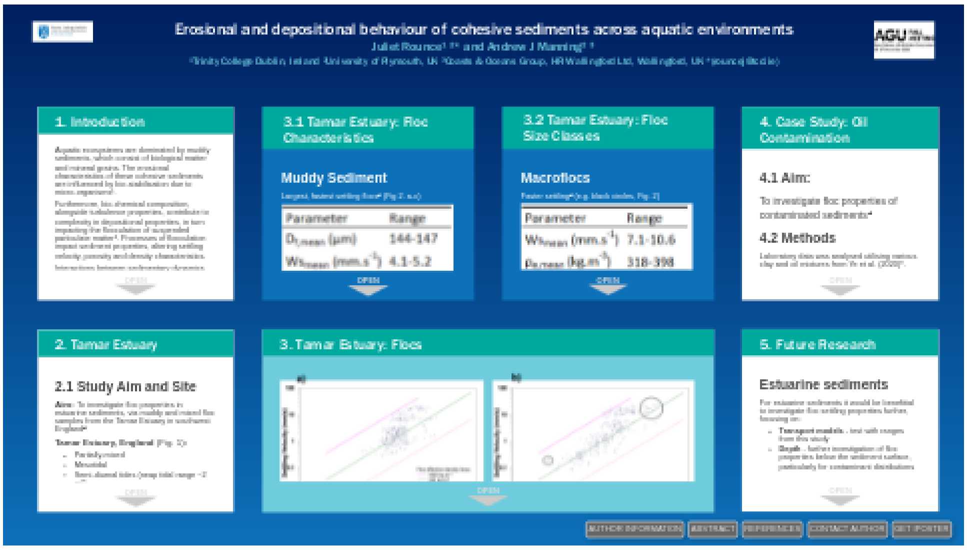
Erosional and depositional behaviour of cohesive sediments across aquatic environments



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AGU FALL MEETING
New Orleans, LA & Online Everywhere
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1. INTRODUCTION

Aquatic ecosystems are dominated by muddy sediments, which consist of biological matter and mineral grains. The erosional characteristics of these cohesive sediments are influenced by bio-stabilisation due to micro-organisms[1].

Furthermore, bio-chemical composition, alongside turbulence properties, contribute to complexity in depositional properties, in turn impacting the flocculation of suspended particulate matter[2]. Processes of flocculation impact sediment properties, altering settling velocity, porosity and density characteristics.

Interactions between sedimentary dynamics and hydrodynamics, influenced bio-physical attributes of the sediment create further complications[3]. On top of this, contaminants may be absorbed by cohesive sediments, thus predicting muddy sediment transport processes, requiring calibrated numerical models, is beneficial. Quantitative erosional and depositional data aids calibration of such predictive models[2].

Key questions arise, for example querying the influence of varying sediment compositions and dynamical conditions on erosional and depositional properties. In this study, field- and laboratory-derived data are utilised to investigate aspects of erodibility and deposition across aquatic environments.

3.1 TAMAR ESTUARY: FLOC CHARACTERISTICS

Muddy Sediment

Largest, fastest settling flocs[4] (Fig 2. a-c)

Parameter	Range
$D_{f,mean}$ (μm)	144-147
Ws_{mean} ($mm.s^{-1}$)	4.1-5.2
$\rho_{e,mean}$ ($kg.m^{-3}$)	317-352

Mixed Sediment

Smallest, slowest settling flocs[4] (Fig. 2. d-f)

Parameter	Range
$D_{f,mean}$ (μm)	109-137
Ws_{mean} ($mm.s^{-1}$)	3.8-4.0
$\rho_{e,mean}$ ($kg.m^{-3}$)	288-508

Highest settling velocity near tributary - **flocculation promoted by turbulence[8]**

3.2 TAMAR ESTUARY: FLOC SIZE CLASSES

Macroflocs

Faster settling[4] (e.g. black circles, Fig. 2)

Parameter	Range
Ws_{mean} ($mm.s^{-1}$)	7.1-10.6
$\rho_{e,mean}$ ($kg.m^{-3}$)	318-398

Microflocs

Slower settling[4] (e.g. black circles, Fig. 2)

Parameter	Range
Ws_{mean} ($mm.s^{-1}$)	1.6-3.4
$\rho_{e,mean}$ ($kg.m^{-3}$)	269-521

Smallest and largest flocs observed near tributary - **flocculation and break-up promoted by turbulence** (e.g. blue circles)

4. CASE STUDY: OIL CONTAMINATION

4.1 Aim:

To investigate floc properties of contaminated sediments[4]

4.2 Methods

Laboratory data was analysed utilising various clay and oil mixtures from Ye et al. (2020)[9].

