature on sediment science in the Bay, as well as literature on building sediment budgets in other coastal systems, is included in this study’s literature review.

SFEI prepared an updated sand budget with clearly defined temporal and spatial boundaries, which included estimation of sand supplies entering the Bay from:

- the Delta (using 2011-2019 water year stream gauge data, bed-material samples, and bathymetry, SFEI 1.2),
- local Bay tributaries (based on modeling analysis for water years 1995-2019, SFEI 1.3),
- flood control channels (as reported by channel managers through 2019 as either removed or stored, SFEI 1.4), and

- from net erosion/accretion within the Bay (based on recently available bathymetric data combined with grain size data from previously collected sediment cores, USGS 1.5),

Culminating in a reconciled accounting of the updated, net sand sediment budget for the Bay (SFEI 1.6). In summary, the Sand Budget study team completed the following tasks:

- Conducted a literature review of previous, relevant studies (SFEI 1.1).
- Generated a new estimate of the Central Valley watershed sand supply to the Bay from the Delta (SFEI 1.2).
- Generated a new estimate of sand supply to the Bay from local tributaries of the nine-county Bay Area (SFEI 1.3).
- Quantified net sand storage and removal from flood control channels to support improved estimates of sand supply in the Bay (SFEI 1.4).
- Modeled and calculated sand deposition and erosion within the Bay using bathymetric and grain size data (USGS 1.5).
- Quantified whole-Bay mud and sand sediment budgets (SFEI 1.6).

2.4.1.2 Bedload Transport and Bathymetric Change

While SFEI focused on the sand budget, Deltares studied a portion of the bed changes in the vicinity of the mining lease areas, which were expected to provide the strongest correlation with sand mining owing to the proximity of mining activities and assessed areas. Conceptually, mining perturbs the geometry of the Bay floor, and the responses to mining likely diminish or diffuse with time and distance from the mined areas. Therefore, analysis of bed elevation from repeated bathymetric surveys, together with reported mined volumes, can be used to identify the intensity and direction of sand transport. This approach also took advantage of ongoing data collection and reporting.

Bathymetry surveys collected between 2008 and 2019 (Deltares 2.1) were used to estimate volumetric change in the bedforms and determine the rates of replenishment (i.e., how quickly a depression is filled in) for each mining area (Deltares 2.2). Diffused effects around the mined areas (measured in “rings”) were analyzed as well. The study team could then draw conclusions about the effect of mining on sand transport and particularly whether the removal of sand from mined areas may alter local sand transport patterns and subsequently trap new incoming sediment (Elias and Roelvink 2023).

In summary, the Bedload Transport and Bathymetric Change study team completed the following tasks:

- Inventoried, summarized, and interpreted recently collected bathymetric data from the lease areas and surrounding environs, specifically analyzing bedform measurements around each of the selected mining sites (Deltares 2.1).

- Analyzed mining area volumetric changes to determine sand captured in the depressions left by selected mining activities (Deltares 2.2).
- Determined the implications of sand transport to areas beyond the selected mined areas (Elias and Roelvink 2023).

Deltares and SFEI's work is synthesized in a report on both the sand budget and transport analysis (McKee et al. 2023).

2.4.2 SAND TRANSPORT MODELING STUDY

The Sand Transport Modeling Team applied a numerical model of Bay hydrodynamics (water flow) and sand transport to simulate various scenarios for determining the hypothetical difference in transport pathways and rates, both with and without sand mining.

Their model provided estimates of sand transport, which can occur as bedload or suspended load, to predict the effects of sand mining on transport and deposition/erosion near the mining lease areas and throughout the Bay. Anchor QEA accomplished this by developing model bathymetry to represent existing conditions with sand mining, and comparable conditions which were modified to be representative of conditions under which sand mining had not recently occurred. They then used the UnTRIM Bay-Delta model[6] to simulate sediment transport and hydrodynamics for two separate periods, dry (low Delta outflow) and wet (elevated Delta outflow), to evaluate sand transport during dry and wet conditions.[7] Wave driven sediment transport and circulation were not included. This work modeling sand (coarse sediment) built on existing modeling capability that was previously developed for fine sediment. Anchor QEA coordinated with other study teams to use the same bathymetric dataset, mined sand volumes, and estimated Golden Gate sand flux.

In summary, the Sand Transport Modeling study team completed the following tasks, all of which are related in the Anchor QEA Sediment Transport Modeling Report (Anchor QEA 2023):

- Developed a model bathymetry representative of conditions without recent sand mining (within 1.4 years) by using mined sand volumes to adjust areas of known mining.
- Coordinated with the Sand Budget and Bedload Transport team to use the outputs of the bathymetric data analysis, sand mining volume analysis, and estimated sand flux at the Golden Gate in their model.
- Modeled sediment transport using four scenarios (i.e. wet year and dry year) proposed by the team with input from the ISP to simulate sand transport and predict the rates and directions of transport under different conditions.

