

# Strategic approaches to sediment management for restoration of a deltaic plain

By

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## ABSTRACT

Sediment resources are essential to fulfill the State of Louisiana's commitment to implement a Coastal Master Plan (CMP) to mitigate its chronic land loss, protect more than 2 million people who live in the coastal zone, and to save Louisiana's rapidly disappearing complex and fragile ecosystem. With increasing rates of sea level rise and increased storm intensities along with continuing subsidence, the future quantity of sediment needed for ecosystem restoration will significantly increase, and at the same time, the accessibility to the sediment resources will become much more technologically challenging and cost prohibitive. These devastating environmental circumstances will compound the complexities of a sustainable ecosystem restoration in coastal Louisiana. Restoration projects must be robust enough (using adequate compatible sediment) to survive future environmental scenarios while the quantity of actively captured sediment resources available for critical restoration projects is likely to decrease, rendering the dredging and transporting of these sediment resources increasingly difficult and costly. These challenges will be an opportunity for Louisiana to utilize more sustainable, passively captured sediment (i.e. using large sediment diversions from the Mississippi River) to help offset limitations concerning actively harvesting sediment and to build and sustain wetlands in coastal Louisiana. Although any large-scale and meaningful restoration of the Louisiana coastal plain must involve sediments from the Mississippi River, the scope of this paper is restricted to offshore sediment resources. A strategic approach to optimize utilization of sediment resources includes minimizing handling and transport costs by first locating potential sediment sources and then identifying the most cost-effective way of using that sediment resource for

restoration. The project cost and its success are defined by the sediment selection process. Thus, it is suggested that improvements in planning and management of multiple-use conflicts be based on regional understandings of sediment resources for an approach that maximizes benefits. The Louisiana Sediment Management Plan (LASMP) was conceptualized and formulated to improve planning and coordination of sediment utilization in Louisiana. This plan has evolved and has been adaptively managed in the absence of any prototype. Restoration activities are further complicated by competing interests and multiple uses of limited sediment resources. To maximize the availability of offshore sediment, the state is collaborating with the Bureau of Ocean Energy Management (BOEM) and engaging with other stakeholders in deciding the fate of decommissioned pipelines and to strategically plan the installation of new pipelines in offshore areas identified as significant sediment resources with the intent of protecting identified sediment resources for future use. Future offshore wind-farms may pose new challenges but simultaneously offer opportunities for conflict resolution via stakeholder engagement. For the past two decades the State of Louisiana/Coastal Protection and Restoration Authority (CPRA) of Louisiana has developed a considerable institutional knowledge base and expertise and improved the art and science of sediment management. A robust process has been adaptively developed with interagency collaboration and coordination to resolve conflicts/issues concerning obstacles to resource access. LASMP is not only a template for sediment management for coastal restoration, but also provides guidance for stakeholder engagement and conflict resolution for competing needs of sea-floor resources especially in Northern Gulf of Mexico (NGOM).

**KEYWORDS:** Beneficial Use of Dredged Material (BUDM), Coastal Master Plan (CMP), coastal restoration, conflict resolution, habitat restoration, Louisiana Sand Resources Database (LASARD), Louisiana Sediment Management Plan (LASMP), Mississippi River Deltaic Plain (MRDP), sedimentological restoration, stakeholder engagement.

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Coastal erosion is a major global problem and is most acutely felt in low-lying, developed deltaic plains where coastal communities and infrastructures are threatened by river flooding, storm surge flooding, sea level rise and rapid subsidence. Sediment is the thread between the river catchments and the delta plains. Management activities, such as dam or reservoir construction, can limit the amount of sediment that reaches coastal deltas and can affect the sustainability of these highly productive but vulnerable areas. Anthropogenic interventions by management of the Mississippi River have exacerbated land

loss in the Mississippi River Deltaic Plain (MRDP). Louisiana's coastline, especially the MRDP is experiencing some of the most extreme erosion rates and land subsidence in the nation (ACRE 2021; CPRA 2021; Olson and Suski 2021). Consequently, it requires urgent mitigative actions to reestablish a sustainable coastal ecosystem (CPRA 2017). Ecosystem restoration in coastal Louisiana depends heavily on the appropriate strategies adopted for robust large-scale sedimentological restoration (Khalil *et al.* 2018a) including both active and passive methods to harvest sediment. This includes harvesting available sediment reserves

and utilizing renewable sediment supplies to nourish and maintain critical habitats. Such an effort will involve enormous sediment volumes and cannot be systematically and efficiently implemented without a robust sediment management plan. A comprehensive Louisiana Sediment Management Plan (LASMP) was initiated that integrates various sediment input mechanisms including beneficial use of sediment dredged annually from navigational channels, harvesting restoration-compatible sediment (sand/mixed sediment) deposits from the Mississippi River and nearshore/offshore Gulf of Mexico, and through the use of large freshwater/sediment diversion projects from the Mississippi River (Khalil *et al.* 2010; Underwood 2012; Khalil and Freeman 2014; Underwood *et al.* 2015).

Khalil *et al.* 2010 has asserted that almost all researchers, managers, and planners realize and agree that any large-scale and meaningful restoration of the Louisiana coastal plain must *per force* involve sediments from the Mississippi River. In fact, the renewable fluvial sediment resources along with sediment diversions, and Beneficial Use of Dredged Material (BUDM) are critical elements of sediment management in Louisiana. In addition, extensive numerical modeling supports State of Louisiana Coastal Protection and Restoration Authority's (CPRA) selection of the "Mid-Barataria Sediment Diversion" (Barataria Basin) and "Mid-Breton Sediment Diversion" (Breton Sound) projects, originally included in the 2012 Coastal Master Plan among several large-scale river diversions designed to reconnect the river to its coastal plain. Predictive models also identify marsh creation projects, in addition to river diversions, as "High-Performing" for future land building (Killebrew and Khalil 2018). Moreover, these efforts must consider and be sensitive to other uses of the river (e.g. navigation) as well as the wetlands that the diversions will influence (e.g. fisheries, endangered species, etc.). Despite the importance of renewable fluvial sediment resources and sediment diversions, the scope of this paper is restricted mainly to the use of offshore sediment resources.

To address concerns related to coastal land loss and flooding, CPRA has been charged with the daunting task of mitigating land loss and providing for the

restoration of coastal Louisiana's fragile ecosystem. CPRA has taken appropriate measures and has developed a long-term (50-year forward-looking) program to restore Louisiana's coast. Under this program, CPRA is now required to develop an update to the Coastal Master Plan (CMP) every six years that describes the issues facing coastal Louisiana as well as the strategies, projects, timeframes, and cost needed to restore and protect this unique and valuable resource. The 2017 CMP recommended a number of projects designed to build and maintain coastal land, reduce flood risk, and improve sustainability of the coast, while balancing short-term needs against long-term goals (CPRA 2017). This CMP includes 124 projects to build or maintain more than 800 mi<sup>2</sup> (2,072 km<sup>2</sup>) of land over the next 50 years. Many of these projects recommend using either active or passive means of harvesting sediment for soft engineering strategies to create and restore marshes, ridges, barrier islands, and back barrier marshes on a regional scale.

