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Hydrodynamically-Driven Deposition of Mud in River Systems

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Key Points:

- Flocculation of mud in water is a ubiquitous phenomenon
- Salinity may have little to no effect on mud floc size as rivers enter marine environments
- Deposition of flocculated mud in river systems is driven by changes in hydrodynamic stress

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Abstract The riverine transport and deposition of mud is the primary agent of landscape construction and evolution in many fluvial and coastal environments. Previous efforts exploring this process have raised uncertainty regarding the effects of hydrodynamic and chemical controls on the transport and deposition of mud, and thus the constructions of muddy coastal and upstream environments. As such, direct measurements are necessary to constrain the deposition of mud by river systems. Here, we combine laboratory evidence and a field investigation in the Mississippi River delta to explore the controls on the riverine transport and deposition of mud. We show that the flocculation of mud, with floc diameters greater than 10 μm, in freshwater is a ubiquitous phenomenon, causing the sedimentation of mud to be driven by changes in local hydrodynamics, and thus providing an explanation for how river systems construct landscapes through the deposition of mud in both coastal and upstream environments.

Plain Language Summary Muddy landscapes are some of the most common and vital environments on Earth's surface, such as floodplains, deltas, and estuaries. Due to their small size, and thus easily suspendable nature, mud particles are thought to be extremely difficult to deposit under typical flow conditions in rivers. As such, the means by which rivers deposit mud has been the subject of much study and debate. Canonically, the deposition of cohesive sediment occurs as rivers approach the ocean, where increases in salinity induce the aggregation of clay and silt particles to form heavier floccules, or "flocs." Recent studies have also explored the influence of organic material on mud aggregation. However, the means by which rivers are able to construct muddy landscapes upstream, in the absence of saline or organic-rich water, remains uncertain. To address this discrepancy, we utilize a combination of laboratory evidence and a field investigation on the Mississippi River delta to show that all mud is transported as flocs, not as individual grains, and as such, the deposition of mud by river systems is controlled by the ability of the river flow to suspend existing mud flocs, and not by abrupt changes in water chemistry inducing flocculation in coastal regions.

1. Introduction

The transport and deposition of riverine mud is the primary agent of landscape construction and evolution across the majority of Earth's surface (Dyer, 1989; FAO, 1988; Kemper & Rosenau, 1984; Lamb et al., 2020; Young & Southard, 1978). Fluvial systems are distribution networks that transport cohesive sediment to construct floodplains, deltas, and estuaries found across the Earth's surface and in the sedimentary record on Mars. While muddy landscapes may not be entirely composed of mud, even small amounts of cohesive sediment may increase the bulk strength of otherwise non-cohesive sand, thus exerting a controlling influence on landscape morphology and morphodynamics (Dunne & Jerolmack, 2018, 2020; Julian & Torres, 2006; Kothyari & Jain, 2008). As such, constraining the transport and deposition of mud is vital to improve our understanding of landscape evolution.

We define mud as a mixture of fine silt, clay, and organic sediment, for which inter-particle attraction, beyond contact friction, results in the aggregation of fine sediment (Ternat et al., 2008). On Earth, mud may often, but not necessarily, contain organic material. The combination of turbulent mixing and inter-particle attraction drives the aggregation of suspended particles to form larger, irregularly shaped sediment floccules, colloquially referred to as "flocs," within the water column (Lawrence et al., 2022; Spencer et al., 2022). The growth and breakup of flocs is shown to be a function of the strength of interparticle attraction and turbulent shear (Hill, 1996; Keyvani & Strom, 2014; Krone, 1986; A. Manning & Dyer, 1999; Mehta, 2022; Mietta et al., 2009; Soulsby et al., 2013; Van Leussen, 1997; Vowinckel et al., 2019) (Figure 1a). Flocs observed in natural environments typically range in

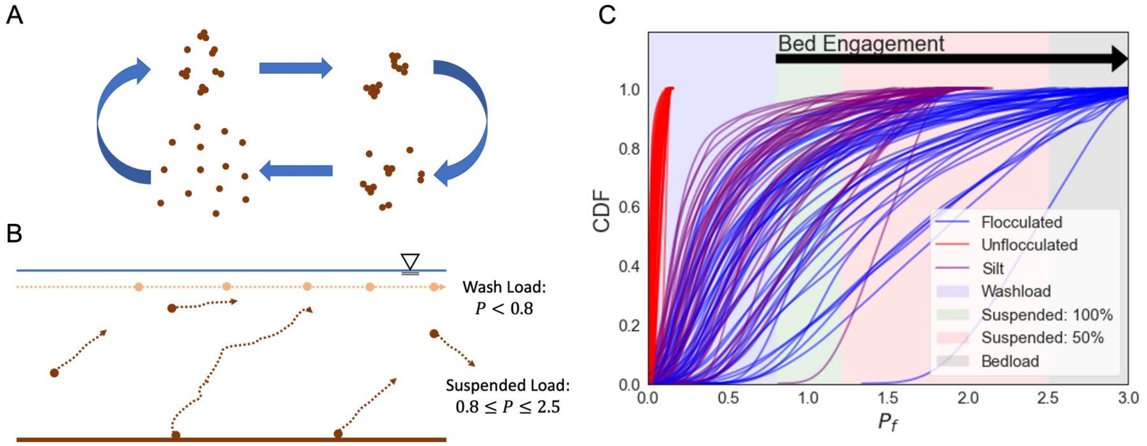

Figure 1. (a) Schematic of the flocculation process. (b) Schematic comparing washload and suspended load transport. (c) Cumulative Distribution Function (CDF) of Rouse Number of 100 μm flocs during overbank flows on floodplains. Line color is indicative of particle size. Background color is indicative of transport type phase space.

diameter from 50–5,000 μm, while flocs processed in laboratory settings typically range between 30 and 800 μm. In both cases, the flocculation process has been empirically and theoretically demonstrated to increase the rate at which aggregates are able to settle out from suspension in the water column, and thus induce the deposition of fine-grained, cohesive sediment (Abolfazli & Strom, 2022, 2023; Adachi & Tanaka, 1997; Alldredge & Gotschalk, 1988; Bungartz & Wanner, 2004; Curran et al., 2007; Droppo et al., 2000; Dyer, 1989; Dyer et al., 1996; Fennessy et al., 1994; Fox et al., 2004; Gibbs, 1985; Graham & Manning, 2007; Gratiot et al., 2005; Gratiot & Manning, 2004; Huang, 1994; Krone, 1986; Kumar et al., 2010; Lamb et al., 2020; Lick et al., 1992, 1993; A. J. Manning & Bass, 2006; A. Manning & Dyer, 1999; Mikkelsen et al., 2007; Nghiem et al., 2022; Osborn et al., 2021, 2023; Soulsby et al., 2013; Sternberg et al., 1996; Strom & Keyvani, 2011; Syvitski et al., 1995; Van der Lee, 2000; Winterwerp et al., 2006; Zeichner et al., 2021).