- Magnetic stirring jar which simulates floc formation in turbulence
- Settling column analysis of oil-mineral aggregates using the LabSFLOC-2 camera to acquire mass Ws and floc properties

4.3 Results

Comparison of physical floc properties for various mineral and oil-mineral aggregate mixtures (Fig. 3).

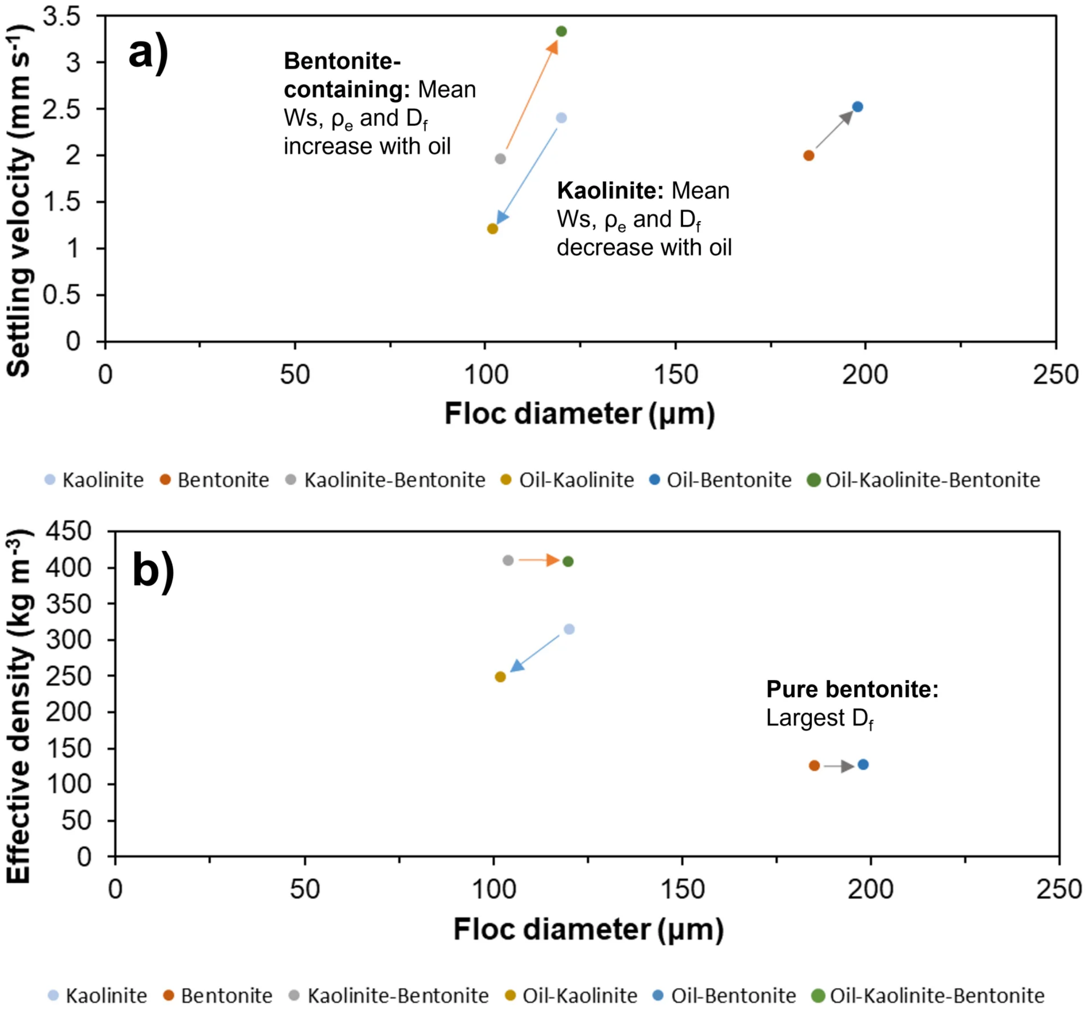


Figure 3 Floc characteristics across various clay mineral mixtures alongside oil-contaminated mixtures, from LabSFLOC-2 analysis[9], for mean floc size against a) mean settling velocity and b) mean floc effective density for each mixture. The effect of adding oil is represented by arrows for kaolinite (blue), bentonite (grey) and kaolinite-bentonite (orange).