The success of Louisiana's coastal restoration effort and the CMP will depend on locating sufficient volumes of sand and mixed sediment (compatible sediment) that are suitable for barrier island, marsh habitat, and ridge restoration, and are extractable or otherwise harvestable at acceptable costs (e.g. Finkl and Khalil 2005). Building, maintenance, and dissolution of the coastal landscape is primarily a mass-balance between sediment input and accommodation space created from various natural and anthropogenic causes of land loss (Khalil *et al.* 2018a). The restoration of Louisiana's ecosystem is complex in the sense that it will require a balance of sedimentological restoration (to replace/restore geomorphic features), ecological restoration (for restoration/maintenance of ecological functions), and a restoration of processes (delta-building). The infusion and emplacement of sediment serves a dual purpose — it restores and creates habitats and at the same time mitigates/offsets perennial land-loss by filling the accommodation space/void created by land loss. It is generally agreed that the sediment needed to offset the land-loss should be brought in from outside sources/system viz. offshore (non-renewable) or the Lower Mississippi River (renewable). In collaboration with the Bureau of Ocean Energy Management (BOEM) and other state, federal and lo-

cal partners, CPRA has been dredging/emplacing offshore sand/sediment for barrier island restoration for decades with great success.

As the need for restoration-quality sediment increases in the near future, greater emphasis is being placed on using renewable fluvial sediment (sediment diversions) to passively build and maintain land in addition to using non-renewable offshore sediment deposits to actively build land. As stated above, one of the most important aspects of ecosystem restoration is adding sediment from outside the system to offset land-loss. If the proposed land/habitats were to be built/restored by dredging the sediment from within the system (e.g. bays) itself, we would not be adding, but rather merely redistributing sediment.

### LOUISIANA'S SEDIMENT NEEDS AND ITS CHALLENGES

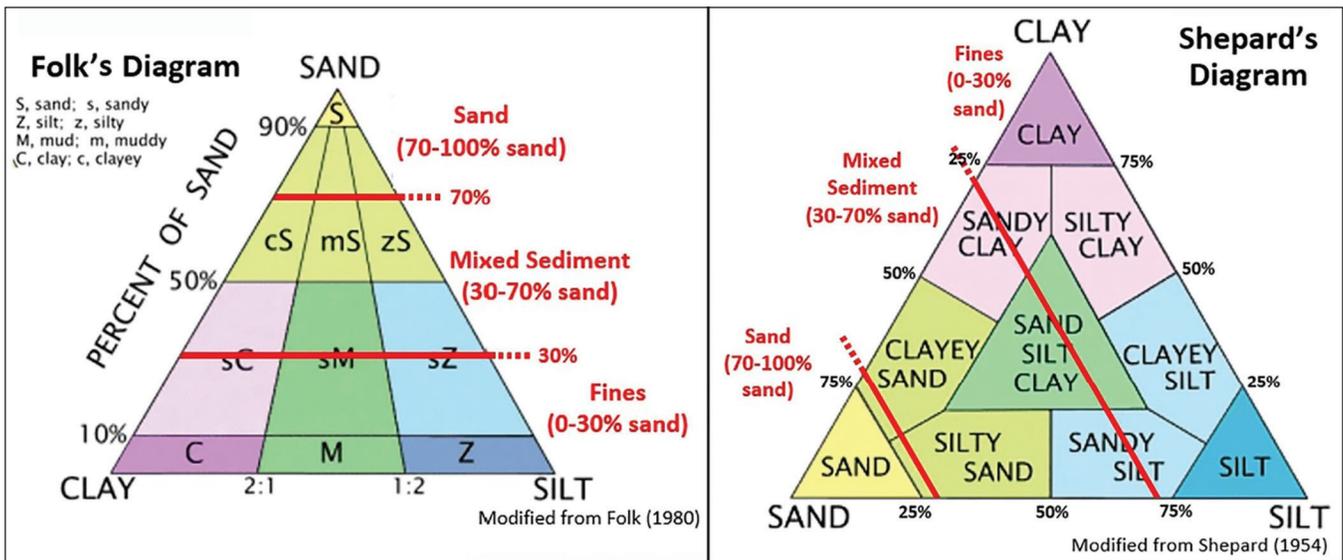
Coastal Louisiana is facing an ecocatastrophe (Khalil *et al.* 2020) due to the continued extreme land loss and its impact on the environment, people, society, culture, and industry of this unique area. The sedimentological aspect of ecosystem restoration needs to be very robust to be sustainable for coastal Louisiana in order to offset not only historical but also ongoing and future land loss. Approximate quantities of restoration-compatible sediment to help offset land/sediment losses are described below:

1) **Near-term sediment need** (current/near future: next five years) = ~148-160 million cubic yards (MCY) (113-122 million cubic meters [MCM]).

2) **Short-term sediment need** (next 10-15 years) = ~1-1.2 billion cubic yards (BCY) (764-917 MCM)

3) **Long-term sediment need** (next 50 years) = In order to offset predicted land loss under both moderate and less optimistic scenarios modeled in the 2017 CMP, it is estimated that between 14 and 24 BCY (11 and 18 BCM) of sediment will be needed (Blum and Roberts 2009; Morton *et al.* 2010; Khalil *et al.* 2018a).

These sediment needs (especially short-term and long-term needs) are first order approximations and subject to change with acquisition and availability of new geoscientific and Relative Sea Level Rise (RSLR) data. With future escalations in sea level rise and increased storm in-



**Figure 1. Various sediment types modified after Folk (1980) (left panel) and Shepard (1954) (right panel) sediment classification systems.**

tensities, the quantity of sediment needed for a sustainable restoration will exponentially increase, whereas at the same time the accessibility, especially to the offshore sediment resources, will become much more challenging (Khalil and Freeman 2014; Khalil *et al.* 2018a). Furthermore, ecosystem restoration, with the main objective of building land, cannot be accomplished by using sand only. There are not enough sand resources from outside of the system to fulfill this requirement. Mixed sediment has been used for ecosystem restoration in Louisiana, especially for marsh platform creation, for decades and is generally considered superior to solely fine-grained sediment. The higher granularity of mixed sediment helps not only in constructability (by reduced dispersion) but in predictability of the final marsh-surface elevation. Concurrently finer sediment once compacted is more resistant to erosion.

**Importance of low-grade sand/mixed sediment in Louisiana restoration-definition of sediment types**

As previously discussed, ecosystem restoration in coastal Louisiana requires a substantial amount of mixed sediment which is defined as a mixture of sand and fines (silt/clay) in which the sand fraction ranges between 30%-70% and fines constitute the remainder. It should be noted that coastal Louisiana itself was built with mixed sediments from the deposition and reworking of riverine sediments through the deltaic cycles of the Mississippi River. CPRA has adopted very broad-based definitions for sand, mixed sediment, and fines exclusively for the purpose of restoration in Louisiana. These definitions are modified after Folk (1980) and Shepard (1954) by adjusting the limits of sand, silt, and clay fractions (Figure 1). Sediment type classifications used for ecosystem restoration are defined in Table 1.