Canonically, flocculation of mud occurs in deltaic and estuarine environments where the presence of cations in marine water neutralizes the repellent surface charge on clay minerals, allowing for particles to aggregate (Hunter & Liss, 1982; Mietta et al., 2009; Sutherland et al., 2015; Whitehouse, 2000). Additionally, various field and laboratory investigations have demonstrated that flocculation will occur in the presence of a high concentration of organics, particularly in response to the introduction of long-chain organic polymers such as Xanthum gum (Abolfazli & Strom, 2023; Deng et al., 2019, 2023; Gregory, 1978; Mietta et al., 2009; Zeichner et al., 2021). However, a recent compilation of suspended sediment vertical concentration profiles has suggested that flocs form across a range of geochemical conditions in freshwater environments (Lamb et al., 2020; Nghiem et al., 2022). Given such a range of environmental conditions, and in combination with the presence of deposited mud upstream, flocs likely form across the full range of environmental conditions.

To date, few studies have directly measured the in-situ size and characteristics of flocs transported in rivers, and, as such, our understanding of the controls on floc size, how flocs are transported, and how fluvial systems deposit mud and construct muddy landscapes remains relatively unconstrained (Lamb et al., 2020; Nghiem et al., 2022; Osborn et al., 2021). Through a combination of laboratory experiments and a field investigation, we provide direct evidence that the baseline state for cohesive sediment transported in water is flocculated, which in turn facilitates mud settling out from suspension under standard turbulent environmental conditions, thus creating the muddy channel beds and floodplains observed on Earth and Mars (Lapôtre et al., 2019; Matsubara et al., 2015).

2. Particle Settling and Transport

Sediment transport is typically described by three categories: bedload, suspended load, and washload (Church, 2006; Rouse, 1937). Bedload is the trundling of grains along the bed, more typical in gravel-bedded rivers or a few specific sandy environments (Church, 2006; Devauchelle et al., 2011; Dunne & Jerolmack, 2018). Grains transported as suspended load make lengthy hops and are supported by the flow for long periods of time. In contrast, washload is the consistent suspension of particles by the flow that never settle out from the flow, and thus do not engage with bed material. These three sediment transport phase spaces are delineated by the Rouse Number (P), which contrasts the grain settling velocity (w_s) with the fluid shear velocity (u_*) of the flow as:

$$P = \frac{w_s}{\kappa u_*}, \tag{1}$$

where κ is von Kármán's constant (Von Kármán, 1930), usually taken to be $\kappa = 0.41$ (García, 2008; Nezu & Nakagawa, 1993; Nezu & Rodi, 1986). Transport states categorize grains for which $P < 0.8$ as washload, $0.8 \leq P \leq 2.5$ as suspended load, and $P > 2.5$ as bedload. The key difference between suspended load and washload is that sediment transported as suspended load will temporarily deposit and exchange with the channel bed, as such $P = 0.8$ can be defined as the threshold of bed engagement, P_B (Figure 1b). For transported sediment of Rouse number $P \geq P_B$, the bed over which sediment is transported will have a composition that reflects the composition of the transported sediment.

To test this supposition, we present an analysis of the distribution of shear velocities exerted on floodplains by overbank flows (Figure 1c). Using instantaneous flow data from USGS gaging stations ($n = 55$), we examine the cumulative distribution function of instantaneous flow data for rivers for which the presence of mud in the floodplains/river banks can be inferred from the combination of their bed grain size and bankfull shear stress (Dunne & Jerolmack, 2018, 2020). The bankfull shear velocity, calculated from the channel geometry using the depth-slope product, was subtracted from the distribution of fluid shear velocities and filtered for shear velocity values in excess of bankfull. This provides a coarse estimate of the u_* values exerted on the floodplain by the overbank flow during floods.

Assuming an average clay particle size of 2 μm and an average floc size of 100 μm, and thus average floc settling velocity of 1 mm s^{-1} (Fall et al., 2021; Lamb et al., 2020; Strom & Keyvani, 2011), we find that under no flow conditions does P for unflocculated particles exceed P_B, and thus unflocculated particles occupy solely the washload phase space during overbank flow. As such, overbank flow cannot deposit unflocculated clay particles. In contrast, the CDFs of silt and flocculated particles passes through the full range of Rouse phase spaces, and as such it is more probable for flocculated cohesive sediment to be deposited and able to construct the observed/inferred muddy floodplains. While this analysis is indeed a rough estimate of overbank shear velocities (e.g., changes in hydraulic roughness between floodplains and channels) and uses an assumed floc settling velocity that can be either increased or decreased by the presence of organic matter, silt, and sand (Fall et al., 2021; A. J. Manning et al., 2010; Tran & Strom, 2017), it provides an indication that for landscapes composed of fine-grained sediment across Earth and Mars, settling of cohesive sediment must be wide-spread for a range of environmental conditions. As such, settling cannot be solely driven by the chemical changes in the river water across the transition from fresh to saline environments.

3. Laboratory Evidence of Mud Flocculation in the Absence of Added Salts

A suite of experiments was conducted in laboratory mixing tanks to explore the response of suspended mud floc size distributions to changes in salinity, type and quantity of organics present, and the composition of inorganic clays and silts. Abolfazli and Strom (2023) have highlighted that the response of suspended mud floc size distributions in laboratory mixing tanks to an increase in salinity is dependent on the type and quantity of organics present and the composition of the inorganic clays and silts. Yet, all laboratory mixing-tank experiments on clay minerals and natural mud consistently point to the prevalence of flocs in the absence of marine salinity. For example, pure kaolinite has been found to flocculate better in pure deionized water than it does in deionized water with the addition of NaCl (Figures 2a and 2b), similar to the observation of Abolfazli and Strom (2023) and Partheniades (2009). While flocs composed of pure inorganic sediment are typically smaller than those observed with natural mud, the manyfold increase in size from constituent grains (D_{50} = 5–10 μm) to floc size (D_{50} = 45 μm) under the simple combination of just clay minerals and deionized water is notable.