Dominant mean D_f was not impacted on addition of oil for any of the mixtures (Fig. 4).

- Kaolinite and kaolinite-bentonite -microflocs dominant
- Bentonite - macroflocs dominant

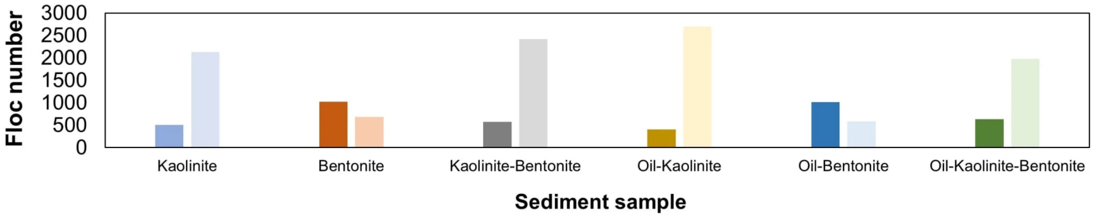


Figure 4 Floc characteristics from LabSFLOC-2 analysis[9], across various clay mineral mixtures alongside oil-contaminated mixtures, indicating floc number, where flocs are classified into macroflocs (>160 μm; dark) and microflocs (<160 μm; light).

4.4 Discussion and Conclusion

Mineral type and influence demonstrated by o-k-b mixture[9]

- Pure bentonite - on addition of oil, large and low-density flocs formed, with the increase in macrofloc proportion causing an increase in diameter
- Kaolinite - decreased diameter due to increase in microfloc population
- Kaolinite-bentonite - kaolinite properties demonstrated by small D_fs (104-120 μm); bentonite properties demonstrated by increased Ws with oil (3.3 $mm.s^{-1}$)

Clay mineral surface properties[9]

- Oil-droplet interaction indicated by variation in Ws_{mean}
- Oil-droplet structure was preserved in kaolinite, forming flocs with a slower Ws and lower ρ_e.
- Bentonite minerals absorbed oil droplets, forming flocs with a faster Ws

2. TAMAR ESTUARY

2.1 Study Aim and Site

Aim: To investigate floc properties in estuarine sediments, via muddy and mixed floc samples from the Tamar Estuary in southwest England[4]

Tamar Estuary, England (Fig. 1)**:**

- Partially-mixed
- Mesotidal
- Semi-diurnal tides (neap tidal range ~2 m)[5]

