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BRIDGING THE DEPTHS: LESSONS LEARNED FROM DEEP-SEA MINING FOR BETTER PREDICTING TURBIDITY PLUMES

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Abstract: The insights gained from deep-sea mining (DSM) research regarding sediment dynamics can be utilized to better predict turbidity plumes in shallow marine environments. Small-scale lab experiments can replicate deep-sea conditions effectively, offering an ideal model system to study turbidity currents, given the reduced hydrodynamics and low biota present in the deep sea. DSM operations involve the deployment of a Polymetallic Nodule Mining Tool (PNMT) that collects ore and discharges excess water and sediments. Organic matter, bound to mineral clay as flocs, is a key driver of sediment transport in the deep sea. Understanding the dispersal and settling patterns of sediments, and the likelihood of flocculation occurring in DSM activities, can be generalized and applied to turbid flows in shallow water areas. Laboratory experiments demonstrate that the interaction between organic matter, mineral clay, and flocs within turbidity currents, results in the reduction of their dispersion. Alongside this, factors like shear rate and sediment concentration significantly influence both floc growth, size and settling velocities. Combining these results with real-time data on sediment concentration, particle size distribution, turbidity, and flow dynamics can be helpful to make dredging decisions, reduce the environmental disruption, and guide dredging equipment selection. By understanding the factors that influence sediment flocculation, deposition, and resuspension, we can design engineered solutions to mitigate the impact of turbidity current.

Key words: Deep-sea mining; dredging; turbidity current; flocculation; settling velocity

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1 INTRODUCTION

Dredging, a widely employed technique, serves a diverse range of purposes, including land reclamation, harbor development, waterway maintenance, and the extraction of minerals from beneath bodies of water. With the burgeoning demand for minerals and metals driven by global population growth and economic activities, the interest in mineral extraction through dredging has witnessed a significant upsurge. However, dredging activities can inflict detrimental effects on the environment, particularly benthic environment as they generate sediment plumes that elevate the concentration of suspended solids. In consequence, bed disturbance caused by human (or economic) activities such as dredging, marine construction, fishing, mining has been recognized as a primary agent of disturbance in marine habitats (Gates and Jones, 2012; Harris, 2014; Hobbs, 2002; Puig et al., 2012; Sharma, 2015c).

Alongside the growing interest in dredging for various purposes, there is a particular focus on metals that are crucial for facilitating a sustainable transition towards renewable energy sources. High demand exists for metals like manganese, nickel, and cobalt, which are essential for manufacturing wind turbines, solar panels, and storage batteries for electric vehicles (Hein et al., 2020). While these valuable metals are conventionally extracted through land-based mining, Deep Sea Mining (DSM) is being considered as a potential substitute to meet the increasing demand. Polymetallic nodules, abundant in metals and rare earth elements, are situated on the abyssal plains of oceans, generally at depths ranging from 4 to 6 kilometers. The most extensive known deposits of these nodules are located in the Clarion Clipperton Fracture Zone (CCFZ) in the Pacific Ocean and the Indian Ocean Nodule Field (Hein et al., 2020). These deposits, while holding economic significance, also serve as crucial habitats for benthic communities (Kaiser et al., 2017). Worries persist regarding the rate of recovery for the area impacted by mining activity (Gollner et al., 2017).

While DSM holds promise for securing essential resources, concerns arise about its environmental impact, particularly the generation of turbidity plumes. These plumes, composed of suspended sediment, can smother benthic communities, alter nutrient cycling, and hinder light penetration, potentially causing long-term ecological damage.

This paper delves into the intricate interplay between deep-sea mining research and the severity of turbidity plumes they (expect to) generate and the bridge of this knowledge to traditional dredging. We begin by providing an overview of deep-sea mining and the turbidity plumes emanating from Polymetallic Nodule Mining Tool (PNMT). We then explore the significance of sediment properties and delve into the extent to which flocculation influences the behavior of turbidity plumes. Finally, we shift our focus to the potential applications of deep-sea mining knowledge in shallow-water plumes, particularly in the context of dredging. Our aim is to enhance plume dispersion prediction and identify strategies to minimize the environmental impact of mining equipment.