This finding is in agreement with other studies on the sedimentation of cohesive sediment that showed negligible change in the zeta potential (and thus colloidal stability) of clay particles in saline water as salinity was increased after the addition of salt to the solution (Chassagne et al., 2009; Seiphoori et al., 2021). Many studies have shown that salt can, at times, interact with sediment and organic matter to change the size distribution of suspended mud

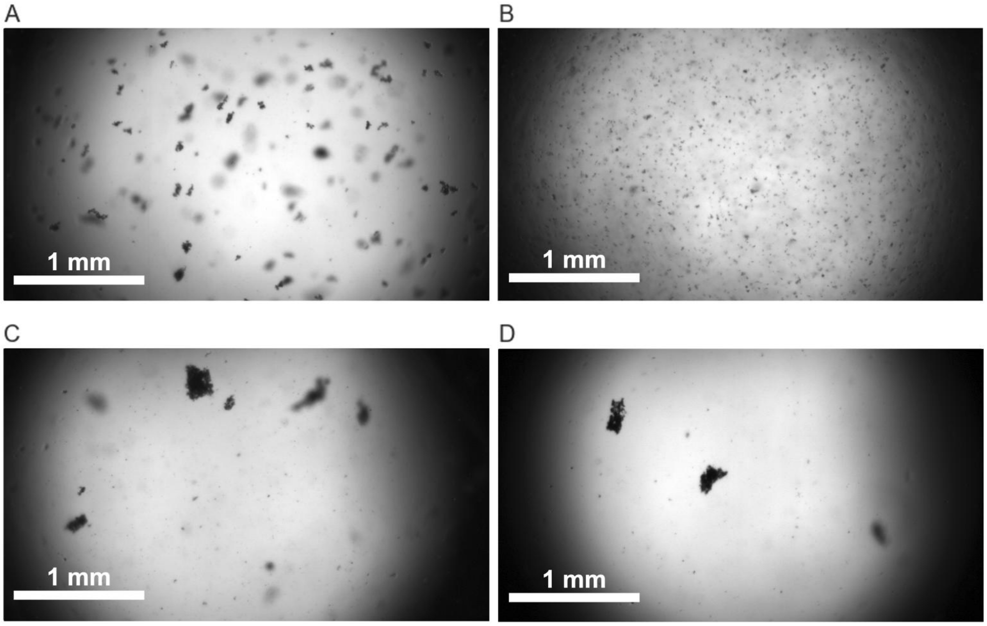

Figure 2. (a) Flocs formed by kaolinite in deionized water ($D_{50} = 45$ µm). (b) Flocs formed by kaolinite in deionized water with added 2 ppt NaCl ($D_{50} = 19$ µm). (c) Flocs observed in mixing tank experiments with water from the Mississippi River near Venice, LA ($D_{50} = 146$ µm). (d) Flocs observed in mixing tank experiments with water and sediment from Stroubles Creek near Blacksburg, Virginia ($D_{50} = 173$ µm).

flocs (Abolfazli et al., 2024; Abolfazli & Strom, 2022, 2023; Deng et al., 2023; Mietta, 2010; Verney et al., 2009). Yet, the point we are making with these examples is that mud can and typically does exist in a flocculated state without the presence of marine water. It is, therefore, likely that mud normally exists in a flocculated state in riverine environments as suggested by Droppo and Ongley (1994) and shown in Osborn et al. (2023) for portions of the Mississippi River.

Furthermore, as part of the study presented in this paper, samples of natural bed sediment and stream water were put into the same laboratory mixing tanks from both the lower reaches of the Mississippi River (near Venice, LA) and its headwaters (i.e., Stroubles Creek near Blacksburg, VA) all produced flocs of substantial size without the addition of salt (Figures 2c and 2d); see Abolfazli (2023) for experimental methods. The ambient salinity in both freshwater test cases was less than 0.1 PSU, contained a mixture of clay mineral types and organic material, and had flocs of substantial size (e.g., the D_{50} of images C and D are 146 and 173 µm, respectively).

4. Field Investigation

Given the discrepancy between the canonical need for saline water to initiate the flocculation of mud, and both laboratory evidence and recent data compilations (Chassagne et al., 2009; Lamb et al., 2020; Seiphoori et al., 2021; Zeichner et al., 2021) suggesting that mud flocs form naturally in freshwater river systems, direct measurements of floc sizes across a range of natural environments is required. The spatially dynamic physical and chemical nature of the Fluvial to Marine Transition Zone (FMTZ), the region over which a river transitions from a freshwater to a saline environment, presents an ideal opportunity to explore the controls on the size and settling rate of mud flocs carried in suspension by the river.

We conducted a field investigation in the FMTZ of the Mississippi River, starting in the main channel (MC) of the Mississippi River near the Bonnet Carré Spillway (station ID: BC, 200 km upstream from Head of Passes [HOP]), and proceeded down the MC to near Venice, LA (station ID: MC, 20 km upstream from HOP), and to the ocean through the South Pass (SP) channel (station IDs: SP1-10, 2.5–20 km downstream from HOP) (Figure 3a). This survey was conducted in late June 2020 under a discharge range of 16,310–25,683 m^3 s^{-1}. At each site, we deployed the FlocARAZI (Osborn et al., 2021) (Figure 3a inset), a conductivity, temperature, and depth sensor, a P6 suspended sediment sampler (Nittrouer et al., 2011), and a Shippek grab sampler. These devices allowed us to

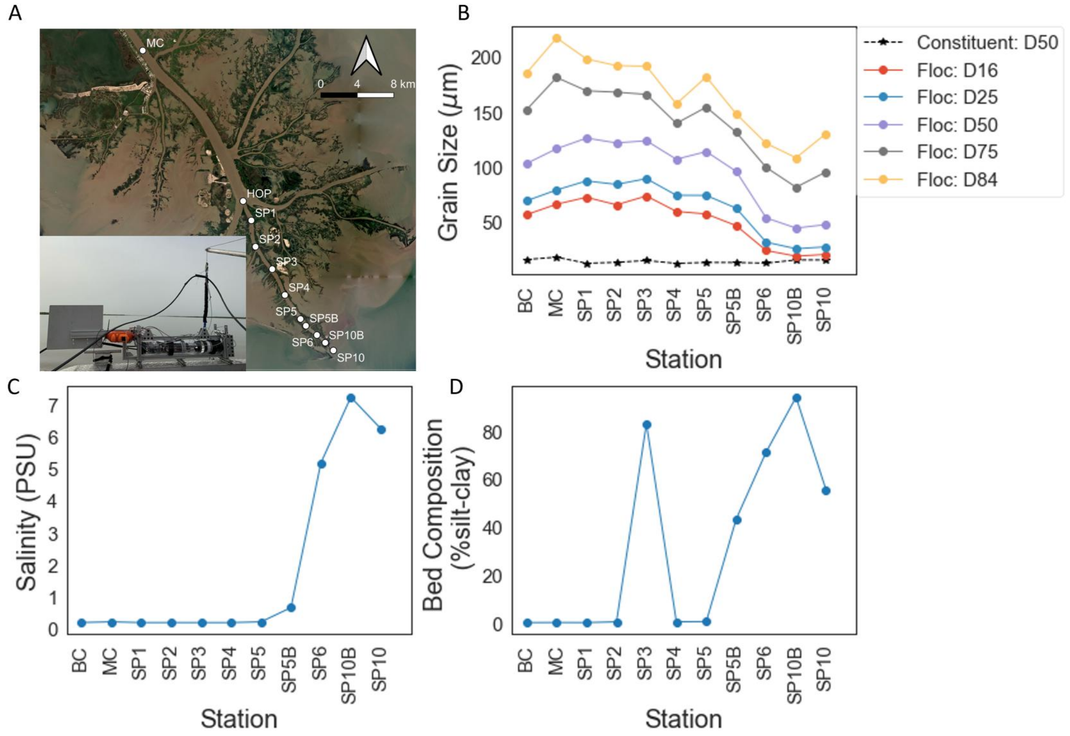

Figure 3. (a) Map of station locations and Head of Passes (HOP) within the Mississippi River Delta (image source: Planet). Inset image: FlocARAZI used to image flocs. (b) Particle size distribution at each station. Line color is indicative of particle size percentile within the distribution. (c) Salinity at each station. (d) Bed sediment % silt and clay by mass at each station.