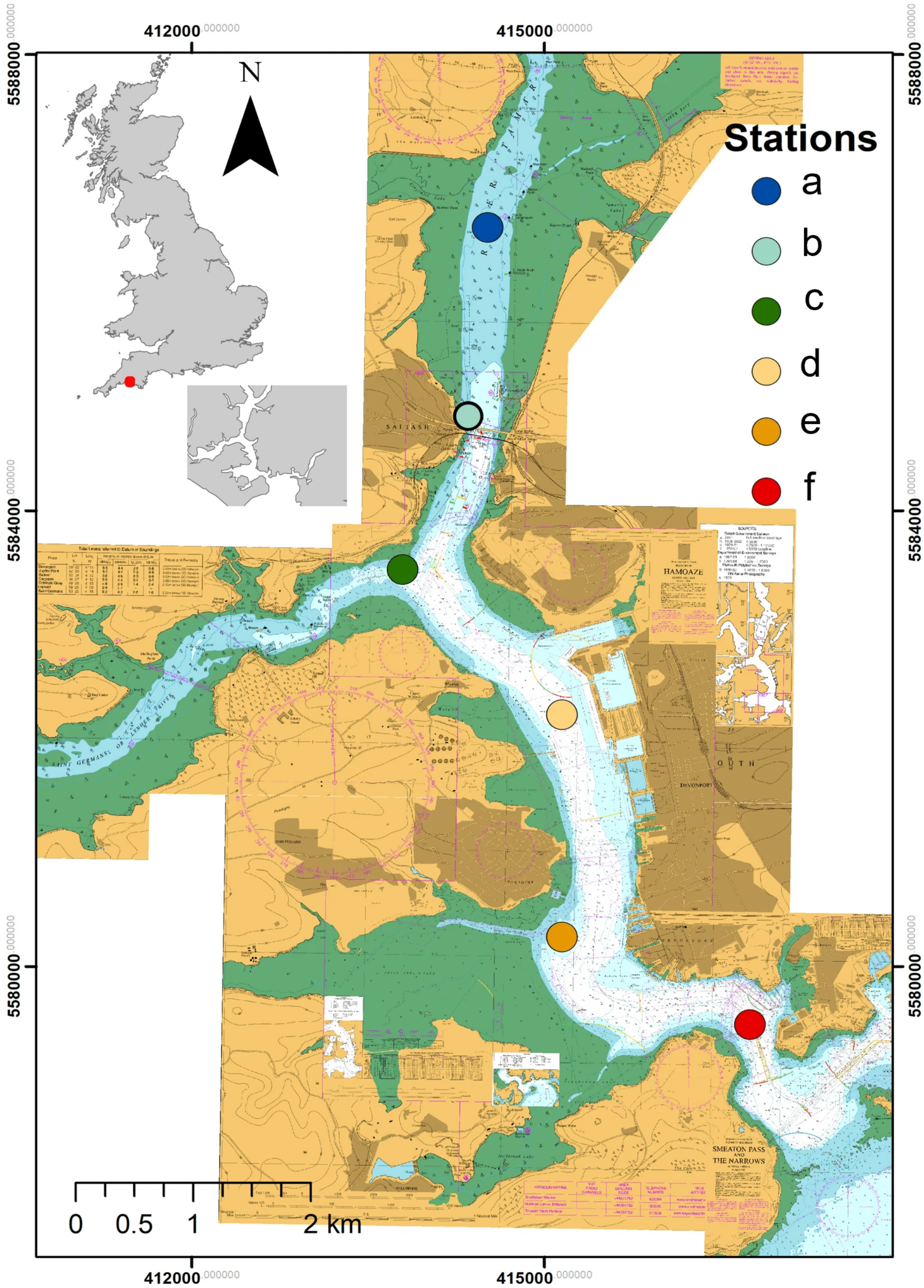


Figure 1 Floc sample stations in the Tamar Estuary: a - near Ernesettle, b - north of Tamar Bridge, c - Lynher tributary, d - Wilcove, e - Devonport and f - estuary mouth. Coordinate system: WGS84. Source: Digimap.

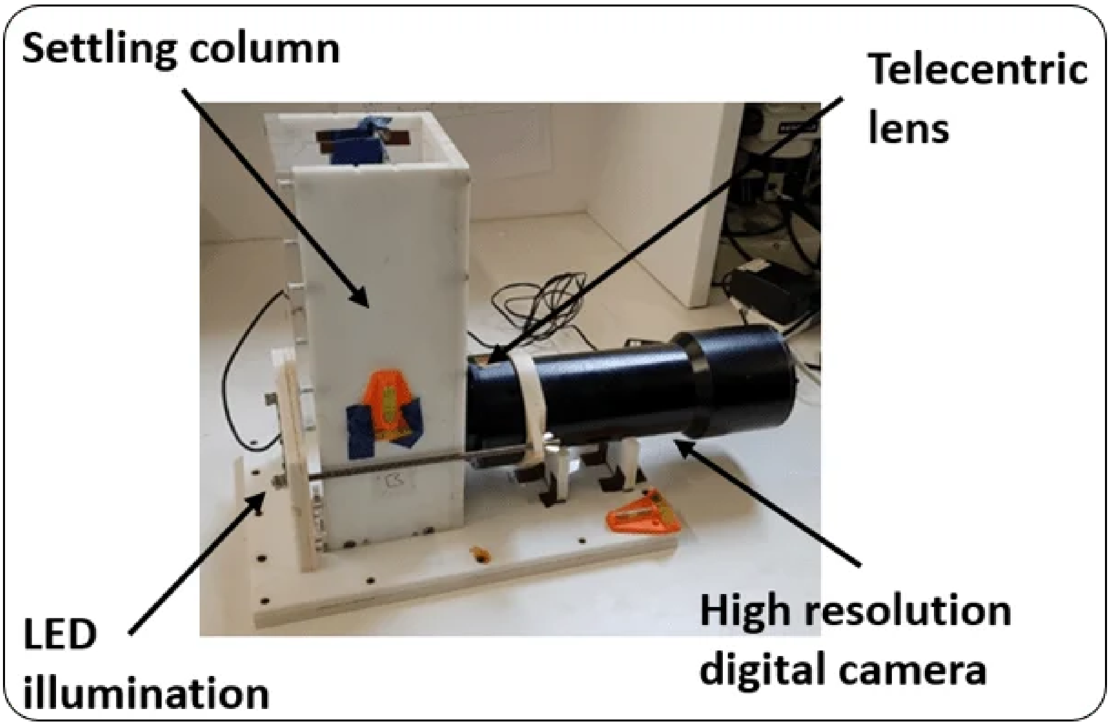
2.2 Floc Sampling and Analysis

- **Sediment cores** taken in November 2019 (Fig. 1)
- Jar test in the laboratory
- **LabSFLOC-2 camera** (Laboratory Spectral Flocculation Characteristics)[6]
- Calculation of surface **floc diameter** (D_f), **settling velocity** (Ws) and **effective density** (ρ_e)