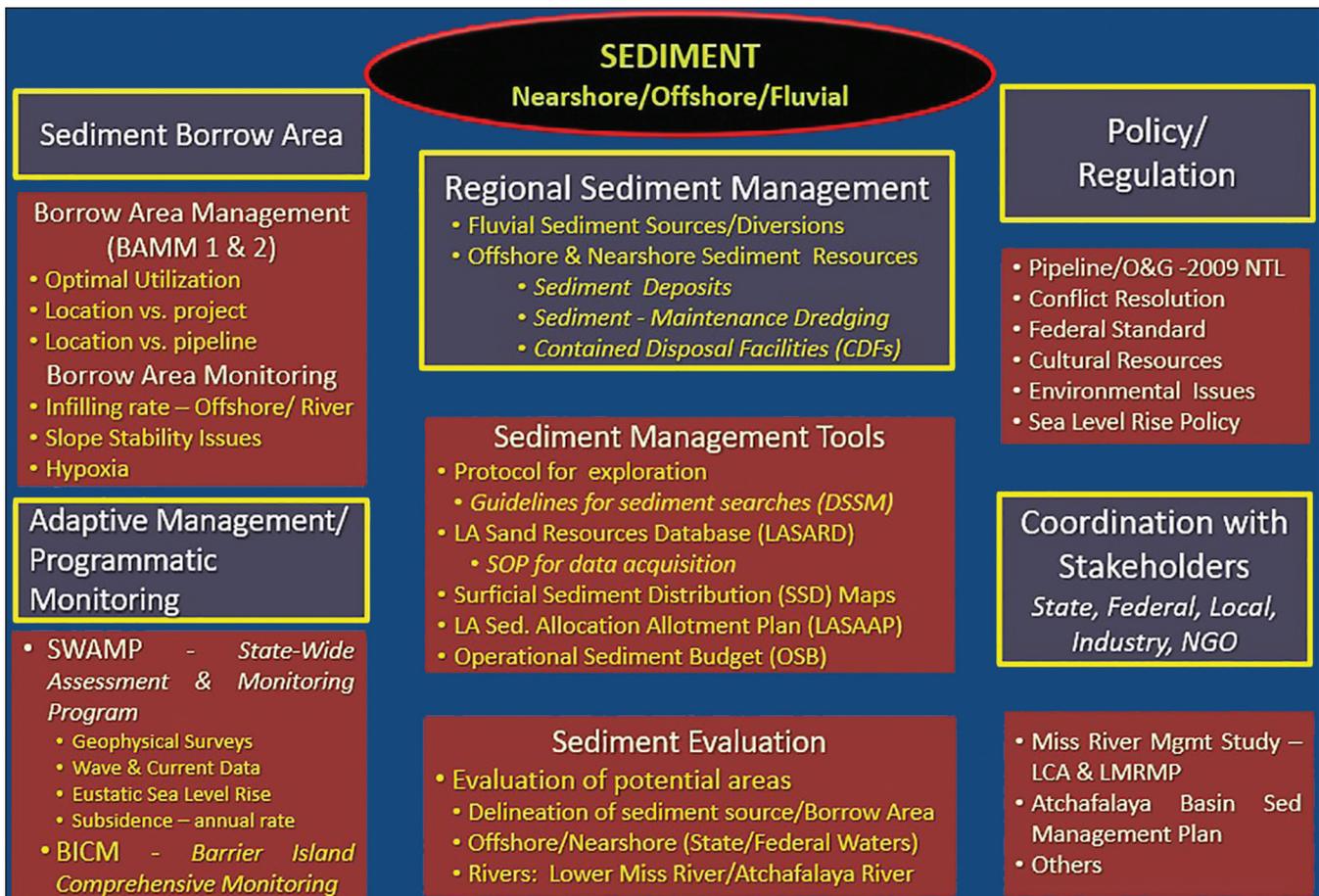
The need for mixed sediment is expected to increase in the near future for restoration of marsh platform/ridges wherein the usage of fluvial or offshore mixed sediment would be preferred over inshore sources. As explained earlier, one of the vital aspects of ecosystem restoration is adding sediment from both active and passive means from outside the system to offset land-loss.

**SEDIMENT MANAGEMENT AND LOUISIANA SEDIMENT MANAGEMENT PLAN (LASMP)**

One of the metrics the State of Louisiana uses to track progress is average rate of land change for the next 50 years. The goal is to change the trajectory of land loss from net loss to one of stability, if not net gain. Over the past two decades Louisiana has invested heavily in restoring its wetlands, especially marshes and barrier islands/shorelines, and intends to continue to

**Table 1. Various sediment types modified after Shepard (1954) and Folk (1980) and defined for restoration purposes in Louisiana.**

<b>1. Sand</b>	Sediment comprised predominantly (70%-100%) of sand with <30% fines (silt/clay)
Surficial sand	Sand deposit delineated based on data spaced less than 1 mile apart.
Potential sand	Sand deposit delineated based on data spaced more than 1 mile apart.
Inferred sand	Sand deposit delineated based on acoustic data, which have not been ground-truthed.
<b>2. Mixed sediment</b>	Mixture of (30 -70 %) sand with remaining fractions made up of fines (silt/clay)
Surficial mixed sediment	Mixed sediment deposit delineated based on data spaced less than 1 mile apart.
Potential mixed sediment	Mixed sediment deposit delineated based on data spaced more than 1 mile apart.
Inferred mixed sediment	Mixed sediment deposit delineated based on acoustic data which have not been ground-truthed.
<b>3. Fines</b>	Sediment comprised predominantly (70%-100 %) of silt/clay with <30% sand
<b>4. Unknown</b>	Very limited or no data to make a meaningful interpretation of sediment type



**Figure 2. Louisiana Sediment Management Plan (LASMP) and its various components — modified after Khalil et al. 2010.**

invest in rebuilding and maintaining these geomorphic features. The critical element in this restoration program is availability of adequate volumes of compatible sediment which could be introduced into coastal Louisiana through sediment diversions, or efficient and cost-effective dredging and emplacement. The state plans to continue exploration and management of compatible sediment via acquisition of geotechnical and geophysical data and improve our overall understanding of sediment management requirements to support the sediment needs and prioritization of 2017 CMP projects as well as plans/projects/programs to be recommended for the future 2023 CMP. To ensure progress, the state must depend upon sound environmental and fiscal management of sediment resources (Khalil and Finkl 2009). As stated earlier, sediment needs are likely to increase considerably due to various natural and anthropogenic causes. Thus, the success of restoration efforts depends on locating, managing, and utilizing not only sand but mixed sediment in a cost-effective manner with robust conservation and preservation strategies for the introduced sediment.