2 DEEP SEA MINING

DSM operations, employ a PNMT to extract nodules, that generate a plumes that can evolve into turbidity current, which is a major concern in near-field mining activities. PNMT collects nodules from the seafloor and separates them from excess water and fine sediments that are inherently entrained. The mining vehicle releases excess water and fine sediment on the seafloor (see Figure 1). While previous studies have focused on various flow regimes associated with the discharge of sediments from PNMTs (Ali et al., 2022; Elerian et al., 2022; Peacock and Ouillon, 2022), this study specifically examines turbidity currents and the potential for mitigation using flocculation techniques. These currents, propelled by mining vehicle discharges, can travel extended distances, potentially exceeding 4-9 kilometers based on modeling including laboratory parameters (Gillard, 2019). Their prolonged persistence in the water column further intensifies their detrimental impact (Blue Nodules D1.7, 2020; Hein et al., 2020; Haalboom et al., 2022). When these currents settle, they bury benthic species, impede respiratory surfaces for filter feeders, and pollute food sources for numerous benthic organisms (Gollner et al., 2017; Jones et al., 2017; Vanreusel et al., 2016). To mitigate the ecological consequences of human activities, controlling the dispersion of these plumes is paramount (Weaver et al., 2022).

The particle size distribution (PSD) and settling velocities play a crucial role in determining the spread of deep-sea sediment plumes (Gillard et al., 2019; Spearman et al., 2020). Coarse debris, settling rapidly, contrasts with clay-sized mineral particles that remain suspended for extended periods, contributing to plume dispersion

(Sharma, 2015). However, flocculation, the process of particles aggregating into flocs, holds the potential to mitigate plume (Ali et al., 2022; Elerian et al., 2023; Muñoz et al., 2022). These flocs, formed by the binding of particles, can grow larger and heavier than individual particles, increasing their settling velocity and, as a result, reducing their dispersion. Flocs, ubiquitous in coastal environments, significantly impact sediment transport (Gratiot and Manning, 2004; Deng et al., 2019; Safar et al., 2019; Ho et al., 2022). Laboratory experiments replicating coastal conditions have revealed that flocculation occurs promptly, often within minutes, particularly when microscopic organic matter is present (Gillard et al., 2019; Shakeel et al., 2020, Ali et al., 2023). In marine and coastal systems, particle aggregation and breakup are dynamic processes that are constantly in flux, influenced by changes in shear, salinity, concentration and the type and quantity of organic matter.

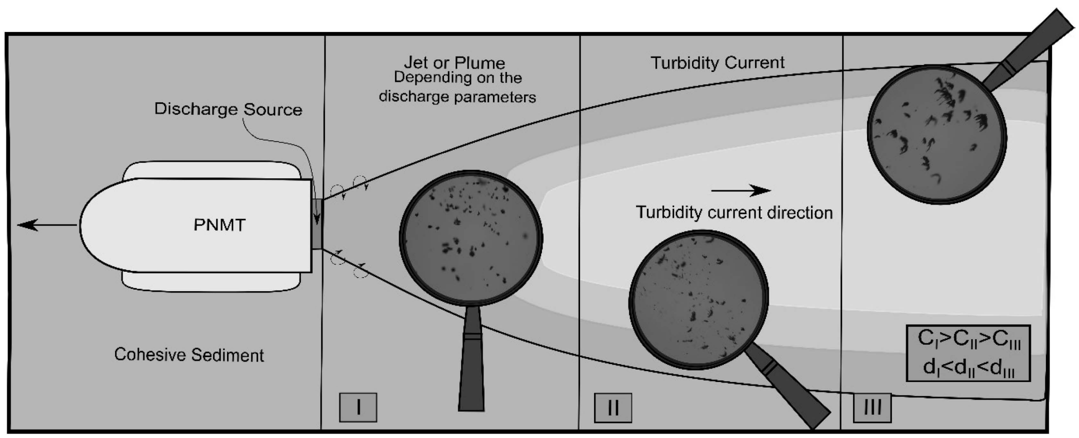

Figure 1. Categorization of near-field turbidity flow and particle size evolution through flocculation in the near-field region. Concentration and particle size are denoted by C and d, respectively. (Figure adapted from Elerian et al., 2023).