measure floc size, water salinity, suspended sediment concentration, and bed grain-size composition from the channel thalweg. Using the FlocARAZI, we see the depth-averaged distribution of floc sizes at each station and note an abrupt shift in the floc-size distribution around station SP5B (Figure 3b). Suspended sediment samples were collected using a P6 sampler and were later dosed with sodium hexametaphosphate, sonicated, and analyzed using a LISST-Portable XR (Pomázi & Baranya, 2020) to determine the grain size of the constituent particles of the observed flocs (Figure 3b). The decrease in floc size coincides with both an abrupt increase in salinity of the river water and in the mud content, determined through proportion of silt and clay by mass of the bed sediment (Figures 3c and 3d).

Measurements of channel depth were made using a LOWRANCE fish finder, and water surface slopes were calculated using river discharge following the formulation developed by Nittrouer et al. (2011). We determine u_* via the depth-slope product. This method is particularly useful during periods of high discharge (Dong et al., 2019). Based on the measured floc size, constituent grain size, and assumed density of 2,650 kg m^{-3} for the constituent grains, and floc fractal dimension $\eta_f = 2.5$, we calculate the floc settling velocity following the formulation of Strom and Keyvani (2011) for the flocs observed at each station. From the floc w_s and u_* values, calculated P for the floc-size distribution at each station shows that under the high discharge conditions during data collection, the observed floc-size distribution overwhelmingly occupies the washload Rouse phase space ($P < 0.8$) (Figure 4a). However, we note a gradual change in the size of the flocs observed in suspension between the MC and SP.

Given SP's downstream position relative to MC and the general similarity between the floc-size distribution at MC and SP1-5, we infer that the MC supplies its floc-size distribution to SP. Given the decrease in floc size in the lower half of SP, the fate of the larger flocs from the MC is in question. Using the floc-size distribution from station MC and the shear velocity values calculated at each station, we calculate the Rouse number for the MC floc-size distribution as it traverses SP (Figure 4b). In this case, the Rouse number of the coarser portion of the floc-size distribution, illustrated by the D_{75} and D_{84}, exceed P_B. This shift across the P_B boundary at SP3 corresponds to a general shift in bed-sediment composition from nearly pure sand to 50% or greater silt-clay content

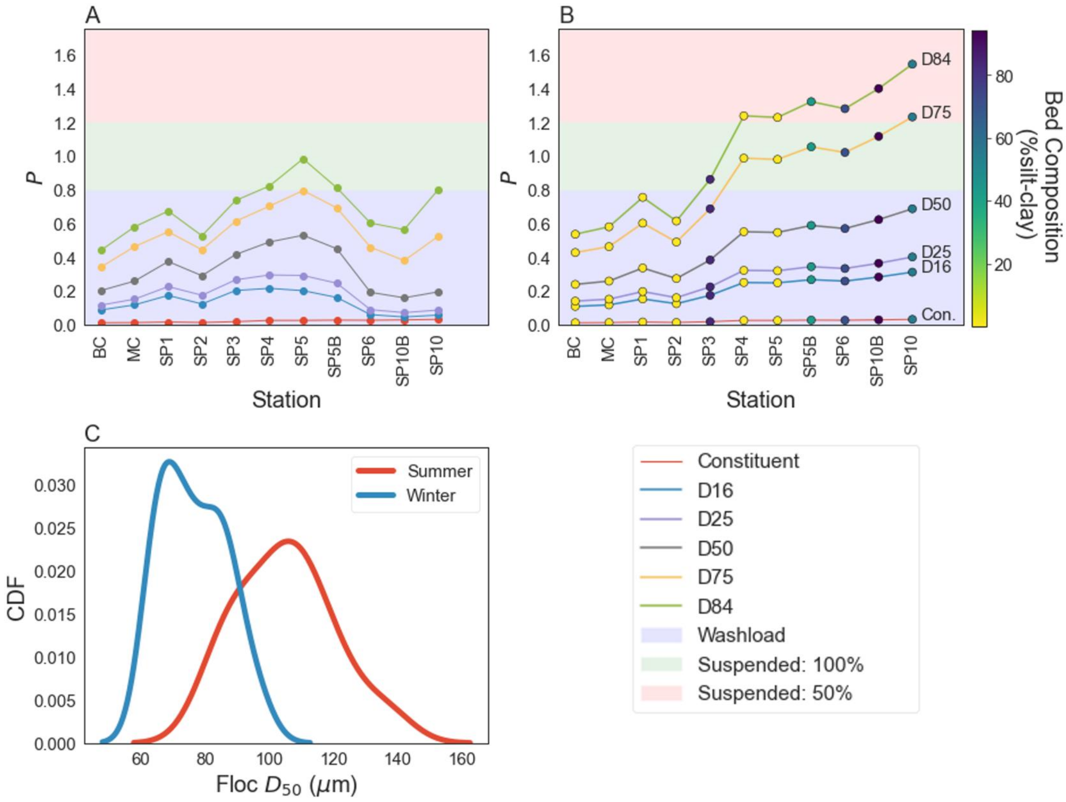

Figure 4. (a) Rouse number (*P*) of floc-size distribution observed at each station. Line color is indicative of particle-size percentile within the distribution. Background color indicates transport type phase space. (b) Rouse number (*P*) of main channel (MC) floc-size distribution at each station. Line color is indicative of particle size percentile within the distribution. Point color is indicative of % silt and clay by mass in the bed sediment at each station. Background color is indicative of transport-type phase space. (c) Comparison on depth-averaged median floc-size distribution at station MC between summer and winter months.

by mass. While there is indeed variability in bed composition downstream from SP3, likely due to seasonal variation in fluid shear stress and rate of deposited mud erosion (Galler & Allison, 2008), the correlation between the Rouse number exceedance of P_B for the coarse fraction of the MC flocs with the shift in bed composition from sand to mud is indicative of hydrodynamically-driven deposition of flocs on the river bed.