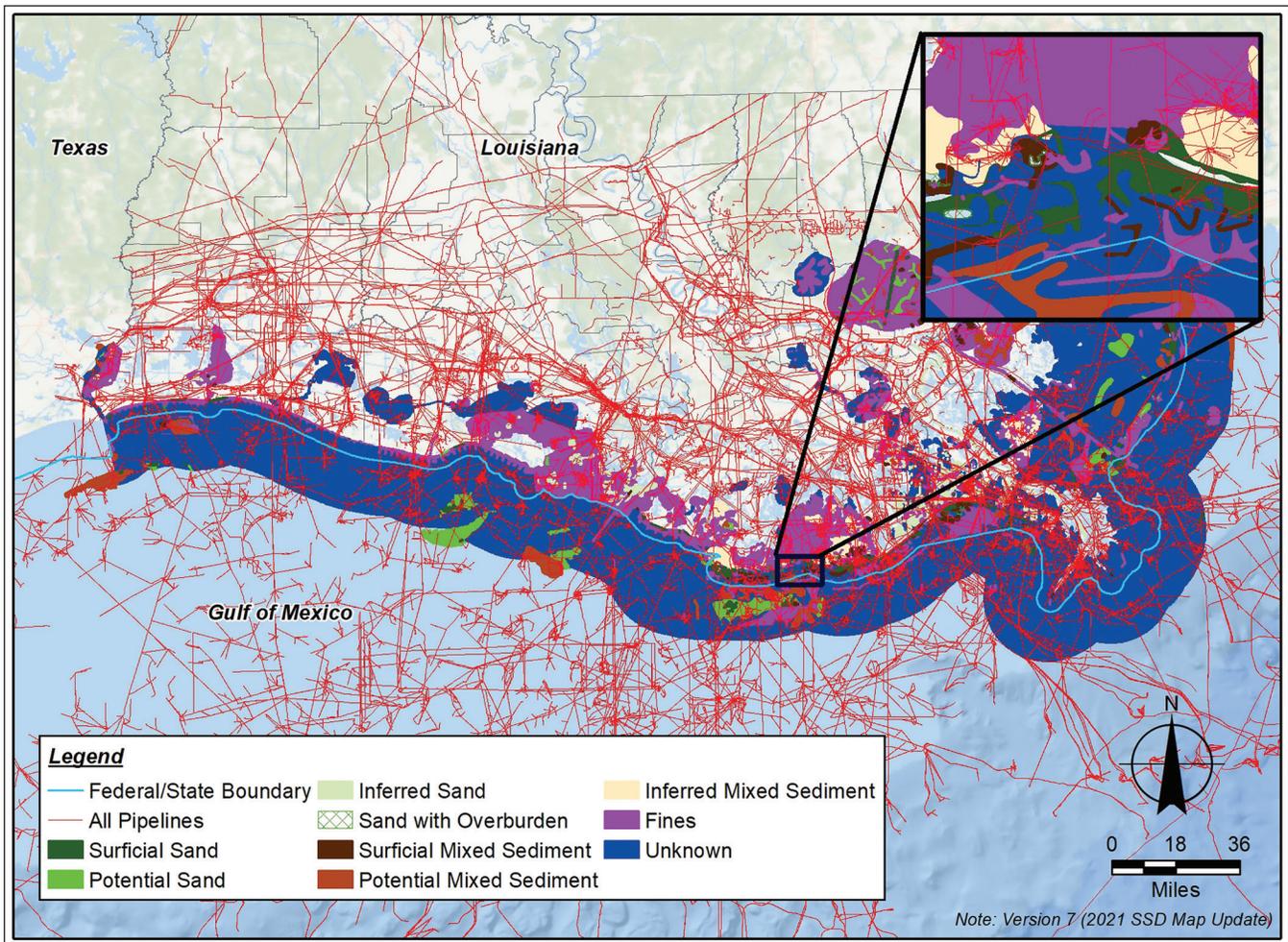
LASMP (Figure 2) is a working model to incorporate the influence of scale on resource availability (fluvial, inshore, and offshore) and resource distribution for effective restoration. Although technical considerations associated with sediment borrow areas, fluvial sediment, and engineering activities are critical for successful plan implementation, coastal policy and regulation requirements along with coordination with stakeholders and adaptive management/programmatic monitoring are expected to have a significant influence on plan implementation. The desired result of LASMP is a cost-effective implementation of the CMP via comprehensive management of renewable and non-renewable sediment resources; a reduction in project costs and environmental impacts; and a long-term, safe and sustainable coast to protect Louisiana communities, national critical energy infrastructure, and state natural resources for future generations.

Under the aegis of LASMP, several tools have been developed as described below. These include: General Guidelines for Exploration for Fluvial and Offshore

Sediment/ Delta Sand Search Model (DSSM), Louisiana Sand Resources Database (LASARD), Operational Sediment Budget (OSB), Surficial Sediment Distribution (SSD) Maps, the Louisiana Sediment Availability and Allocation Program (LASAAP) and the Barrier Island System Management (BISM) program. These tools are extremely helpful in implementation of the sediment management principles, and also in conflict resolution via stakeholder engagement.

**Exploration for sediment resources for coastal restoration**

Exploration for offshore sediment in muddy deltaic environments, similar to those in coastal Louisiana, is complicated due to inherent lateral and vertical variability of sediment facies associated with a complex deltaic environmental regime (e.g. Finkl and Khalil 2005; Khalil 2019). This complexity may require higher than normal spatial-data density for proper interpretation and establishment of the prospect area's litho-stratigraphy (Khalil et al. 2010). It also requires an understanding of geologic processes as well as use of highly sophisticated state-of-the-



**Figure 3. Surficial Sediment Distribution (SSD) map with boundaries of various sediment types delineated/developed from the relevant data in LASARD with inset showing the details along with the oil and gas pipelines.**

art acoustic remote sensing geophysical instruments (e.g. sidescan sonar, high-resolution seismic reflection profiling, high-resolution multi-beam bathymetric survey, etc.). Magnetic anomaly detection using a magnetometer is not directly used for resources assessment but in detecting pipeline and debris, which can limit resource access and thus are critical in resources evaluation.

The “General Guidelines: Exploration for Sediment Resources for Coastal Restoration” (Khalil *et al.* 2010; Khalil 2019) was the first tool developed for implementation of LASMP. It was developed for offshore sediment investigations in a sedimentologically complex deltaic environment for a cost-effective, comprehensive, flexible, systematic sediment investigation. Its phased approach, with initial reconnaissance-level geophysical surveys and geotechnical investigations to identify target areas followed by detailed investigation and cultural resource investigations, is flexible enough for ad-

justments made in the field on the basis of data interpretation as it becomes available in real-time. Over the years, this protocol has been adapted and used successfully to investigate sediment in the Lower Mississippi River as well.

Application of these protocols facilitates comprehension of the sets of circumstances under which restoration-quality sediments are likely to be found (Finkl and Khalil 2005). This understanding abbreviates the need to conduct random geophysical and geotechnical surveys over large expanses of continental shelf seabed and focuses on more informed surveys that directly target potential deposits (Khalil *et al.* 2010). Restoration-quality sediments are highly organized into restricted distribution patterns in accordance with predetermined deltaic patterns of deposition (Khalil 2019). The deltaic models for facies distribution and sedimentary architecture require detailed comprehension before undertaking any exploratory survey (Khalil *et al.* 2010).