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[6] *Unstructured Tidal, Residual, Intertidal Mudflat Model (UnTrim) Bay-Delta Model* is a three-dimensional hydrodynamic model of San Francisco Bay and Sacramento–San Joaquin Delta.
[7] This model was calibrated against data describing suspended sediment concentrations due to lack of data to calibrate or validate computed bed loads (Downing-Kunz et al. 2021, Erikson et al. 2013).

2.4.3 FINGERPRINTING SAND SOURCES STUDY

Prior to these studies, the contemporary sources and supply rates for sand were uncertain. Because the sand minerology was similar to the Sierra mountains, it was presumed that sand was being delivered to the Bay from inland California, via the watersheds of Sacramento and San Joaquin rivers to the Bay, and out to the Pacific Ocean through the Golden Gate.

The Fingerprinting Sand Sources Team analyzed the characteristics of sediment moving through the Bay to interpret the sand sources and dispersal patterns using existing core samples and various geochemical processes (such as detrital zircon geochronology analysis, mass spectrometry, and optically stimulated luminescence) to determine the age and provenance of the samples.

In summary, the Fingerprinting Sand Sources study team completed the following tasks in their work, all of which are related in the Final Report (Malkowski et al. 2023):

- Used a bathychronology tool to help determine which existing core samples would be the most advantageous to sample and analyze to achieve the study objectives.
- Collected subsamples from previously extracted cores, samples from outside the Golden Gate Bridge, and samples from the sand mining lease areas.
- Analyzed these samples in a lab using the above-mentioned geochemical processes, including comparison of the fingerprints to existing geological data sources to understand provenance and age.
- Interpreted these data in conjunction with shallow core sample data collected through previous studies.
- Informed management questions about sand provenance and transport patterns and the associated impacts of sand mining on those processes.

2.5 Limitations

While priority management questions were identified, the time and funds available to carry out the studies in a comprehensive pursuit of the management questions in full was limited. By necessity, not all questions could be addressed. The ISP found the following impacts of sand mining were not sufficiently addressed in the existing studies to respond to corresponding management questions:

- Effects at timescales longer than studied.
- Effects on the way sand moves from subtidal shoals to intertidal flats, marshes, and beaches.
- Effects on Bay-ocean fluxes and thus on beaches along the open coast.
- Alterations to grain size distribution of in-Bay or outer coast deposits.

These and other considerations are further explored in Section 4: Recommendations for Future Studies and Monitoring.

2.6 Iterative Process to Interpret Findings

Throughout the duration of the studies (roughly between April 2021 and April 2023) the STAC and ISP monitored and reviewed the study teams' progress and participated in quarterly research update meetings held with the study contractors. These Quarterly Research Update Meetings provided opportunities for research teams to share progress and interim findings. Because the studies were designed to be cumulative and to build off one another, these quarterly updates were instrumental in facilitating iterative discussions across research teams, members of the ISP, and STAC. Summaries from the Quarterly Research Updates Meetings are included in **Appendix F**.

Following the conclusion of the studies, the ISP held meetings to confer on how the studies' findings related to each other, and what the best available science indicates across the study areas. As part of those discussions, the ISP reviewed and provided comments on how the studies answer the original sand mining management questions. A full record of those discussions is provided in **Appendix E**, and the ISP's summary responses to the Tier 1 questions are included in Section 3.3 below.

Over the course of these studies, members of the ISP have researched and reviewed scientific literature independent of their affiliation to this group. They have also relied on their own expert opinion as leaders in their field to generate a synthesis of findings from these sand mining studies. To the extent practicable, this Summary Report provides reference to those outside studies that have or may have influenced the ISP's analysis.

3.0 Synthesis of Findings

Upon completion of the scientific studies, the ISP compiled and integrated information gained from the studies to summarize the best available science on how sand mining alters sand transport and bathymetry in the Bay.

While the ISP's knowledge is incomplete and uncertainty remains, it provides an interpretation and synthesis of new insights on the impacts of sand mining for consideration by managers of the Bay. The findings are grouped into local and regional scales. Local-scale findings relate primarily to observations of bathymetric change near mining lease areas and to modeling of short-term change (time scales of a year or shorter). Regional scale findings relate to Bay-scale sediment budget studies and fingerprinting sand sources studies that reveal long-term changes (time scales of decades and longer). Primary sources for each finding are provided in parentheses, and the documents are included in **Appendix G**.

3.1 Local Scale Findings

Local-scale findings relate observations of bathymetric change in the vicinity of mining operations to sand transport modeling of short-term changes to shed light on how sand transport and deposition/erosion of sand relate to bed replenishment in the mining areas.