2.1 Effect of flocculation

Studies of turbidity current propagation have revealed that flocculation indeed takes place during sediment transport, attributed to the rapid flocculation kinetics induced by organic matter-clay interactions. This flocculation process exerts a profound impact on the propagation of turbidity currents (Gillard et al. 2019, Ali et al., 2022, Elerian, 2023). Laboratory investigations of turbidity currents have predominantly utilized lock exchange experiments, a technique involving the controlled release of dense material from a confined space (Baker et al., 2017; Craig et al., 2020; Helena et al., 2013). These experiments, also known as fixed-volume turbidity currents, effectively simulate the behavior of turbidity currents generated by sudden releases of sediment-laden water from reservoirs or cliff faces. A recent study by Ouillon et al. (2021) demonstrated that the front propagation of a traditional lock-release turbidity current closely resembles that of a turbidity current emanating from a moving source, further supporting the applicability of lock exchange experiments in understanding turbidity current dynamics.

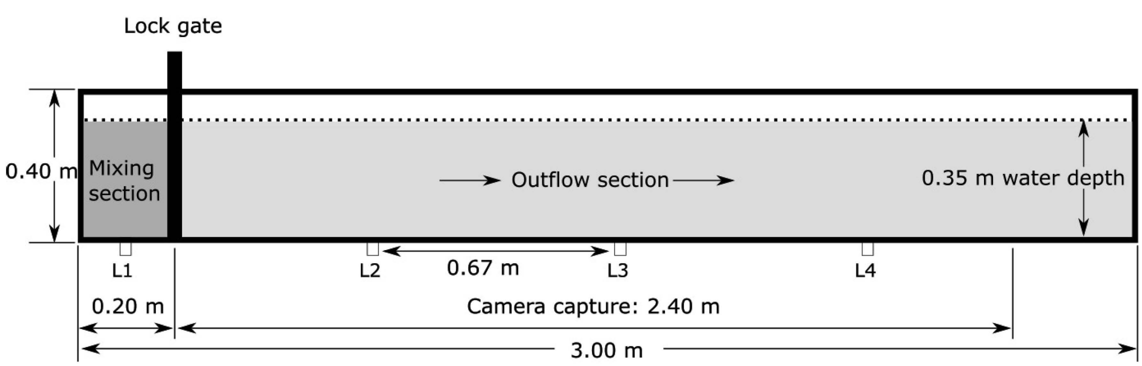

Figure 2. Schematic representation of the Lock exchange setup. The samples are taken at L1, L2, L3 and L4 locations (Ali et al., 2022).

Figure 2 depicts the schematic of a lock exchange used to generate turbidity current with artificial deep-sea clay in the presence of an organic matter surrogate (Ali et al., 2022). Lock exchange experiments were conducted in both freshwater and saline solutions. In figure 3 (B,E) a distinct shift in particle size is evident between sampling locations L1 (initiation of the lock exchange) and L4 (conclusion of the lock exchange). This alteration is primarily attributed to floc formation during flow and the interaction between clay particles and unbound flocculant upon contact with freshwater enriched in cations. Flocculation by polyelectrolytes is an extremely rapid process, occurring within seconds (Ali and Chassagne, 2022; Ibanez Sanz, 2018; Shakeel et al., 2020, Zhang et al., 2024a,b). It is observed that a sizable portion of flocs generated during the propagation of the turbidity current are elongated, resulting in flocs of considerable equivalent diameter (as indicated by the red circle in Figure 3D). These substantial flocs exhibit a low settling velocity due to their composition of low-density, uncoiled flocculant with a modest quantity of clay attached to it. These flocs are shown in the snapshot presented in Figure 3 (A,D). Owing to their limited residence time in the water column, these flocs were unable to ensnare additional clay particles and retain an open structure; they did not have enough time to coil. The coiling of flocs occurs over a more extended period when turbulent shear forces induce the dangling ends of the polyelectrolyte to collapse onto the floc. As a result, the flocs transform into rounder and denser structures (Shakeel et al., 2020). It is noteworthy to mention here that the amount of clay and organic matter play a key role in flocculation process.