### **Louisiana Sand/Sediment Resources Database (LASARD)**

LASARD was developed to populate, maintain and archive the geoscientific (geological, sedimentological, and geophysical including but not limited to bathymetric, seismic, sub-bottom profile, side scan sonar, and magnetometer) and related data (data related to oil and gas and cultural resources) acquired for ecosystem restoration in a Geographic Information System (GIS) platform. The objective of LASARD is to standardize and centralize relevant geoscientific data from various sources for archival and better project coordination while avoiding duplication during subsequent data collection efforts. This facilitates future planning for delineation and utilization of sediment resources by streamlining access to existing data sources, which will minimize the cost and time required to identify appropriate resources. To keep pace with the large amount of data being delivered to the CPRA from ongoing projects, the current LASARD database

**Table 2.**

**Volume of sediment AVAILABLE and INACCESSIBLE due to safety buffer of 1,000 feet on both the sides of pipeline and around the oil and gas infrastructure.**

Sediment type	Total volume AVAILABLE — MCY (MCM)	Volume INACCESSIBLE due to pipeline safety buffers (active & decommissioned)	% of total volume INACCESSIBLE due to pipeline safety buffers (active & decommissioned)	Volume INACCESSIBLE due to decommissioned pipeline safety buffers	% of total volume INACCESSIBLE due to decommissioned pipeline safety buffers
		— MCY (MCM)	— MCY (MCM)	— MCY (MCM)	— MCY (MCM)
Sand (surficial)	1,340 (1,020)	310 (240)	23	20 (15)	1
Sand (potential)	3,480 (2,660)	1,090 (830)	31	530 (405)	15
Mixed sediment (surficial)	900 (690)	340 (260)	38	50 (40)	5
Mixed sediment (potential)	4,090 (3,130)	1,010 (770)	25	290 (220)	7

**Notes:** The prefix “surficial” indicates a higher degree of confidence in volume estimates than “potential” due to the availability of more/higher quality data.

has been updated to incorporate these new data sets. Keeping LASARD current, facilitates the benefit of real cost savings to upcoming projects by not only providing valuable data for planning, but also by reducing the potential for costly, redundant, duplicative, data collection efforts. This includes finalizing updates to the LASARD attribute formats, updating existing data to match these new formats, and processing additional data sets that are generated by ongoing implementation of coastal restoration projects. LASARD along with the SSD maps, is an important tool of the LASMP. The LASARD Standard Operating Procedures (SOP) for Geo-scientific Data Management outlines procedures for data acquisition and data formatting by detailing standard data formats using appropriate attribute tables (Khalil *et al.* 2015).

#### **Surficial Sediment Distribution (SSD) maps**

Having an inventory of potential sediment resources and the ability to track sediment needs are crucial to the development of regional strategies for the sedimentological components of ecosystem restoration. SSD maps for nearshore, offshore, and the Lower Mississippi River (Figure 3) were developed based mainly on existing sedimentological, geotechnical, and geophysical data residing in LASARD to help fulfill the goals of the LASMP (Khalil *et al.* 2018b; APTIM 2020b). Keeping the needs of coastal restoration in mind, the mapped sediment deposits were broadly classified as sand, mixed sediment, and fine-grained sediment (Figure 3; Table 1). However, a large portion of offshore areas were classified as “unknown” due to a lack of sufficient reliable data. Based on these maps, total “AVAILABLE” and “ACCESSIBLE” (by

excluding sediment volume made inaccessible due to safety buffers around oil and gas infrastructure) volume estimates were calculated for sand and mixed sediment (Table 2). These volumes are first order estimates as these calculations are based on various types of geoscientific information with varying degrees of confidence. Estimates based on these maps indicate the potential availability of sediment, however, dredging all of these sediment resources is neither feasible nor technically sound even with sufficient funding resources (Khalil *et al.* 2018b). These maps are generally updated annually and are living documents depending on acquisition of new geoscientific data, which has increased in recent years due to increased restoration activities.

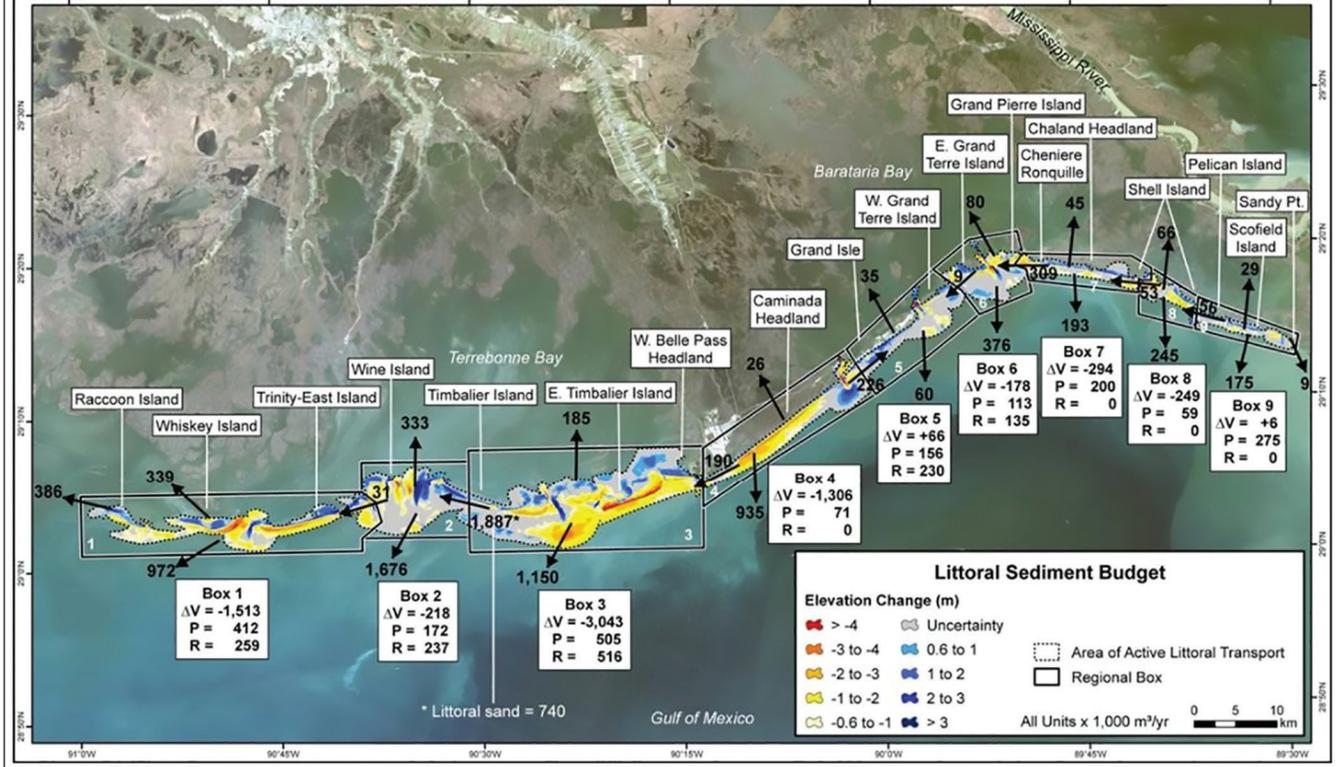
These SSD maps are basic but important tools that were initially compiled for resource planning and play a critical role in the management of sediment resources at a regional level. Interestingly, they also play a vital role in stakeholder engagement, coastal zone management, conflict resolution and in the enforcement of federal and state regulations related to the removal or abandonment-in-place of decommissioned pipelines. The removal of decommissioned pipelines, as stated previously, provides access to offshore sediment resources. These maps support state regulatory efforts to enforce the Coastal Zone Management program. They also provide background data for the development of federal regulations to protect sediment resources through BOEM’s Offshore Significant Sediment Resources Areas (SSRA) blocks, which play a critical regulatory role in decision making for removal of decommissioned pipelines. Based on a State of Louisiana request to the then-Minerals Manage-

ment Service (MMS) (now BOEM) to protect offshore sediment resources, in 2009 a Notice to Lessees (NTL) No.2009-G04 — “Significant OCS Sediment Resources Avoidance and Protection Policy” was enacted.