An identical survey was attempted in January 2021, however, the SP locations were unreachable due to channel navigability issues. Measurements of floc-size distributions in the MC at station MC were made under comparable discharge conditions to the summer (18,293 $m^3\ s^{-1}$). Water temperature was 6.3°C in the winter versus 27.9°C in the summer. Results show seasonality could have a profound effect on the depth-averaged distribution of the median floc size: D_{50} was 37% larger, and variance of floc D_{50} being 128% greater, during the summer than winter.

5. Discussion

Our study shows through in-situ measurements that flocculation in both field and laboratory environments is a ubiquitous phenomenon that greatly increases the ability of cohesive sediment to settle out from suspension. The tendency for clay minerals in water to flocculate, regardless of the presence of dissolved salts or organic matter, offers a potential explanation for how rivers transport and deposit cohesive sediment. This leads to the development of cohesive floodplains, even upstream of marine water intrusions or in the absence of organic material, such as is understood to-date on Mars. Our field results show a consistent state of flocculation for mud transported by the Mississippi River. A trend of decreasing floc size downstream toward the marine outlet, from a median floc size of approximately 100–50 μm, corresponds to a decrease in shear velocity, and thus ability of the flow to maintain floc suspension. Observed increases in salinity moving down the pass, from 0 to 7 PSU, did not result in a corresponding increase in suspended floc size. While this finding may appear to be in contrast to previous assertions that flocculation initiates or intensifies as rivers enter saline, coastal environments, previously observed changes in floc size within this region could also be due to a range of other physical and biochemical influences within the coastal zone.

The onset of bed interaction with the exceedance of P_B leads to the accumulation of mud on the bed. The diminishing capacity of the flow to maintain a washload transport state ($P < 0.8$) for the floc-size distribution due to decreasing u_* allows for the coarse fraction of the floc-size distribution to exceed the P_B and interact with the bed through either ephemeral or perennial deposition under flow conditions that would otherwise prohibit the deposition of unflocculated clay particles. Comparisons of floc-size distributions between summer and winter months demonstrates a strong effect on the depth-averaged median floc-size distribution, despite comparable discharge and shear conditions. We attribute this 37% increase in the median floc size and 128% increase in the variance of the floc size distribution to increased biological activity due to warmer water temperatures in summer months leading to enhanced production and availability of organic matter, which has been previously demonstrated to result in the formation of larger flocs (Eisma, 1986; Verney et al., 2009; Zeichner et al., 2021). Seasonal variations in floc size, driven by changing levels of biological activity, and fluid shear stress, driven by changes in discharge and/or form drag, likely result in spatially variable deposition of mud on the channel bed.

In the regions of the study area without deposition of mud on the bed, our observed median floc sizes were approximately 100 μm. This is consistent with the range of back-calculated and observed floc sizes in previous studies of flocs in a variety of other freshwater environments and laboratory conditions (Abolfazli & Strom, 2023; Lamb et al., 2020; Lawrence et al., 2022; Nghiem et al., 2022; Osborn et al., 2023; Soulsby et al., 2013; Zeichner et al., 2021). We find that, despite the range of floc sizes observed in the field between stations, the D_{50} of the floc constituent particles remained constant at approximately 14 μm. This indicates that the observed suspended sediment behaviors are driven by changes in the floc-size distribution and not by changes in the constituent grain size. Previous studies of Mississippi River suspended sediment composition have shown that the fine portion of the suspended sediment load (≤62.5 μm) is comprised of a mixture of various silt sizes and clay mineralogies (Johns & Grim, 1958; Johnson & Kelley, 1984). Additionally, previous laboratory investigations have demonstrated that, while flocs do contain the silt fraction of the suspended sediment load, floc size is unaffected by silt content and driven by clay particle interactions (Tran & Strom, 2017).

For all analyzed suspended sediment samples, we find particles that occupy the clay-size range (≤2 μm) comprise, on average, less than 5% of the cumulative volume distribution of the constituent particles (see Dunne et al., 2024), despite the sonication and dispersant treatment that the flocs were subjected to. Given that approximately 95% of the cumulative volume concentration of the treated sediment is outside the size range of clay, and that field evidence demonstrates that the sampled suspended sediment was indeed flocculated at the time of sampling, we propose that the average constituent grain size of 14 μm is indicative of the presence of hyper-stable clay aggregates within the flocs that even vigorous sonication and the use of chemical dispersants were not able to disaggregate. This is consistent with previous work that has suggested that mud flocs should not be thought of as structures comprised of individual cohesive grains with uniform density and stability, but rather size-dependent path of a hierarchy of aggregate stability where larger, more fragile flocs are comprised of smaller, more stable aggregates (Fall et al., 2021; Krone, 1963; Michaels & Bolger, 1962; Soulsby et al., 2013; Van Leussen, 1988).

Data suggest that order 1 μm diameter clay particles, and possibly organic materials (Fall et al., 2021), appear to be able to form hyper-stable order 10 μm diameter stable aggregates, which in turn appear to form semi-stable order 100 μm diameter aggregate. This hierarchy of stability offers a possible explanation for the reactive nature of floc size to environmental forcings, including turbulent shear or biological activity, despite the ubiquitous tendency of clay in water to flocculate. Bonds between the particles that comprise small, hyper-stable aggregates are strong. However, bonds between the hyper-stable aggregates are relatively weaker and thus more likely to form or break under various environmental conditions, resulting in the macroscopic floc size being driven by external environmental forcings. Further work will be necessary to explore the controls on the yield strength of bonds between aggregates of varying sizes and bonds of various origin.

Our findings demonstrate through field and laboratory studies that the flocculation of clay in water is a ubiquitous phenomenon that allows for the deposition of cohesive sediment by river systems both on the bed of river channels and during overbank flows. While floc size does appear to be enhanced by biological activity and/or the presence of organic matter, the first order control on the deposition of mud by river systems, and thus the construction of muddy channels and floodplains found across a range of environments on Earth and Mars, is changes in local hydrodynamic stresses and the capacity of a flow to transport flocculated mud as either washload or suspended load.

Data Availability Statement

Data associated with this study is available at Dunne et al. (2024).

Acknowledgments

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References

Abolfazli, E. (2023). Laboratory experiments on mud flocculation dynamics in the fluvial and estuarine environments (Unpublished doctoral dissertation). Virginia Tech.

Abolfazli, E., Osborn, R., Dunne, K. B. J., Nittrouer, J. A., & Strom, K. (2024). Flocculation characteristics of suspended Mississippi River mud under variable turbulence, water and salt sources, and salinity: A laboratory study. *Frontiers in Earth Science*, *12*, 1268992.