The studies found that each sand mining extraction creates a pothole or depression in the bed and that bathymetric changes dissipate quickly with distance from the mined area. The depression created by mining in a specific area does not fill in much by slumping or localized transport of sand adjacent to the mined area (Deltares 2.2) and over time these depressions merge and will result in a broader lowering of the elevation of the bed in the mined portion of the lease area (Elias and Roelvink 2023). Replenishment rates for these depressions vary depending on the location of these depressions, ranging from 11-28% in a low replenishment area, and 91 to 351% in a high replenishment area (Deltares 2.2).

This change in bed elevation may in turn alter local sand transport and trap new incoming sediment. Where there is no sand transport in the vicinity of a mined area, that area will not fill in and the effect of mining is to create a localized depression that is not filled in. Alternately, where there is significant sand transport through a mined area, that area may fill in quickly, resulting in a sand loss that is not spatially confined. While deposition of sand in a mined area leads to a reduction in sand transported past the mined area, this mining-induced reduction in sand transport decreases with distance from the mined area (Anchor QEA 2023). For example, the effect of Suisun Bay mined areas on sand transport is predominantly limited to Suisun Bay (Anchor QEA 2023).

Recognition of a sand budget implies that sand that fills a mined area will not be transported to other areas. This may cause a deficit elsewhere or reduce the flux from the Bay to the ocean and outer coast. While this effect may be sufficiently diffuse to be negligible at any one location, there is concern for the worst-case scenario that occurs when sand transport to a valuable natural sand resource, such as a beach, is reduced by sand mining upstream of the valuable resource (Barnard et al. 2013, Thornton 2016). However, beaches were not specifically included in the study and the studies did not determine to what extent the transport pathways linked mining areas to beaches.

The ISP concluded that, generally, mining sand from areas that do not replenish might limit the potential for far-reaching effects from sand mining, although it results in pronounced local effects. Conversely, mining from areas of high replenishment or at zones of convergence would have dispersed effects. It is very difficult, however, to establish cause and effect between sand mining and bathymetric change trends due to other confounding factors and significant anthropogenic influences (such as historical hydraulic mining[8]), and potential long-term effects that were not analyzed in these studies.

Mining in Suisun Bay and Central Bay does not have the same effects on sand transport pathways and associated impacts. Central Bay is close to the ocean and influenced by tidal exchange between the bay and ocean, whereas Suisun Bay is close to the source of freshwater inflow to the Bay. Consequently, the two areas are examined separately.

3.1.1 SUISUN BAY LEASE AREAS

Of the areas included in the studies, Suisun Bay lease blocks are among the slowest areas to replenish sand (i.e., fill in). Thus, Suisun Bay lease areas closely resemble the case where sand mining digs a depression that is not filled in and local sand transport is not substantially altered (Deltares 2.2 and Anchor QEA 2023). Over time, the bed elevation has been lowered.

3.1.2 CENTRAL BAY LEASE AREAS

The Central Bay lease areas 7779 West and 7780 North also replenish slowly and are close to the case where sand mining digs a depression that is not filled in and local sand transport is not substantially altered (Deltares 2.2).

Of the areas included in the studies, Central Bay lease area 709 South (709S) has the fastest rate of replenishment and is closest to the case where the mined area fills quickly and sand transport to other locales is reduced by that same amount (Deltares 2.2). Lease area 709S is located on a flood-tide shoal where sand moving along the bed from the west and east converge, creating the shoal and resulting in rapid replenishment from sand mining. This is true more broadly across the flood-tide delta where there is convergent sand transport and sand is readily replaced, precluding localized impacts, and spreading the effects of sand mining over a larger area.

Lease area 2036 in Point Knox Shoal exhibited an intermediate case example, with about 55% replenishment (i.e., the volume of sand deposited is 55% of the volume of sand extracted) from 2008-2019 (Deltares 2.2). In that area, significant and persistent bed deformations were also observed.

[8] Historical hydraulic mining refers to gold mining in California using hydraulic sorting of sediment. This mining occurred in the mid to late 1800s and resulted in increased sediment supply to San Francisco Bay.

3.2 Regional Scale Findings

While sand mining results in small, localized changes in bathymetry and sand transport, these small changes occur hundreds of times over a year and thousands of times over a decade. The regional findings pertain to Bay-scale sediment budget and sand source fingerprinting studies that reveal these long-term changes. It is important to note that the transport patterns of sand and finer sediment (e.g., silts and clays) are not the same (McKee et al. 2023). While a conceptual model[9] of a river system or conveyor belt, where sediment is delivered from inland drainages to the Bay and then out to the ocean, is appropriate for fine sediment, it is not a valid model for sand throughout the Bay. A tidal exchange model with fluxes from ocean to bay and from the bay to the ocean may be more apt for Central Bay, resulting in a coupling between sand deposits in the bay and ocean.