LabSFLOC camera

The LabSFLOC camera is a settling velocity device, which enables *in situ* measurements to be obtained. Both floc population and individual floc properties may be characterised. Subsamples from the jar test were placed in the settling column to obtain video observations of flocs.

Assessment of the sampling procedure was carried out via a comparison of values alongside the measured suspended particulate matter concentration (150 mg.L^{-1}).



Post-processing

Post-processing involved the following floc calculations[7]:

1. **Floc diameter** (spherical equivalent), D_f

$$D = (D_x \cdot D_y)^{0.5}$$

where major/minor axis floc dimensions from LabSFLOC image stills are represented by D_x and D_y.

2. **Settling velocity**, *Ws*, estimated from the vertical distance travelled by flocs in a known time interval across digital floc images.

3. **Floc effective density,** ρ_e, estimated from a modified Stoke's law equation:

$$\rho_e = (\rho_f - \rho_w) = (18\mu \cdot Ws) / (D^2 \cdot g)$$

where subscript *f* and *w* represent bulk and water densities respectively, molecular velocity is represented by μ and acceleration due to gravity is represented by *g*. The LabSFLOC camera provides the *D* and *Ws* measurements.

3. TAMAR ESTUARY: FLOCS

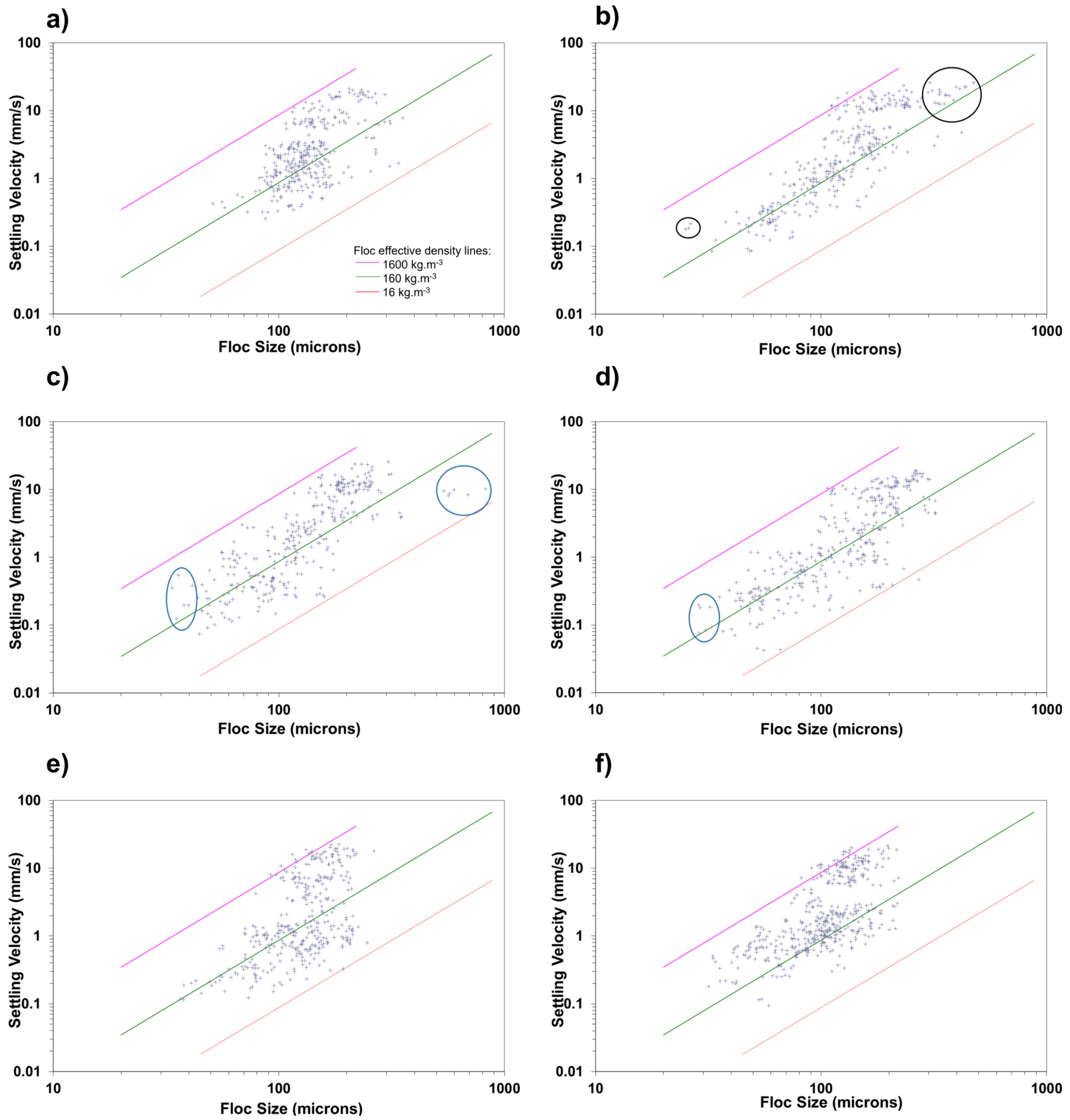


Figure 2 Floc populations from the upper (a-c, muddy) and lower (d-f, mixed) Tamar Estuary, comparing floc size and settling velocity for each station: a) furthest inland, 31.7 m depth, b) 10.7 m, c) 17.2 m, d) 14 m, e) 6.9 m and f) most seaward, 6.9 m.

- **Muddy sediment: e.g. Fig. 2a**
- **Mixed sediment: e.g. Fig. 2e**

5. FUTURE RESEARCH

Estuarine sediments

For estuarine sediments it would be benefitial to investigate floc settling properties further, focusing on:

- **Transport models** - test with ranges from this study
- **Depth** - further investigation of floc properties below the sediment surface, particularly for contaminant distributions

Contaminated sediments

Contamination studies could investigate the influence of differing natural sediment and oil mixtures on:

- **Flocculation mechanisms** and formation of flocs, including **size and shape**, to further understand settling dynamics
- **Sediment surface cohesion properties** across various floc size classes
- **Transport models** should consider these floc and mineral surface properties