Abolfazli, E., & Strom, K. (2022). Deicing road salts may contribute to impairment of streambeds through alterations to sedimentation processes. *ACS ES&T Water*, *2*(1), 148–155. https://doi.org/10.1021/acsestwater.1c00300

Abolfazli, E., & Strom, K. (2023). Salinity impacts on floc size and growth rate with and without natural organic matter. *Journal of Geophysical Research: Oceans*, *128*(7), e2022JC019255. https://doi.org/10.1029/2022jc019255

Adachi, Y., & Tanaka, Y. (1997). Settling velocity of an aluminium-kaolinite floc. *Water Research*, *31*(3), 449–454. https://doi.org/10.1016/s0043-1354(96)00274-6

Alldredge, A. L., & Gotschalk, C. (1988). In situ settling behavior of marine snow 1. *Limnology and Oceanography*, *33*(3), 339–351. https://doi.org/10.4319/lo.1988.33.3.0339

Bungartz, H., & Wanner, S. C. (2004). Significance of particle interaction to the modelling of cohesive sediment transport in rivers. *Hydrological Processes*, *18*(9), 1685–1702. https://doi.org/10.1002/hyp.1412

Chassagne, C., Mietta, F., & Winterwerp, J. (2009). Electrokinetic study of kaolinite suspensions. *Journal of Colloid and Interface Science*, *336*(1), 352–359. https://doi.org/10.1016/j.jcis.2009.02.052

Church, M. (2006). Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Sciences*, *34*(1), 325–354. https://doi.org/10.1146/annurev.earth.33.092203.122721

Curran, K., Hill, P., Milligan, T., Mikkelsen, O., Law, B., de Madron, X. D., & Bourrin, F. (2007). Settling velocity, effective density, and mass composition of suspended sediment in a coastal bottom boundary layer, Gulf of Lions, France. *Continental Shelf Research*, *27*(10–11), 1408–1421. https://doi.org/10.1016/j.csr.2007.01.014

Deng, Z., He, Q., Manning, A. J., & Chassagne, C. (2023). A laboratory study on the behavior of estuarine sediment flocculation as function of salinity, EPS and living algae. *Marine Geology*, *459*, 107029. https://doi.org/10.1016/j.margeo.2023.107029

Deng, Z., He, Q., Safar, Z., & Chassagne, C. (2019). The role of algae in fine sediment flocculation: In-situ and laboratory measurements. *Marine Geology*, *413*, 71–84. https://doi.org/10.1016/j.margeo.2019.02.003

Devauchelle, O., Petroff, A. P., Lobkovsky, A., & Rothman, D. H. (2011). Longitudinal profile of channels cut by springs. *Journal of Fluid Mechanics*, *667*, 38–47. https://doi.org/10.1017/s0022112010005264

Dong, T. Y., Nittrouer, J. A., Czapiga, M. J., Ma, H., McElroy, B., Il'icheva, E., et al. (2019). Roles of bank material in setting bankfull hydraulic geometry as informed by the Selenga River Delta, Russia. *Water Resources Research*, *55*(1), 827–846. https://doi.org/10.1029/2017wr021985

Droppo, I., & Ongley, E. (1994). Flocculation of suspended sediment in rivers of southeastern Canada. *Water Research*, *28*(8), 1799–1809. https://doi.org/10.1016/0043-1354(94)90253-4

Droppo, I., Walling, D., & Ongley, E. (2000). Influence of floc size, density and porosity on sediment and contaminant transport. *IAHS Publication (International Association of Hydrological Sciences)*, (263), 141–147.

Dunne, K. B., & Jerolmack, D. J. (2018). Evidence of, and a proposed explanation for, bimodal transport states in alluvial rivers. *Earth Surface Dynamics*, *6*(3), 583–594. https://doi.org/10.5194/esurf-6-583-2018

Dunne, K. B., & Jerolmack, D. J. (2020). What sets river width? *Science Advances*, *6*(41), eabc1505. https://doi.org/10.1126/sciadv.abc1505

Dunne, K. B., Nittrouer, J. A., Abolfazli, E., Osborn, R., & Strom, K. B. (2024). Hydrodynamically-driven deposition of mud in river systems. *Open Science Framework*. https://doi.org/10.17605/OSF.IO/ZAW3V

Dyer, K. (1989). Sediment processes in estuaries: Future research requirements. *Journal of Geophysical Research*, *94*(C10), 14327–14339. https://doi.org/10.1029/jc094ic10p14327

Dyer, K., Cornelisse, J., Dearnaley, M., Fennessy, M., Jones, S., Kappenberg, J., et al. (1996). A comparison of in situ techniques for estuarine floc settling velocity measurements. *Journal of Sea Research*, *36*(1–2), 15–29. https://doi.org/10.1016/s0077-7579(96)90026-5

Eisma, D. (1986). Flocculation and de-flocculation of suspended matter in estuaries. *Netherlands Journal of Sea Research*, *20*(2–3), 183–199. https://doi.org/10.1016/0077-7579(86)90041-4

Fall, K. A., Friedrichs, C. T., Massey, G. M., Bowers, D. G., & Smith, S. J. (2021). The importance of organic content to fractal floc properties in estuarine surface waters: Insights from video, LISST, and pump sampling. *Journal of Geophysical Research: Oceans*, *126*(1), e2020JC016787. https://doi.org/10.1029/2020jc016787

FAO, F. (1988). Unesco soil map of the world, revised legend, with corrections and updates. *World Soil Resources Report*, *60*, 140.

Fennessy, M., Dyer, K., & Huntley, D. (1994). INSSEV: An instrument to measure the size and settling velocity of flocs in situ. *Marine Geology*, *117*(1–4), 107–117. https://doi.org/10.1016/0025-3227(94)90009-4

Fox, J., Hill, P., Milligan, T., & Boldrin, A. (2004). Flocculation and sedimentation on the Po River Delta. *Marine Geology*, *203*(1–2), 95–107. https://doi.org/10.1016/s0025-3227(03)00332-3

Galler, J. J., & Allison, M. A. (2008). Estuarine controls on fine-grained sediment storage in the lower Mississippi and Atchafalaya Rivers. *Geological Society of America Bulletin*, *120*(3–4), 386–398. https://doi.org/10.1130/b26060.1

García, M. H. (2008). Sediment transport and morphodynamics. In *Sedimentation engineering* (pp. 21–163). ASCE.

Gibbs, R. J. (1985). Estuarine flocs: Their size, settling velocity and density. *Journal of Geophysical Research*, *90*(C2), 3249–3251. https://doi.org/10.1029/jc090ic02p03249

Graham, G., & Manning, A. (2007). Floc size and settling velocity within a *Spartina anglica* canopy. *Continental Shelf Research*, *27*(8), 1060–1079. https://doi.org/10.1016/j.csr.2005.11.017

Gratiot, N., & Manning, A. (2004). An experimental investigation of floc characteristics in a diffusive turbulent flow. *Journal of Coastal Research*, 105–113.