The prevalent notion that the pipelines could be removed as and when sediment resources are needed is untenable. It is not possible to plan to dredge areas where pipelines exist due to the uncertainty of time and resources needed to remove the pipelines in a timely manner. This is further complicated by the fact that ownership of the pipelines can change frequently, and the time needed to notify and remove pipelines adds further uncertainty. Thus, it is suggested/recommended that removal of pipelines should be based on future needs of the program and not necessarily on the immediate needs of these resources. With the increase in available funding that will allow for a concurrent increase in sediment need for accelerated project construction, it is crucial to ensure that these sediment resources are available to meet these needs.

The State of Louisiana/CPRA has been coordinating with the federal government/BOEM for its sediment needs and availability/accessibility on the Outer Continental Shelf (OCS). CPRA and BOEM also collaborate to identify, delineate, and evaluate sand and mixed sediment sources that are then classified as SSRAs based on the SSD maps. However, these priorities are based mainly on short-term needs only and should not imply that other areas will not become priorities in the future, especially as new data become available. As the identified sediment resources are currently being utilized for several near-term projects,

**Louisiana Operational Sediment Budget**  
**Regional Budget: Raccoon Point to Sandy Point (1985-89 to 2013-16)**



**Figure 4. Macro-scale littoral sediment budget for the south Louisiana barrier shoreline, 1985-89 to 2013-16. Arrows represent net direction of sediment movement and numbers reflect magnitudes of net sediment transport in thousands of m<sup>3</sup>/yr. P= Placement; R = Removal.**

the other sediment resources will be needed for the state's short-term and long-term needs as restoration proceeds and as the need for sediment increases. This has resulted in very productive and effective stakeholder engagement where all agencies have a clear understanding of each other's needs and challenges. This is further elaborated later in this paper.

**Impact of pipeline infrastructure — reduction in sediment volume due to reduced accessibility**

Decades ago, when many of the oil and gas pipelines and related infrastructure were put in place, their impediment to restoration efforts by restricting/limiting access to sediment resources was not envisioned or contemplated (See Table 2). The required safety buffer of 1,000 feet (300 m) along both sides of pipelines and around infrastructure considerably reduces (by 38% in some cases) the volume of dredgeable sediment for restoration. Table 2 also shows that it is not only active pipelines which restrict access to the dredging of sediment, but decommissioned pipelines which are abandoned-in-place also obstruct access to a substantial (up to 15%) amount of sediment.

As discussed in detail following, the presence of thousands of miles of pipelines prohibiting access to the sediment resources is a limiting factor in accessibility of offshore sediment. It is estimated that a mile-long pipeline can inhibit access to approximately 4 MCY (3 MCM) of 10-foot (3.1 m) thick sediment resources (Khalil *et al.* 2018a). Improving availability and accessibility to “free up” sediment sources will provide more choices for sediment usage. This will reduce costs and thereby help wetland restoration by more new project construction through an enhanced collaborative relationship with various stakeholders.

**Louisiana Operational Sediment Budget (OSB): Raccoon Point to Sandy Point (1985-1989 and 2013-2016)**

The OSB for the barrier shorelines of Louisiana between Raccoon Point and Sandy Point was developed to determine net littoral sediment transport rates for use with barrier island restoration planning and design, and for estimating project longevity based on analysis of existing survey data sets (ACRE 2020). These survey data were analyzed to improve knowledge of regional sediment

transport controls on barrier island system evolution as guidance for present-day restoration efforts. Comparison of topographic/bathymetric surfaces for the same geographic area but different time periods documented erosion and deposition patterns that revealed net sediment transport pathways. Erosion and deposition volumes defined the magnitude of sediment exchange associated with transport pathways, providing the foundation for development of a littoral sediment budget.

Effective design and management of barrier island restoration requires reliable net sediment transport estimates for predicting project longevity and planning for future restoration needs. It was observed that net littoral sand movement in the project area is controlled regionally by dominant east-to-west directed waves and currents, hydraulics associated with passes between the islands, and barrier shoreline restoration activities. An analytical comparison of topography/bathymetry data isolated areas of erosion and deposition for documenting sediment transport patterns and quantifying trends. Sediment sources and sinks in the

littoral zone were identified based on net geomorphic changes between 1985-1989 and 2013-2016. Overall, ebb shoals were net erosional (sediment sources) as passes widened, and channels present in the 1980s filled (sediment sinks). Although coastal restoration projects along all segments of the Louisiana barrier coastline have been critical for establishing a more resilient barrier island system to protect estuarine environments in Barataria and Terrebonne Bays against Gulf of Mexico marine processes, average sediment losses over the 30-year analysis period illustrated that the pace of restoration with sediment from outside the littoral system should take place at 1.5-3 times the existing rate to keep pace with historical sediment losses from the littoral zone. Surface sediment samples and cores from LASARD for areas adjacent to the sediment budget boundaries documented about 10%-20% seafloor sand content, the exception being west of Racoon Point where sediment samples indicated 70%-80% sand. This suggested that approximately 1.3-2.2 MCY (1.0-1.7 MCM) of sediment lost from the littoral system annually was sand. Large-scale restoration efforts over the last 30 years have offset losses at a rate of approximately 0.8 MCY/yr. (0.6 MCM/yr.) of additional sand from outside of the littoral zone.

The significance of sediment to the sustainability of coastal Louisiana demands the development of a sediment budget to promote effective utilization of sediment resources, which is a critical element for implementation of the CMP. The sediment budget helps quantify the volume of sediment necessary to minimize/mitigate the effects of relative sea level rise. It facilitates a better assessment of long-term sediment movement trends within the coastal system, and also ensures cost-effective and optimal usage of sediments during restoration. Further, it helps to quantify the regional sediment budget in and adjacent to proposed restoration areas especially the barrier islands. The OSB is a very effective tool to effectively implement the CMP 2017 recommendation for restoration of barrier islands as a coastal system, rather than a series of individual projects (CPRA 2017). This tool is also very helpful in implementation of Barrier Island System Management (BISM) as proposed by CMP 2017 (Dalyander *et al.* 2021). The goal of BISM is to implement a holistic, long-term approach to adaptively manage

Louisiana's coastal systems by maintaining barrier island functions over the next 50 years.

#### **Louisiana Sediment Availability and Allocation Program (LASAAP)**

LASAAP was developed to implement LASMP with the primary goal of linking the sediment needs of the state's marsh, barrier island and ridge creation/restoration projects to the coast-wide potential sediment sources within river, state and federal waters. This tool analyzes borrow areas and project locations along with existing sediment resource development data in a spatial format to manage limited compatible sediment resources. The long-term goal of this program is to enhance state planning capabilities to optimize sediment resource utilization, capitalize on synergistic project opportunities, reduce project costs, maximize land-building potential, and ensure projects have the necessary sediment available for the full 50-year planning horizon of the CMP. The tool's effectiveness and functionality were tested in a pilot study conducted in Barataria Basin (APTIM 2020a). Eleven CMP restoration projects fall within the Barataria Basin. Three of these projects are marsh creation projects and one is a barrier island restoration project. These four projects were broken down into their individual barrier island or marsh components and each was evaluated using the tool to identify potential sand and/or mixed sediment resources. Current program improvements are focused on increasing the accessibility of the tool to nontraditional GIS users by exploring the steps necessary to host the tool in a web environment. In addition to tool access improvements, a standardized state report is being developed that gives LASAAP a baseline for understanding the current project needs and potential resources available. The LASAAP prototype is currently being advanced beyond Louisiana to develop the Northern Gulf Sediment Availability and Allocation Program (NGSAAP). Like the LASARD/LASMP leveraging basis for LASAAP, NGSAAP will look to ongoing efforts by the NGOM states, USACE and BOEM to provide information necessary for a functional allocation tool.