Fundamentally, the net effect of sand mining over decades is a removal of sand from a finite sand budget, which results in less sand elsewhere in the Bay-ocean system. Further, based on the studies conducted, there is a consistent finding that sand is being mined faster than it is being replenished in the Bay (i.e., sand is a non-renewable resource over the long term). While this removal of sand could have effects beyond the Bay (i.e., outer coast), this potential impact is not resolved by these sand studies owing to the dynamic nature of processes coupling in-Bay and out-of-Bay sand reservoirs, the likelihood of parallel fluctuations in sand transport along the open coast, and the potential for multi-decadal time lag before effects are reliably observed. Further, changes in the size and position of the San Francisco Bar as well as effects of sea level rise have unknown implications for sand transport and erosion/accretion, which confound assessment of sand mining impacts near the mouth of the Bay.

The ring analysis, described previously as analysis of the effects around the mined areas (measured in “rings”), generally found that short-term impacts of sand mining on bed elevation were apparent locally but were not discernable with greater distance (i.e., no effect beyond time and spatial scales of ring analysis, Deltares 2.2). At the scale of each of the lease areas, the ISP concluded that the studies do not show discernable evidence of geomorphic effects beyond local mining areas. However, the ISP cautions that, while discernable effects were not observed, it cannot be concluded that those effects will not occur. Further, continued mining in areas of low replenishment may result in bathymetric changes sufficient to alter water flows and sediment transport. This may include effects related to waves and water density that were not included in the study. The ISP expressed interest in better understanding longer-term implications for areas that appear to replenish more slowly, since it is possible that there could be significant impacts.

All sub-embayments, except the lower South San Francisco Bay (South Bay), lost sand from 2001 to 2020 (McKee et al. 2023), including those areas with no sand mining. Sand mining is the largest net loss of sand from the Bay, while loss due to navigational dredging is also a significant loss of sand and transport out to the ocean is uncertain but potentially large (McKee et al. 2023). The quantity of sand removed by mining from

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[9] Prior to these studies, the conceptual model of sediment transport in the Bay was similar to a river system where a “conveyor belt” of sediment was moving from the Bay and discharging to the ocean. These studies indicate that the conveyor belt conceptual model is not indicative of contemporary hydraulics and sediment processes for sand. The contemporary condition is dominated by tidal exchange, especially in Central Bay and near the Golden Gate, where sand moves back and forth with the ebb and flow of the tides. This is called a tidal bay conceptual model. See Malkowski et al. 2023, figure 14A and 14B for examples of the two conceptual models.

2001 to 2020 is about equal to the lowering of the bed during these decades (McKee et al. 2023). This does not necessarily indicate cause and effect or that cessation of sand mining would eliminate Bay erosion, but it does indicate that the magnitude of sand mining is significant.

Sand mining may have an impact on the volume or characteristics of sand supplied to beaches; however, there is not enough information to assess the effect. The lack of an inventory of beach sands is also a known data gap.

The studies concluded with some certainty that the majority of mined sands in Suisun Bay and Central Bay are relic[10,11] (Malkowski et al. 2023). Sands derived from the watersheds of the Sacramento and San Joaquin Rivers are no longer a significant source to the Bay and Pacific Ocean (Malkowski et al. 2023). Flood control channels decrease sand supply and the sand dredged for navigation is estimated to be similar to the tributary sand yield (McKee et al. 2023). The studies also suggested that large volumes of sand do not move through the system during significant high flow, fluvial events (e.g., a wet winter) (Anchor QEA 2023 and McKee et al. 2023).

Sands in the Suisun Bay and Central Bay are likely from separate sources (Malkowski et al. 2023) and there appears to be no sand transported between the sand mining area in Suisun Bay and the sand mining areas in Central Bay. As described previously, Suisun Bay and Central Bay are largely disconnected, and they should be considered separately.

3.2.1 SUISUN BAY LEASE AREA

Almost no sand deposition occurs in the Suisun Bay mining area. The rate of deposition is 1% of what is mined (Deltares), meaning that sand transport is negligible at the landward end of Suisun Bay.

Sand in the Suisun Bay lease area appears to be sourced from local Coast Range drainages, which includes sand input to the Bay from historical hydraulic gold mining. Sand mining is larger than sand inflows (McKee et al. 2023, Figure 5). The sand yield from tributaries does contribute to the sand budget and thus influences the calculated net discharge from the Bay to the ocean (McKee et al. 2023).