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ABSTRACT

Muddy sediments are abundant across aquatic ecosystems, consisting of mineral grains and biological material. Erosional characteristics of these cohesive sediments are impacted by micro-organisms providing bio-stabilisation. Deposition may be impacted by chemical and biological composition, along with turbulence properties, which in turn influence flocculation of suspended particulate matter. Flocculation processes affect settling velocity, porosity and density characteristics. Cohesive sediments absorb contaminants, as well as influencing interactive processes between sedimentary dynamics and hydrodynamics, through their bio-physical attributes. It is therefore beneficial to predict muddy sediment transport processes via numerical modelling. Accurate modelling relies on quantitative erosional and depositional data for calibration.

Through collation and analysis of field- and laboratory-derived data sets, this study examined aspects of erodibility and deposition across several aquatic environments (including estuarine, intertidal and lake sediments). A range of case studies examined floc properties, sediment composition, erosion thresholds, turbulent shear stress and suspended particulate matter concentration. Investigation of floc dynamics in estuarine sediments revealed larger, faster settling flocs in muddy sediment (mean settling velocity, Ws_{mean} = 4.1-5.2 mm.s^{-1}; mean floc effective density, $\rho_{e,mean}$ = 317-352 kg.m^{-3}). In mixed sediment, flocs were smaller and settled more slowly (Ws_{mean} = 3.8-4.0 mm.s^{-1}; $\rho_{e,mean}$ = 288-508 kg.m^{-3}). Comparison of oil-contaminated sediments revealed the importance of floc size class and mineral type. On the addition of oil, larger, faster settling flocs were produced in pure bentonite cases, while smaller, slower settling flocs were observed in kaolinite cases. In highly organic lake sediments (organic content = 62%), settling velocity varied over increasing suspended sediment concentration and between floc size classes (macroflocs faster than microflocs by 0.95 mm.s^{-1}). Such findings may be utilised to increase the understanding of complex sedimentary and hydrodynamic interactions within aquatic environments. This study provides quantitative data, applicable to the improvement of predictive numerical model reliability.

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