Gratiot, N., Michallet, H., & Mory, M. (2005). On the determination of the settling flux of cohesive sediments in a turbulent fluid. *Journal of Geophysical Research*, *110*(C6). https://doi.org/10.1029/2004jc002732

Gregory, J. (1978). Effects of polymers on colloid stability. In *The scientific basis of flocculation* (pp. 101–130). Springer.

Hill, P. S. (1996). Sectional and discrete representations of floc breakage in agitated suspensions. *Deep Sea Research Part I: Oceanographic Research Papers*, *43*(5), 679–702. https://doi.org/10.1016/0967-0637(96)00030-1

Huang, H. (1994). Fractal properties of flocs formed by fluid shear and differential settling. *Physics of Fluids*, *6*(10), 3229–3234. https://doi.org/10.1063/1.868055

Hunter, K., & Liss, P. (1982). Organic matter and the surface charge of suspended particles in estuarine waters 1. *Limnology and Oceanography*, *27*(2), 322–335. https://doi.org/10.4319/lo.1982.27.2.0322

Johns, W. D., & Grim, R. E. (1958). Clay mineral composition of recent sediments from the Mississippi River Delta. *Journal of Sedimentary Research*, *28*(2), 186–199. https://doi.org/10.1306/74d7079a-2b21-11d7-8648000102c1865d

Johnson, A. G., & Kelley, J. T. (1984). Temporal, spatial, and textural variation in the mineralogy of Mississippi River suspended sediment. *Journal of Sedimentary Research*, *54*(1), 67–72. https://doi.org/10.1306/212f83a5-2b24-11d7-8648000102c1865d

Julian, J. P., & Torres, R. (2006). Hydraulic erosion of cohesive riverbanks. *Geomorphology*, *76*(1–2), 193–206. https://doi.org/10.1016/j.geomorph.2005.11.003

Kemper, W., & Rosenau, R. (1984). Soil cohesion as affected by time and water content 1. *Soil Science Society of America Journal*, *48*(5), 1001–1006. https://doi.org/10.2136/sssaj1984.03615995004800050009x

Keyvani, A., & Strom, K. (2014). Influence of cycles of high and low turbulent shear on the growth rate and equilibrium size of mud flocs. *Marine Geology*, *354*, 1–14. https://doi.org/10.1016/j.margeo.2014.04.010

Kothyari, U. C., & Jain, R. K. (2008). Influence of cohesion on the incipient motion condition of sediment mixtures. *Water Resources Research*, *44*(4). https://doi.org/10.1029/2007wr006326

Krone, R. B. (1963). *A study of rheologic properties of estuarial sediments* (Tech. Rep.). California University Berkeley Sanitary Engineering Research Lab.

Krone, R. B. (1986). The significance of aggregate properties to transport processes. In *Estuarine cohesive sediment dynamics* (Vol. 14, pp. 66–84).

Kumar, R. G., Strom, K. B., & Keyvani, A. (2010). Floc properties and settling velocity of San Jacinto estuary mud under variable shear and salinity conditions. *Continental Shelf Research*, *30*(20), 2067–2081. https://doi.org/10.1016/j.csr.2010.10.006

Lamb, M. P., de Leeuw, J., Fischer, W. W., Moodie, A. J., Venditti, J. G., Nittrouer, J. A., et al. (2020). Mud in rivers transported as flocculated and suspended bed material. *Nature Geoscience*, *13*(8), 566–570. https://doi.org/10.1038/s41561-020-0602-5

Lapôtre, M. G., Ielpi, A., Lamb, M. P., Williams, R. M., & Knoll, A. H. (2019). Model for the formation of single-thread rivers in barren landscapes and implications for pre-Silurian and Martian fluvial deposits. *Journal of Geophysical Research: Earth Surface*, *124*(12), 2757–2777. https://doi.org/10.1029/2019jf005156

Lawrence, T., Carr, S., Wheatland, J., Manning, A., & Spencer, K. (2022). Quantifying the 3D structure and function of porosity and pore space in natural sediment flocs. *Journal of Soils and Sediments*, *22*(12), 3176–3188. https://doi.org/10.1007/s11368-022-03304-x

Lick, W., Huang, H., & Jepsen, R. (1993). Flocculation of fine-grained sediments due to differential settling. *Journal of Geophysical Research*, *98*(C6), 10279–10288. https://doi.org/10.1029/93jc00519

Lick, W., Lick, J., & Ziegler, C. K. (1992). Flocculation and its effect on the vertical transport of fine-grained sediments. In *Sediment/water interactions: Proceedings of the fifth international symposium* (pp. 1–16).

Manning, A. J., & Dyer, K. (1999). A laboratory examination of floc characteristics with regard to turbulent shearing. *Marine Geology*, *160*(1–2), 147–170. https://doi.org/10.1016/s0025-3227(99)00013-4

Manning, A. J., & Bass, S. J. (2006). Variability in cohesive sediment settling fluxes: Observations under different estuarine tidal conditions. *Marine Geology*, *235*(1–4), 177–192. https://doi.org/10.1016/j.margeo.2006.10.013

Manning, A. J., Baugh, J. V., Spearman, J. R., & Whitehouse, R. J. S. (2010). Flocculation settling characteristics of mud: Sand mixtures. *Ocean Dynamics*, *60*(2), 237–253. https://doi.org/10.1007/s10236-009-0251-0

Matsubara, Y., Howard, A. D., Burr, D. M., Williams, R. M., Dietrich, W. E., & Moore, J. M. (2015). River meandering on Earth and Mars: A comparative study of Aeolis Dorsa meanders, Mars and possible terrestrial analogs of the Usuktuk River, AK, and the Quinn River, NV. *Geomorphology*, *240*, 102–120. https://doi.org/10.1016/j.geomorph.2014.08.031

Mehta, A. J. (2022). *An introduction to hydraulics of fine sediment transport* (Vol. 56). World Scientific.

Michaels, A. S., & Bolger, J. C. (1962). Settling rates and sediment volumes of flocculated kaolin suspensions. *Industrial & Engineering Chemistry Fundamentals*, *1*(1), 24–33. https://doi.org/10.1021/i160001a004

Mietta, F. (2010). Evolution of the floc size distribution of cohesive sediments.

Mietta, F., Chassagne, C., Manning, A. J., & Winterwerp, J. C. (2009). Influence of shear rate, organic matter content, pH and salinity on mud flocculation. *Ocean Dynamics*, *59*(5), 751–763. https://doi.org/10.1007/s10236-009-0231-4

Mikkelsen, O. A., Hill, P. S., & Milligan, T. G. (2007). Seasonal and spatial variation of floc size, settling velocity, and density on the inner Adriatic Shelf (Italy). *Continental Shelf Research*, *27*(3–4), 417–430. https://doi.org/10.1016/j.csr.2006.11.004

Nezu, I., & Nakagawa, H. (1993). *Turbulence in open-channel flows*. A. A. Balkema.