[10] "Relic" can refer to sand deposited 20,000 to 6,000 years ago, during a period when sea level rose about 400 feet and the river mouth draining the Central Valley migrated from the vicinity of the Farallon Islands to the present-day Delta inland of the San Francisco Bay. This conceptual framework applies to the Central Bay and nearby Pacific Ocean bed and beaches, and the entire study area in general (Malkowski et al. 2023). "Relic" can also refer to sand deposited before present but sourced from erosion of local watersheds. This conceptual framework applies primarily to the Suisun Bay area (Malkowski et al. 2023). The studies indicate that some relic sand is in transit under existing conditions (e.g., Ocean Beach, Crissy Field Beach, and Presidio Shoal mining areas) while other relic sand is likely not in transit except following disturbance by mining or dredging activities, e.g., Suisun Bay mining area, Central Bay north sand mining areas, and dredging of deep tidal channels in San Francsico Bay (Deltares, 2.1).

[11] A sand mining management question framed "relic" and "new" sands in contrast to one another. The ISP clarified that relic Bay sands could be connoted as "new" to the system in the sense that the resource moves into and around the Bay, even though the sand that is moved is "relic" in terms of its age signature.

3.2.2 CENTRAL BAY LEASE AREAS AND THE GOLDEN GATE

The average rate of recovery of sand in the Central Bay lease areas between 2008-2019 was calculated to range between 14% in Lease 7780N to 141% in Lease 709S (Tables 2-4 to 2-9 in Deltares 2.2). The appropriate conceptual model for sand transport in Central Bay is a tidal bay in which sand is exchanged between the ocean and the bay. Sand is transported in both directions by different processes and the net sand transport is difficult to quantify. Sand transport is driven by complex currents that are affected by tides, water density differences, waves, islands, rock outcrops, and the sand deposits themselves (Elias and Roelvink 2023). Nevertheless, the net sand transport directions found by Deltares in the vicinity of the mining areas are consistent with those found by Barnard et al. (2013).

In each tidal cycle, a huge amount of sand is transported between the Bay and the ocean, but the net effect is much smaller than the tidal influx and efflux. On the time scale of a year, sand that leaves to the ocean is likely a little greater than the amount of sand that enters the Bay (i.e., a net loss of sand from the Bay) (Anchor QEA 2023 and McKee et al. 2023), but not conclusively so. Sand mining reduces this net outflux of sand (Anchor QEA 2023 and McKee et al. 2023), but the effect may be diffuse and locally negligible and the significance of this on the open coast and ocean was not addressed by these studies.

Sand in the Central Bay lease areas is interpreted as relic from a delta, deposited offshore of the Golden Gate during a period of lower sea levels several thousand years ago. A lesser relic source of sand in the Central Bay lease blocks are sands eroded from open-coast shorelines accumulated over the last 15,000 years (Malkowski et al. 2023). The large amount of sand that is exchanged between Central Bay and coastal regions seaward of Golden Gate (Anchor QEA 2023) creates a common pool of sand (Malkowski et al. 2023) which sand mining reduces (McKee et al. 2023). How big the pool of relic sand is and thus the significance of that reduction is unknown.

3.3 Responses to Sand Mining Management Questions

The ISP’s responses to the Tier 1 Management Questions are summarized here. Full responses to the Tier 1 and Tier 2 questions are included in **Appendix E**.

3.3.1 IS SAND MINING AT EXISTING LEASE AREAS, AT PERMITTED LEVELS, HAVING A MEASURABLE OR DEMONSTRABLE IMPACT ON SEDIMENT TRANSPORT AND SUPPLY WITHIN SAN FRANCISCO BAY?

Sand mining at existing lease areas at permitted levels has a measurable and demonstrable impact on the sand budget and bathymetry of the Bay and storage of sand within the lease areas. However, it is more difficult to measure and demonstrate impacts on specific sediment transport and supply processes within the Bay. The effects on sand transport pathways and associated impacts differ between Suisun Bay and Central Bay and they should be examined separately. Sand mining may have an impact on the volume and characteristics of sand supplies to beaches, but there is not enough information to assess this effect. Changes to the way sand moves from subtidal shoals to intertidal flats, marshes, and beaches were also not addressed in the studies and there is no available inventory of regional beach sands. Similarly, while the studies indicate that mining may influence the flux of sand to the outer coast, this potential impact is also not assessed here.

3.3.2 WHAT ARE THE ANTICIPATED PHYSICAL EFFECTS OF SAND MINING AT PERMITTED LEVELS ON SAND TRANSPORT AND SUPPLY WITHIN SAN FRANCISCO BAY AND THE OUTER COAST?

This question was not answered by the sand mining studies except to note that, over the time scales investigated, Central Bay mining removes primarily relic sand at a rate that is equivalent to estimated sand supply from San Pablo Bay and South Bay (0.88 metric tons per year, McKee et al. 2023) and larger than the estimated net sand transport out of the Golden Gate (0.25 metric tons per year). These data, although uncertain, indicate that sand mining may directly reduce sand supply to nearby beaches and sand shoals if that mining occurs within an active sand transport pathway. In addition, sand mining may indirectly reduce sand supply to beaches and sand shoals if mining reduces the quantity of transported sand.