#### **STAKEHOLDER ENGAGEMENT — MANAGING MULTIPLE USES**

Stakeholder engagement, especially for managing the multiple uses of the nearshore/offshore seafloor, is a very

important component of LASMP. There are several stakeholders with interest in the nearshore/offshore seabed viz. the Bureau of Safety and Environmental Enforcement (BSEE), BOEM, Louisiana Department of Natural Resources (LDNR), CPRA, along with numerous energy producers (e.g. oil and gas companies, and now wind-farm developers), the aquaculture sector, and both recreational and commercial fishery interests. Resource extraction companies are interested in establishing infrastructure, including platforms and laying pipelines, on and along the most convenient and cost-effective locations. In most cases, providing access to the underlying sediment is not a consideration and ultimately vast sediment resources become inaccessible for restoration. Although regulations require that companies remove pipelines after decommissioning, historically this wasn't enforced. Consequently, the seabed off Louisiana is littered with decommissioned pipelines. Stakeholder engagement is crucial. Stakeholders must work together to resolve conflicts in order to manage the multiple uses of the offshore seabed, which includes not only development/exploration of new resources, but also the decommissioning of old or abandoned infrastructure.

The State of Louisiana is interested in the restoration and protection of its coast, enforcing Coastal Zone Management (CZM) and related regulations, and protecting its limited restoration-compatible sediment resources. The federal agencies (BSEE, BOEM) are custodians for OCS minerals including oil and gas, and sand and gravel, and must balance these multiple uses. With the understanding that oil and gas industries are also important for the state economy, there is a need for a balanced approach for "coexistence." Keeping in mind the differing missions of every agency/stakeholder (Figure 5), the federal and state partners have come up with a process (Figure 6) to resolve conflicts fairly and equitably as discussed following.

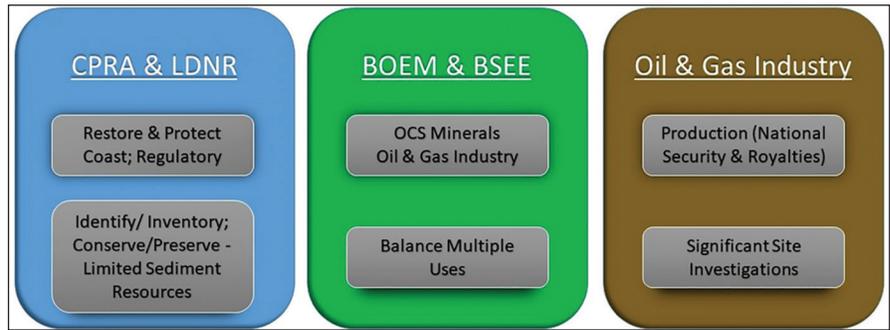
#### **Process developed for conflict resolution regarding oil and gas pipelines — a conservative approach**

The conflict resolution process (Figure 6) initiates in federal OCS waters once an application is submitted by the operator (oil and gas company representative) to BSEE for decommissioning a pipeline, and in most cases this request is to aban-

don-in-place. BSEE engages BOEM to review for compliance with the National Environmental Policy Act (NEPA) and the Outer Continental Shelf Lands Act (OCSLA) especially with respect to how the action may affect mineral resources in identified SSRA blocks. This review includes a thorough and careful analysis of the best available geologic and geophysical data, density of infrastructure, and evaluation of other potential uses of the OCS resources. Concurrently, a state's consistency determination is initiated. The oil and gas company makes an application to LDNR, which is the state's lead regulatory agency. LDNR engages CPRA (the lead state agency responsible for coastal protection and restoration) to review the application related to sediment resource conservation and protection. CPRA performs a balancing act with a conservative approach realizing the value of the oil and gas industries to the nation's economy. While CPRA is aware that BOEM performs a thorough review, CPRA conducts its own review by consulting geological/geophysical reports; SSD maps; restoration plans; density of pipelines; presence of oil and gas infrastructure, wellheads, etc.

**Balancing act by CPRA for multiple use of the seafloor**

Renewable energy via wind farms is potentially as crucial and important for the economy and future of the State of Louisiana and the nation as is the oil and gas industry. Our understanding is that the scale of the footprint of these wind-farms, which would include multiple turbines, substations located offshore near the turbines, and subsea cables transmitting the power generated by the turbines to shore, has the potential to be large. The important role of the CPRA is that of a balancing act via stakeholder engagement and conflict resolutions in such cases of multiple use. CPRA along with the Coastal Management Division of the LDNR and BOEM intends to continue the same approach for wind farms, aquaculture industries, and oyster farming as they have been undertaking in the case of oil and gas industry. The importance



**Figure 5. Figure showing various federal and state agencies and oil and gas industry with their respective mission in multiple uses of seabed.**

of this relationship and process cannot be overstated. It is expected, and critically important, that BOEM continues to work with CPRA and LDNR on these issues as they have been working with the State of Louisiana for years on how to effectively manage the needs of oil and gas industry as well as the need for sediment resources for coastal protection and restoration. As with oil and gas pipelines and infrastructure, the locations of the turbines and substations as well as the transmission cables have the potential to limit accessibility to crucial restoration-compatible sediment resources in the OCS. To understand and preempt any possible conflicts, lessons learned from years of working with oil and gas industries may help understand and resolve any future issues relating to accessibility of sediment resources.

**DISCUSSION**

Louisiana's CMP provides strategies for long-term sustainability of communities, economies, and coastal ecosystems in Louisiana. It also provides a framework for resource managers to understand expectations and manage responses of the ecosystems to natural and anthropogenic changes. Understandably, managing and restoring a degrading ecosystem like coastal Louisiana is very complex and challenging. With the accelerated pace of wetland loss in Louisiana along with the projected future RSLR and storm activities, the need for mitigative actions/restoration will significantly increase. Sustainable ecosystem restoration is inextricably linked with sedimentological

restoration for replication and/or replacement of the lost geomorphic features/substrate. In order to mitigate the ongoing ecocatastrophe, ecosystem restoration in coastal Louisiana depends on strategies adopted for robust large-scale sedimentological restoration. The sustainability and success of this mega-effort/program depends on availability of adequate quantities of compatible sediment, specifically sand and mixed sediment, suitable for restoration of diverse wetland habitats via barrier island restoration, marsh platform creation, and ridge restoration.

The Louisiana Sediment Management Plan (LASMP) is a living plan that has evolved over decades. Having no previous template to follow, it began as a framework to identify sediment needs and sources and has matured to include various additional components supporting the implementation of Louisiana's CMP. In addition to policy/regulation and stakeholder considerations, additional LASMP components include: General Guidelines for Exploration for Fluvial and Offshore Sediment/Delta Sand Search Model (DSSM); Louisiana Sand Resources Database (LASARD); Operational Sediment Budgets (OSB); Surficial Sediment Distribution (SSD) Maps; the Louisiana Sediment Availability and Allocation Program (LASAAP); and the Barrier Island System Management (BISM) program.