Nezu, I., & Rodi, W. (1986). Open-channel flow measurements with a laser Doppler anemometer. *Journal of Hydraulic Engineering*, *112*(5), 335–355. https://doi.org/10.1061/(asce)0733-9429(1986)112:5(335)

Nghiem, J. A., Fischer, W. W., Li, G. K., & Lamb, M. P. (2022). A mechanistic model for mud flocculation in freshwater rivers. *Journal of Geophysical Research: Earth Surface*, *127*(5), e2021JF006392. https://doi.org/10.1029/2021jf006392

Nittrouer, J. A., Mohrig, D., & Allison, M. (2011). Punctuated sand transport in the lowermost Mississippi River. *Journal of Geophysical Research*, *116*(F4), F04025. https://doi.org/10.1029/2011jf002026

Osborn, R., Dillon, B., Tran, D., Abolfazli, E., Dunne, K. B., Nittrouer, J. A., & Strom, K. (2021). Flocarazi: An in-situ, image-based profiling instrument for sizing solid and flocculated suspended sediment. *Journal of Geophysical Research: Earth Surface*, *126*(11), e2021JF006210. https://doi.org/10.1029/2021jf006210

Osborn, R., Dunne, K. B. J., Ashley, T., Nittrouer, J. A., & Strom, K. (2023). The flocculation state of mud in the lowermost freshwater reaches of the Mississippi River: Spatial distribution of sizes, seasonal changes, and their impact on vertical concentration profiles. *Journal of Geophysical Research: Earth Surface*, *128*(7), e2022JF006975. https://doi.org/10.1029/2022jf006975

Partheniades, E. (2009). *Cohesive sediments in open channels*. Butterworth-Heinemann/Elsevier.

Pomázi, F., & Baranya, S. (2020). Comparative assessment of fluvial suspended sediment concentration analysis methods. *Water*, *12*(3), 873. https://doi.org/10.3390/w12030873

Rouse, H. (1937). Modern conceptions of the mechanics of fluid turbulence. *Transactions of the American Society of Civil Engineers*, *102*(1), 463–505. https://doi.org/10.1061/taceat.0004872

Seiphoori, A., Gunn, A., Kosgodagan Acharige, S., Arratia, P. E., & Jerolmack, D. J. (2021). Tuning sedimentation through surface charge and particle shape. *Geophysical Research Letters*, *48*(7), e2020GL091251. https://doi.org/10.1029/2020gl091251

Soulsby, R., Manning, A., Spearman, J., & Whitehouse, R. (2013). Settling velocity and mass settling flux of flocculated estuarine sediments. *Marine Geology*, *339*, 1–12. https://doi.org/10.1016/j.margeo.2013.04.006

Spencer, K., Wheatland, J., Carr, S., Manning, A., Bushby, A., Gu, C., et al. (2022). Quantification of 3-dimensional structure and properties of flocculated natural suspended sediment. *Water Research*, *222*, 118835. https://doi.org/10.1016/j.watres.2022.118835

Sternberg, R., Ogston, A., & Johnson, R. (1996). A video system for in situ measurement of size and settling velocity of suspended particulates. *Journal of Sea Research*, *36*(1–2), 127–130. https://doi.org/10.1016/s0077-7579(96)90042-3

Strom, K., & Keyvani, A. (2011). An explicit full-range settling velocity equation for mud flocs. *Journal of Sedimentary Research*, *81*(12), 921–934. https://doi.org/10.2110/jsr.2011.62

Sutherland, B. R., Barrett, K. J., & Gingras, M. K. (2015). Clay settling in fresh and salt water. *Environmental Fluid Mechanics*, *15*(1), 147–160. https://doi.org/10.1007/s10652-014-9365-0

Syvitski, J. P., Asprey, K., & Leblanc, K. (1995). In-situ characteristics of particles settling within a deep-water estuary. *Deep Sea Research Part II: Topical Studies in Oceanography*, *42*(1), 223–256. https://doi.org/10.1016/0967-0645(95)00013-g

Ternat, F., Boyer, P., Anselmet, F., & Amielh, M. (2008). Erosion threshold of saturated natural cohesive sediments: Modeling and experiments. *Water Resources Research*, *44*(11). https://doi.org/10.1029/2007wr006537

Tran, D., & Strom, K. (2017). Suspended clays and silts: Are they independent or dependent fractions when it comes to settling in a turbulent suspension? *Continental Shelf Research*, *138*, 81–94. https://doi.org/10.1016/j.csr.2017.02.011

Van der Lee, W. T. (2000). Temporal variation of floc size and settling velocity in the Dollard estuary. *Continental Shelf Research*, *20*(12–13), 1495–1511. https://doi.org/10.1016/s0278-4343(00)00034-0

Van Leussen, W. (1988). Aggregation of particles, settling velocity of mud flocs a review. In *Physical processes in estuaries* (pp. 347–403). Springer.

Van Leussen, W. (1997). The Kolmogorov microscale as a limiting value for the floc sizes of suspended fine-grained sediments in estuaries. In *Cohesive sediments* (pp. 45–62).

Verney, R., Lafite, R., & Brun-Cottan, J.-C. (2009). Flocculation potential of estuarine particles: The importance of environmental factors and of the spatial and seasonal variability of suspended particulate matter. *Estuaries and Coasts*, *32*(4), 678–693. https://doi.org/10.1007/s12237-009-9160-1

Von Kármán, T. (1930). Mechanische Ähnlichkeit und turbulenz. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Fachgruppe 1 (Mathematik)*, *5*, 58–76.

Vowinckel, B., Biegert, E., Luzzatto-Fegiz, P., & Meiburg, E. (2019). Consolidation of freshly deposited cohesive and noncohesive sediment: Particle-resolved simulations. *Physical Review Fluids*, *4*(7), 074305. https://doi.org/10.1103/physrevfluids.4.074305

Whitehouse, R. (2000). *Dynamics of estuarine muds: A manual for practical applications*. Thomas Telford.

Winterwerp, J., Manning, A., Martens, C., De Mulder, T., & Vanlede, J. (2006). A heuristic formula for turbulence-induced flocculation of cohesive sediment. *Estuarine, Coastal and Shelf Science*, *68*(1–2), 195–207. https://doi.org/10.1016/j.ecss.2006.02.003

Young, R. N., & Southard, J. B. (1978). Erosion of fine-grained marine sediments: Sea-floor and laboratory experiments. *Geological Society of America Bulletin*, *89*(5), 663–672. https://doi.org/10.1130/0016-7606(1978)89<663:eofmss>2.0.co;2

Zeichner, S. S., Nghiem, J., Lamb, M. P., Takashima, N., de Leeuw, J., Ganti, V., & Fischer, W. W. (2021). Early plant organics increased global terrestrial mud deposition through enhanced flocculation. *Science*, *371*(6528), 526–529. https://doi.org/10.1126/science.abd0379