Mining in Suisun Bay does not appear to have a large effect on sand supply to Suisun Bay, San Pablo Bay, and the rest of the Bay.

3.3.3 Are There Other Feasible Sand Mining Approaches to Consider in San Francisco Bay?

The studies did not address this question. Members of the ISP offered considerations for regulators: Mining lease areas that are isolated and do not replenish are more likely to limit or constrain potential far-reaching effects of sand mining. Mining in areas of high replenishment or at zones of convergence, on the other hand, would have a dispersed effect. It may be possible to mine some of the deeper, Meritt sand deposits, or other sands that are dredged for navigation (like at the Port of Oakland or San Francisco Marina), and it may be worthwhile to reuse the coarse sediment from the tributary drainage areas that are trapped and removed for flood management purposes. The ISP acknowledged that mining in those areas may or may not be feasible based on the grain size, grain consistency, or limited available volumes (of order 0.01 metric tons per year). Feedback from sand miners indicates these sources are not practical substitutes.

4.0 Recommendations for Future Studies and Monitoring

Recognizing the limitations of the existing studies and informed by the findings that were obtained, the ISP suggests areas for potential future work. For details on ISP member recommendations for future studies discussed during ISP meetings, refer to ISP Meeting Summaries in **Appendix E.**

4.1 Key Information Gaps

The following are key information gaps that limit the ISP's understanding and ability to assess the effects of sand mining.

Exchange of sand between the Bay and Pacific Ocean: The ISP identifies the net flux of sand at the Golden Gate as the most confounding information gap and potentially most significant. Both the sand budget and numerical modeling found small net seaward sand transport probably within the expected error of those methods, but modeling did not include wave-driven littoral processes that may be important for transport of sand into the Bay. Net sand transport at the Golden Gate is potentially large but remains uncertain and small adjustments in this bi-directional exchange may change the direction of net flux. Conversely, a reduction in sand transport from Bay to ocean has the potential to affect coastal beaches. At the Golden Gate, the contributions of tidal, wave, and density-driven processes to sediment transport are not well quantified.

Sand supply to Bay beaches: Shallow sand deposits in the Bay, such as beaches and shoals, are not quantified sufficiently to include in the sediment budget, and shallow-water processes are not adequately resolved in models. Also, these features are not characterized sufficiently to determine their provenance (i.e., where did the sand come from?) and trajectory (e.g., are the beaches eroding or accreting?). Sand transport in these shallow environments is often dominated by wave forcing, which was not included in the studies. An inventory of beaches and other sand shoals in the Bay is a fundamental step toward assessing potential effects of sand mining on these features. Ideally, the inventory would include characteristics, such as sand grain size, deposit volume, sand samples for assessment of sand sources (e.g., see Fingerprinting Study), and changes over time.

Sand transport pathways not included in these studies: Wave-induced and density-driven sand transport is not well defined in the Bay. The sand transport model focused on tidal circulation and current-driven sediment transport, with limited inclusion of the effects of waves and stratification due to differences in water density. The lack of attention to both wave and stratification effects may result in an underestimation of transport of sand from ocean into the Bay. In addition, suspended sediment is dominated by fine sediment so there is little information on concentrations of suspended sand and there are no measurements of bed load transport (Downing-Kunz et al. 2021, Erikson et al. 2013). Both data gaps preclude robust calibration of formulae and numerical models of sand transport.

Sands and gravels respond to the asymmetry of wave hydrodynamics, causing a net movement in the direction of the waves over shoals. Wave-driven sand transport and accumulation (beaches, shoals) occurs primarily in relatively shallow waters and were not resolved in the studies. In addition, density-driven currents are landward at the bed where most sand transport occurs and thus are expected to cause sand transport in the landward direction. The exclusion of these shallow water transport processes and the exclusion of sand beaches results in uncertainty in the sand budget.

Variation of sand transport caused by grain size: There are a range of sand grain sizes in the sand mining lease areas. Coarser sands are found in the Central Bay mining areas, primarily in the northern lease areas, whereas finer sands are found in the Suisun Bay and southern Central Bay lease areas. Finer sands are more likely to be entrained in suspension and transported longer distances and thus more likely to be transported between the mining areas and beaches. Coarser sands and gravels are likely moved only along the bed (not in sustained suspension) and are likely not in active transport beyond the extent of the deposits. Medium to coarser sands are more prevalent in beaches. However, the sand transport model used a single representative sand grain size of 0.25 millimeters. The use of a single grain size likely under-represents sand transport in suspension, obscures the effect of sand mining on beaches, and reduces the accuracy of the bed load transport estimates. Understanding how grain size affects sand transport can help determine whether or not mining specific grain sizes affects coastal erosion.

4.2 Future Studies, Monitoring, and Data Analysis

Future studies: Future studies should be designed to fill the information gaps identified in section 4.1. The identified gaps are related and likely need to be addressed concurrently to fill them.