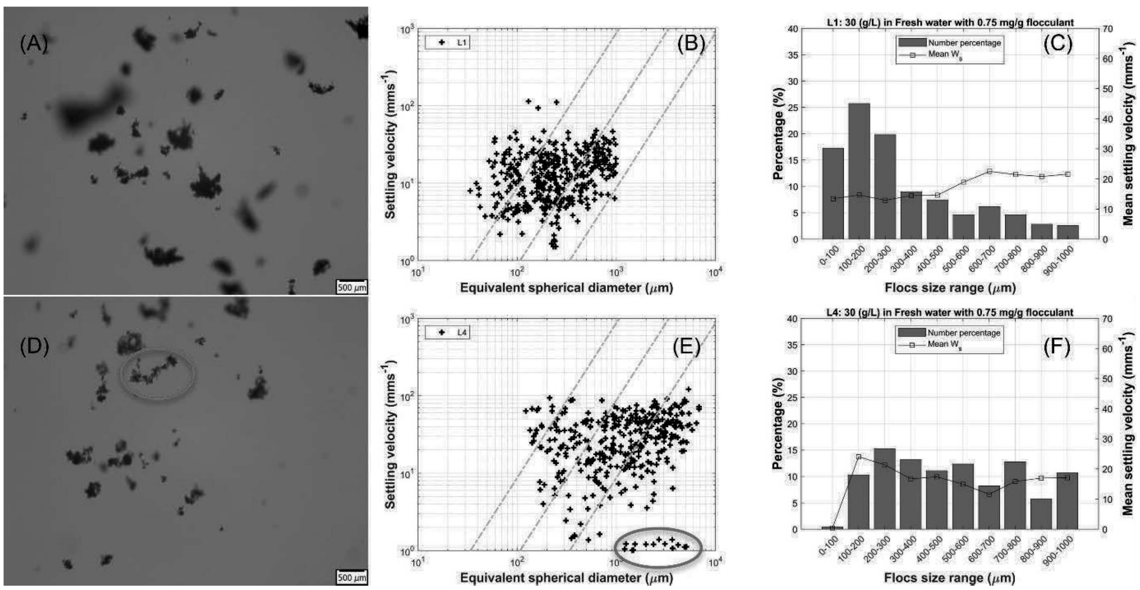

Figure 3. Settling velocity analysis of flocs collected from the turbidity current induced in a lock exchange setting at locations L1 (A-C) and L2 (D-F), which correspond to the initiation and conclusion of the lock exchange, respectively. A,D) Video snapshots. ; B,E) Settling velocity and particle size analysis of the samples collected at location L1 and L4 during lock exchange experiments with 30 (g/L) artificial deep sea clay and 0.75 (mg/g) of zetag 4120 flocculant in freshwater. Settling velocity is derived as a function of equivalent spherical diameter, with diagonal dashed lines representing the contours of effective density calculated by using Stokes equation (from left to right: 1600, 160, 16 kg/m^3). C,F)Floc size range and mean settling velocity (Ali et al., 2022).

Recent flocculation experimental studies with deep-sea clay have shed light on the rapid aggregation of clay particles in the presence of abundant organic matter, even under varying clay concentrations and shear rates (Ali et al., 2023). These experiments were conducted on two distinct clay samples, designated Clay 1 and Clay 2, collected from separate regions of the CCFZ. Clay 1 was collected from the German licensing zone of CCFZ, while Clay 2 was obtained from the Belgian contracted area of CCFZ. Total organic carbon (TOC) in Clay 1 is approximately 0.53 wt.%, and for Clay 2 is 0.55 wt.%. The organic matter in Clay 2 exhibited a visual distinction from that in Clay 1. In Clay 2, organic matter appeared as long, elongated strings, a feature not observed in the organic matter of Clay 1. The Clay 1 and Clay 2 samples exhibit a d50 of approximately 20 µm, as determined by static light scattering through a Malvern Master Sizer 2000 (Ali and Chassagne, 2022). Figure 4 depicts the impact of mixing time and clay concentration on flocculation. The median floc size of Clay 1 is compared with the median floc size of Clay 2 for various concentrations and mixing times. This comparison clearly demonstrates that the presence of organic matter contributes to rapid flocculation in both clays. Intriguingly, Clay 2 exhibits a significantly faster flocculation rate and produces larger flocs compared to Clay 1, regardless of the concentration or mixing time. This distinct behavior is attributed to the differential abundance and composition of organic matter in the two clay samples. The accelerated flocculation observed in Clay 2 highlights the crucial role of organic matter in deep-sea sediments, particularly in regulating the dispersion of sediment plumes generated by deep-sea mining activities. The findings of these flocculation experiments underscore the importance of understanding the complex interplay between organic matter, clay properties, and environmental conditions in deep-sea sediments. These results are in line with the findings of Gillard et al. (2019) who did experimental study of flocculation with deep sea clay.