As expected, the future need will increase for both active and passive sediment input into the system. Sediment accessibility will also become more



**Figure 6. Various steps involved in the process of consistency determination from application for request for decommissioning of pipeline to decision for removal or abandonment-in-place.**

challenging in the future due to natural causes (e.g. sea level rise, subsidence, hurricanes,) and enhanced human activities (e.g. oil & gas/wind farms and other related activities). Mitigating for the increased quantity of sediment needed is fundamental to the success of large-scale, sustainable coastal restoration efforts in Louisiana. As we have discussed, oil and gas and other infrastructure obstructs access to already limited sediment resources, resulting in higher costs for restoration projects. It is also expected that the present approach to sediment management may need future adjustment and modification to accommodate other emerging multiple uses of offshore seafloor viz. wind farms, aquaculture, oyster beds. This calls for managing sediment on a regional scale with more emphasis on a holistic approach. Sediment management plays a major role in restoration activities of coastal Louisiana. Hence, the approach was to develop a sediment management plan custom-made for the needs pertaining to Louisiana. LASMP was developed to manage the state's sediment needs and plays a vital role in balancing restoration needs related to addressing environmental concerns as well as accommodating other multiple uses of the seafloor, which are important for the national and state's economy. This plan identifies and delineates potential sediment sources for restoration and provides a framework for managing these resources wisely, cost-effectively, and in a systematic manner. Various strategies, along with appropriate tools were developed to implement LASMP (Khalil *et al.* 2010).

Since the initial development of the LASMP framework, it has evolved and has been adaptively managed but the fundamental components remained the same viz. Regional Sediment Management, Borrow Area Management and Monitoring, Policy/Regulation, Stakeholder Engagement, and Adaptive Management/Programmatic Monitoring. This evolution has helped not only in sediment resource management for planning restoration efforts, but during the last several years it has developed the added benefit of serving as a tool to engage various stakeholders involved in alternate uses of the seabed as well as a tool for conflict resolution arising out of such uses. SSD maps for nearshore, offshore, and the Lower Mississippi River are one of the tools, which not only facilitates resource evaluation but also plays a vital role in stakeholder

engagement, conflict resolution and in the enforcement of federal and state regulations related to decisions regarding decommissioned pipelines. LASMP informs a successful collaborative process for conflict resolution via stakeholder engagement, which is the most important aspect of "co-existence." Thus, sediment management, which involves detailed coordination among many stakeholders (with diverging interests and missions), is fundamental to coastal restoration/protection efforts. Conflict resolution via collaboration with state agencies, federal agencies, the energy industry, and fisheries interests is a balancing act and LASMP and its tools have been very effective so far.

Sediment management is a loosely defined term and has been used on various temporal or spatial scales for various purposes viz. inlet management, investigation for sediment resources, etc., but there is no one prototype/model to follow to develop a comprehensive sediment management plan for coastal restoration—especially for a deltaic plain such as the MRDP. LASMP was designed specifically for both active and passive sediment management to address mitigative measures to offset land loss in coastal Louisiana. It had very focused objectives and accordingly has developed its supportive components and implementation tools. LASMP is a comprehensive sediment management plan for restoration purposes and can be a showcase for not only regional but also global sediment management practices specifically for restoration needs of globally degrading deltaic plains.

## CONCLUSIONS

Deltaic plains are degrading and sinking globally and are not steady-state sedimentary coastal environments, still they are identified to be among the most important sources of ecosystem goods and services. Their restoration is a necessity if human habitation and commerce are to be maintained in these regions, which are multifaceted, extremely intricate and complex. Such is the case of coastal Louisiana. By launching a 50-year program to restore coastal Louisiana, the state has proactively put themselves at the forefront of coastal restoration efforts. It also means that the state has to develop its own path without any template to follow. Louisiana's CMP has identified land building as one of the major decision drivers (CPRA 2017). Mitigating land

loss using strategies aligned with sedimentological restoration plays a major role. These strategies include both actively introducing sediment into the system through direct dredging of restoration-quality sediment along with more passive approaches to introduce sediment through sediment diversions from the Mississippi River to mimic historic delta-building processes. Anticipating the critical role of sediment, LASMP was conceptualized and implemented along with its major component tools. The overarching goal is to enhance the ability to make informed management decisions related to availability and accessibility of sediment both qualitatively and quantitatively for an environmentally effective and economically feasible restoration strategy. The main components of the initial baseline framework which was developed for Louisiana's needs (Khalil *et al.* 2010) has not significantly changed over the years. However, during the last several years, LASMP has evolved from a traditional planning tool for resource management to a most important tool that involves detailed coordination among many stakeholders (with diverging interests and missions) and is fundamental to coastal restoration/protection efforts. Conflicts in resource needs are inescapable, and LASMP acts as a conflict-resolution tool for identifying and minimizing conflict with respect to usage of sediment resources. Through collaboration with state agencies, federal agencies, the energy industry, and fisheries interests, and other stakeholders, conflicts can often be minimized and avoided. Louisiana is a leader in sediment management amongst the five coastal states of the NGOM and has collaborated closely with these states in the development of the Gulf Regional Sediment Management Master Plan (GRSMMP). Various strategies developed and adopted in Louisiana including LASMP are showcased regionally and globally for coastal restoration. But most importantly for coastal Louisiana and its 2 million inhabitants, sediment means survival and LASMP helps manage that.

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## DEDICATION

This paper is dedicated to the memory of late K. Krishnanunni, former Director General of Indian Geological Survey who was a finest human being besides being a brilliant geologist. The first author was fortunate enough to be a friend of this very modest, humble and great visionary worth emulating.

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## Acronyms:

- **BCM**: Billion Cubic Meters
  - **BCY**: Billion Cubic Yards
  - **BISM**: Barrier Island System Management
  - **BOEM**: Bureau of Ocean Energy Management
  - **BSEE**: Bureau of Safety and Environmental Enforcement
  - **BUDM**: Beneficial Use of Dredged Material
  - **CMP**: Coastal Master Plan
  - **CPRA**: Coastal Protection and Restoration Authority
  - **CZM**: Coastal Zone Management
  - **DSSM**: Delta Sand Search Model
  - **GIS**: Geographic Information System
  - **GRSMMP**: Gulf Regional Sediment Management Master Plan
  - **LASAAP**: Louisiana Sediment Availability and Allocation Program
  - **LASARD**: Louisiana Sand Resources Database
  - **LASMP**: Louisiana Sediment Management Plan
  - **LDNR**: Louisiana Department of Natural Resources
  - **MCM**: Million Cubic Meters
  - **MCY**: Million Cubic Yards
  - **MMS**: Marine Minerals Service
  - **MRDP**: Mississippi River Delta Plain
  - **NEPA**: National Environmental Policy Act
  - **NGOM**: Northern Gulf of Mexico
  - **NGSAAP**: Northern Gulf Sediment Availability and Allocation Program
  - **NTL**: Notice to Lessees
  - **OCS**: Outer Continental Shelf
  - **OSB**: Operational Sediment Budget
  - **OCSLA**: Outer Continental Shelf Lands Act
  - **RSLR**: Relative Sea Level Rise
  - **SMT**: Sediment Management Team
  - **SOP**: Standard Operating Procedures
  - **SSD**: Surficial Sediment Distribution
  - **SSRA**: Significant Sediment Resource Area
  - **USACE**: U.S. Army Corps of Engineers
  - **USGS**: U.S. Geological Survey
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