Specific ideas for future studies from the study teams: Each study discusses future work needed to improve their study and fill information gaps.

- **Sand Budget and Bedload Transport Study**
    - ***Sand Budget*** – Collect a set of representative dry bulk density data in mining lease and dredging areas; complete field studies to make flux estimates of suspended and bedload sand at the Golden Gate Bridge and Suisun - San Pablo bays boundaries; fill data gaps in modern bathymetry of the Bay; conduct a scale-cascade analysis of the Central Bay; and conduct a fifth-order micro-scale analysis using a dynamic model constrained by the scale-cascade sediment budget-based analysis to determine the pathways of sand and the mining influences on those pathways (Key Findings - Sand Budget).
    - ***Bedload Transport and Bathymetric Change*** – Continue more frequent bathymetric measurements of individual mining areas to create long-term datasets that will confirm observed relations between mining and morphodynamic change, and that will improve understanding of morphodynamic system interactions (e.g., diffusion effects of mining to the surrounding shoals) (Elias and Roelvink 2023).
- **Sand Transport Modeling Study** – Conduct additional studies focused on measuring sand transport in the Bay and the transport of sand directly supplied to the Bay by local tributaries, to and past head of tide, to address limitations of current hydrodynamic and sediment transport modeling associated

with lack of available data on sand transport for model calibration and validation (Key Findings - Sediment Transport Modeling).

- **Fingerprinting Sand Sources Study** – Determine the primary source of sand to Suisun Bay, the residence time of sand in each of the bays, and acquire deep cores to determine the pre-anthropogenic natural sediment routing patterns and the magnitude of anthropogenic impacts on sand sourcing and transport through the Bay (Malkowski et al. 2023).

Continue surveys of lease areas and collection of mining data: Surveys, repeated in time, combined with mining data, allow for determining the effect of mining on the lease areas. These data have been and will be valuable for present and future sand mining studies. Additional data on grain sizes mined would be useful. In addition, improved estimates of sand loss could be developed based on more frequent surveys of the lease areas and occasional broader regional surveys.

Ongoing analysis and periodic review of surveys and mining data: Economic and regulatory factors that affect mining and climate and geomorphic factors that affect sand transport provide an ongoing set of experiments related to the response of the Bay floor to mining. Ongoing analysis of data will provide ongoing science-based information to managers.

5.0 Glossary

bathychronology	Method of visualizing sediment layers and determining sediment gains and losses over time.[12]
bathymetry	The depths (elevations) and changes to the ocean floor.[13]
bathymetric change analysis	A method of analyzing these changes over time to determine patterns of erosion and deposition of sediment to the ocean or bay floor.[14]
bay-ocean fluxes	Quantity of sand and sediment moving between the San Fransisco Bay and the Pacific Ocean, typically at the Golden Gate Narrows (vicinity of the Golden Gate Bridge).
bedload transport	Movement of individual particles rolling, sliding, or jumping along the bed.[15]
boundary conditions	Known conditions at the boundaries of a region being modeled that drive the model, e.g., river flow and ocean tide.
bulk density	The total mass of mineral and organic sediment within a defined volume. (SFEI).
density-driven	Ocean water is saltier and thus denser than freshwater. The difference in water density along an estuary favors landward currents near the bed and seaward currents near the surface. Density-driven sand transport refers to the difference in sand transport occurring in the presence of water density differences and that which would occur in the absence of density differences.
deposition	The laying down of sediment carried by wind, flowing water, the sea, or ice.
depression	A place or part that is lower than the surrounding area: a depressed place or part, in this case created by mining equipment. (www.merriam-webster.com)
detrital zircon geochronology	The science of analyzing the age of zircons deposited within a sedimentary unit by examining their inherent radioisotopes. Zircon is a common trace mineral found in most granite and felsic igneous rocks.[16]

[12] USGS (2005). Bathychronology: Reconstructing Historical Sedimentation from Bathymetric Data in a GIS. https://pubs.usgs.gov/of/2005/1273/of2005-1273.pdf
[13] NOAA (2023). What is Bathymetry?
[14] USGS (2023). Bathymetric change analysis in San Francisco Bay, California, from 1971 to 2020. https://usgs.gov/data/bathymetric-change-analysis-san-francisco-bay-california-1971-2020
[15] Rickets, B. (2020). www.geological-digressions.com/sediment-transport-bedload-and-suspension-load
[16] Wikipedia (2024). Detrital zircon geochronology. https://en.wikipedia.org/wiki/Detrital_zircon_geochronology