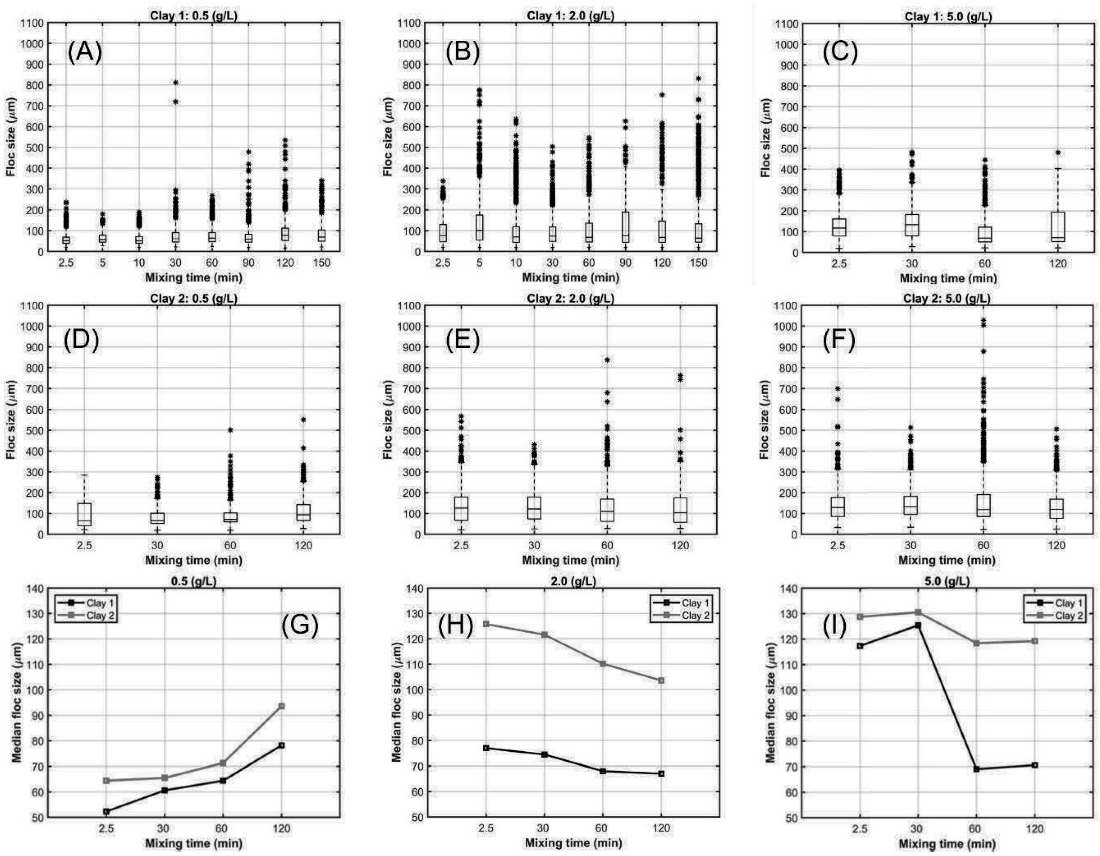

Figure 4. Effect of mixing time on flocculation of Clay 1 (A-C) and Clay 2 (D-F) concentrations of (A,D) 0.5 (g/L), (B,E) 2.0 (g/L) and (C,F) 5.0 (g/L). Median floc size for Clay 1 and Clay 2 concentrations of (G) 0.5 (g/L), (H) 2.0 (g/L) and (I) 5.0 (g/L). (Ali et al., 2023).

3 DREDGING PLUMES

One of the most common occurrences of turbidity flows in shallow water applications is in the form of dredging. The trailing suction hopper dredger (TSHD) is commonly employed in dredging operations such as for maintaining waterways and creating new land. It functions by drawing a mixture of sediment and water from the bed into a hopper. The plume generated by TSHD, is known as the overflow plume, and is primarily consists of fine sediment that has not fully settled in the hopper. The overflow plume typically represents the primary source of turbidity during dredging with a TSHD (Bray, 2008; Laboyrie and Kolman, 2018). The overflow plume, being denser than the surrounding water, initially descends towards the seabed. However, due to turbulence and interaction with the dredging vessel, it can mix with the ambient water and be transported upwards,