ebb-tidal delta	Sand deposition on seaward side of a narrow channel where ebb tidal current slows down and sand is deposited onto the shallow sandy bed, i.e., seaward of San Francisco Bay, outside of the Golden Gate.[17]
environ	The area surrounding a place.
flood-tidal delta shoals	Sand deposition on landward side of a narrow channel where flood tidal current slows down and sand is deposited onto the bed shallow sandy bed i.e., at the bayward side of the inlet channel in San Francisco Bay.[18]
fingerprinting	A technique used to trace sand dispersal pathways in natural sedimentary systems by using the compositional “fingerprints” from the unique surface geology in the catchment from which the sand was eroded.[19]
flux/sand flux	Quantity of water, sand, or sediment in motion at a specific location. Sand flux refers to sand flowing in or out of a natural sedimentary system.
hydrodynamics	A branch of physics that deals with the processes that control water motion and the associated forces acting on solid bodies immersed in flowing water.[20]
morphodynamics	The study of processes controlling landscape changes due to erosion and sedimentation.[21]
net sand discharge	The overall volume of sand that is moved from one system into another over a given period of time.
relic sand	Sand deposited 3,000 to 10,000 years ago during the post-glacial period of sea level rise to present levels (Malkowski et al. 2023) and differentiates that sand from sand originating from shoreline erosion or river-borne supplies over recent decades/centuries.
reconciled accounting	A procedure used to describe the sand budget process that compares sets of records to check that the figures are correct and used once.
sand budget	A quantitative tool to track the gain or loss of sand from a defined region and balance this with the net accumulation of sand in that region (positive or negative); this is a specific form of a mass budget based on the principle of conservation of mass.

[17] Holzhauer, H. et al. (2022). The geomorphology of an ebb-tidal-delta linked to benthic species distribution and functionality. Ocean and Coastal Management. https://www.sciencedirect.com/science/article/pii/S096456912100421X
[18] *Ibid*
[19] Sickmann, Z.T., Lammers, N.C. & Torres (2023). A. Fingerprinting construction sand-supply networks for traceable sourcing. Commun Earth Environ 4, 405 https://doi.org/10.1038/s43247-023-01071-218
[20] Merriam-Webster. (n.d.). Hydrodynamics. In Merriam-Webster.com dictionary. Retrieved May 14, 2024. https://www.merriam-webster.com/dictionary/hydrodynamics
[21] Wiktionary (2023). Definition: morphodynamic. The Free Dictionary. https://en.wiktionary.org/wiki/morphodynamic

sand transport modeling study	The use of computational modeling to simulate the movement and settlement of sand (or sediment) in fluids, such as water and air.[22]
sediment yield	the amount of sediment per unit area removed from a watershed by flowing water during a specific period of time.[23]
stratigraphy	The study of "sedimentary rocks and layers, and how they relate to geologic time."[24]
suspended load	Sediment suspended in a water body by turbulence results in a flux of sediment that is refer to as suspended load. This does not include 'bed load' (see above). Suspended load generally consists of fine sand, silt and clay size particles although larger particles (coarse sand) may be transported in suspension in highly turbulent flows.[25]
temporal boundary	A starting or finishing time, in this case for developing a sand budget.
spatial boundary	A real or imaginary line separating two spatial regions.
transport dynamics	Referring generally to the processes that cause sediment transport.
transport pathways	Areas in a body of water where currents of a certain velocity occur with enough frequency or consistency to enable movement of sediment along a particular pathway or direction; Transport Pathways link sand sources (eroding areas) and sinks (e.g., depositional areas).
wave-induced sand transport	Movement of sand due to wave forcing.
zone of influence	The area in which an activity could directly or indirectly impact part of the environment.

[22] Zhang, W. (2014). Sediment Transport Models. In: Harff, J., Meschede, M., Petersen, S., Thiede, J. (eds) Encyclopedia of Marine Geosciences. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6644-0_176-1
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[24] Source: Hauptvogel, D., Sisson, V. (Currators). (N.d.). 1.6: Stratigraphy, LibreTexts, GEOSCIENCES. https://geo.libretexts.org/Bookshelves/Geography_(Physical)/The_Story_of_Earth_-_An_Observational_Guide_(Hauptvogel_and_Sisson)/01%3A_Labs/1.06%3A_Stratigraphy
[25] Fondriest Environmental, Inc. (2014). "Sediment Transport and Deposition." Fundamentals of Environmental Measurements. https://www.fondriest.com/environmental-measurements/parameters/hydrology/sediment-transport-deposition

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APPENDIX A

Independent Science Panel Members

APPENDIX B

BCDC Permits

APPENDIX C

Sand Studies Technical Advisory Committee Member Roster

APPENDIX D

Study Scopes and Supporting Documents

APPENDIX E

Independent Science Panel Report Development Meeting Summaries and Discussion/Responses to Sand Mining Management Questions

APPENDIX F

Quarterly Research Update Meeting Summaries

APPENDIX G

Study Deliverables and Key Findings

APPENDIX H

STAC Comment Letters