sometimes reaching the water surface. The suspended fine sediment in the overflow plume can remain in suspension for hours to days, particularly in the surface layer. This can lead to the dispersion of sediment to areas far from the dredging site, potentially impacting sensitive ecosystems. Numerous studies have investigated the environmental impact of dredging, primarily focusing on heightened turbidity levels and sedimentation (e.g., Capello et al., 2013; Erftemeijer et al., 2012; Gilkinson et al., 2003; Kim and Lim, 2009; Laboyrie and Kolman, 2018; Mestres et al., 2013).
The dynamics of the overflow plume are primarily governed by the near field, where the plume is influenced by the dredging vessel and density differences. The far field is dominated by sediment settling and ambient currents. The settling velocity of sediment in the overflow plume varies depending on particle size, ranging from millimeters per second for flocculated mud to centimeters per second for fine sand. This implies that coarser sediment will deposit near the dredging vessel, while the finer fractions may remain suspended for extended periods. The flocculation of fine sediment particles within the overflow plume is a crucial factor. Flocculation occurs due to turbulence, differences in settling velocity, and Brownian motion, resulting in flocs with sizes of 0.01 to 1 mm. Strong flocculation has been observed for mud fractions inside an overflow plume, with floc diameters ranging from 40 to 800 micron and settling velocities from 0.1 to 6 mm/s (Smith and Friedrichs, 2011). To effectively assess the environmental impact of dredging projects, it is essential to understand the dynamics of overflow plumes, particularly the near-field processes that govern their initial vertical distribution. This knowledge can help predict the fate of suspended sediment and minimize potential ecological harm.

4 INSIGHTS GAINED FROM DEEP-SEA MINING RESEARCH APPLICABLE TO DREDGING

Dredging activities also generate sediment plumes that can form turbidity currents, potentially causing similar environmental impacts as those associated with deep-sea mining. The lessons learned from the study of flocculation in deep-sea mining plumes can be applied to improve turbidity current management practices in dredging operations. By understanding the factors that influence flocculation, such as organic matter content, salinity, and particle size distribution, settling velocities dredging companies can implement strategies to minimize the formation and spread of turbidity currents. By incorporating flocculation effects in dynamic flows, we can achieve more accurate plume dispersion modeling. This enhancement results in improved Particle Size Distribution (PSD) and settling velocity distribution for far field models. Furthermore, better predictions enable more effective utilization of the flocculation effect, ultimately aiding in the reduction of turbidity dispersion at the source. Flocculation is most likely to occur in proximity to the equipment, presenting an opportunity to make a significant difference.

- **Organic Matter Addition:** Adding organic matter, such as natural polymers or synthetic flocculants, can accelerate the aggregation of sediment particles, leading to the formation of larger flocs. This can significantly reduce the duration and intensity of turbidity currents, minimizing their environmental impact.
- **Dredging Location and Depth:** Selecting appropriate dredging locations and depths can minimize the impact of turbidity currents. Dredging in areas with high organic matter content can enhance flocculation and reduce the spread of sediment plumes.
- **Salinity Manipulation:** The rate of flocculation is influenced by salinity, with higher salinity enhancing the aggregation process in the presence of organic matter. In some cases, increasing the salinity of the water can be an effective way to promote flocculation and control turbidity currents. Tidal cycles, in conjunction with river discharges, can be strategically utilized to determine the ideal time and location for dredging activities based on the prevailing salinity levels. This approach is particularly significant in coastal regions characterized by the mixing of fresh and saltwater, known as brackish water. By monitoring salinity thresholds, dredging operations can be optimized to minimize environmental impact and enhance efficiency.
- **Water Flow Management:** The rate of flocculation in the dredged material is influenced by the surrounding flow conditions. Maintaining sufficient water circulation and turbulence is essential for dispersing organic matter and facilitating particle aggregation. In optimizing the turbidity source, considerations include altering sediment flux, adjusting concentrations (e.g., through recirculation), and managing the momentum of material discharge.

The insights gained from flocculation studies in deep-sea mining plumes can be applied to enhance turbidity current management in dredging operations. Understanding the factors influencing flocculation, such as the role of organic matter and particle interactions, can aid in optimizing dredging strategies. Real-time monitoring of flocculation dynamics during dredging activities can guide equipment selection, operational decisions, and environmental impact assessment. Utilizing this knowledge can minimize turbidity levels, reduce sediment dispersion, and mitigate potential ecological disturbances in shallow marine environments.

Flocculation is a complex phenomenon that plays a significant role in the dynamics of turbidity currents generated by dredging and deep-sea mining activities. Understanding the factors that influence flocculation and employing strategies to enhance it can significantly reduce the environmental impact of these activities. By harnessing the power of flocculation, dredging companies and marine mining operators can minimize the disturbance to marine ecosystems and contribute to sustainable practices in the marine environment.

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