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Coastal and Hydraulics Laboratory

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Regional Sediment Management (RSM) Program

Sediment Sorting by Hopper Dredging and Pump-Out Operations: Sampling Methods and Analysis

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Abstract

Hopper dredging operations for beach and nearshore placement typically include periods of overflow, which produces some degree of separation between the size fractions of the dredged sediment. The degree of separation and the controlling factors are presently poorly known. This report focuses on laboratory experiments aimed at determining (1) suitable sampling methods on a dredge, (2) composite sampling techniques to reduce analysis cost, (3) associated sampling intervals to achieve suitable sediment representation of a hopper load, and (4) a hydraulic means of sample splitting. Results showed that no statistical difference exists among the three methods used to sample the hopper weir overflow. The method used to sample deposited hopper sediment identified a bias in the percent fines that resulted from flow sheltering. Further, it was found that composited samples were able to quantify the concentration and percent fines accurately, although an analytical data experiment showed that the accuracy of a composited sample is dependent on the sampling intervals. The accuracy of the fines and concentration from a hydraulic sample splitter was found to be dependent on median grain size, with fine sediment being evenly distributed and coarser sediment increasing the error in concentration and grain size distribution.

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Preface

This study was conducted for the Regional Sediment Management (RSM) Program through an Interagency Agreement (IAA, number M16PG00023) between the US Department of the Interior, Bureau of Ocean Energy Management (BOEM); the US Army Corps of Engineers (USACE), Jacksonville District (SAJ); and the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), RSM Program under Program Element No. 110; Project Number 484149; Task No. A1040; Funding Acct Code U4371904; AMSCO Code 008303. Funding was provided by BOEM and the USACE ERDC RSM Program.

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1 Introduction

1.1 Background

In shore protection, ecosystem restoration, and navigation projects where sediment is placed on the beach or in the nearshore, coastal project managers are required to ensure that sediment taken from source areas (e.g., offshore borrow site, navigation channel, inlet complex) is compatible with the sediment characteristics at the placement site (e.g., the beach or nearshore). Important factors to consider are sediment grain size, composition, sorting, and color (Dean 2003). Additionally, some state regulations across the nation (such as Florida's "Sand Rule") specify allowable thresholds of percent fine sediment relative to sand content (Florida Department of Environmental Protection 2017; FL Administration Code r. 62B-41.007(2)(j)). The definition of fine sediment may differ from state to state; however, it is generally recognized as either the sediment passing the no. 200 (75 µm)* sieve in accordance with the Unified Soil Classification System or the material passing the no. 230 (63 µm) sieve in accordance with the Udden-Wentworth scale. The latter classification was used in this study.

When determining compatibility between the source sediment and the native sediment, it is typically assumed that textural properties (e.g., sorting, mean grain size, and percent sand) are unchanged from the in situ borrow area through dredging and conveyance to the placement site. However, it is generally recognized that hopper dredges implementing overflow (the intentional discharge of supernatant water) coarsen their load respective to the source material through preferential loss of fines suspended in overflow (the gain in hopper load through this process is known as economic loading). Additional loss of fines may occur at the draghead and during pump-out beach placement operations. Presently, regulations do not consider any possible reduction in fine sediment through the dredging process when assessing sediment compatibility.

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* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

It is hypothesized that, based on this coarsening process, dredged material containing a higher concentration of fines than currently permitted by law could be used in coastal flood risk management, ecosystem restoration, and navigation projects, potentially saving money on the project by making use of previously undesirable sediment resources. Thus, the volume and availability of offshore sediment deemed compatible for coastal restoration projects to support resiliency of both coastal infrastructure and habitat could be increased. Understanding and quantifying the loss of fines through the dredging process would allow coastal managers to better estimate the compatibility of dredged material for beneficial use projects.

The potential loss of fines through dredging was first observed from geotechnical investigations of the Florida Sediment Assessment and Needs Determination (SAND) study (Ousley et al. 2014) and later quantified by Coor and Ousley[*]. Here, the authors attempted to quantify the total loss of fines by examining the sediment compatibility data of borrow and post-fill sediment sources for multiple dredging and shore protection projects. In essence, this involved examining the composite grain size statistics recorded at the borrow sites and beaches. From this it was discovered that the mean reduction in fines was approximately 75% (range <63 µm: 0.86%—25%). In one instance, the fines content was reportedly reduced from 25% at the borrow site (Tampa Harbor Entrance Channel) to 2.5% at the placement site. However, the percent fines recorded at the other borrow sites were very low (3% or less), and therefore it is not well understood if the same magnitude of fine sediment losses should be expected from borrow sites with a much greater fines content (e.g., 20%). Additionally, where in the dredging and placement process fine sediment loss occurred could only be speculated. Therefore, this present study is meant to fill in some of the gaps to predict fine sediment losses through dredging and placement activities.

1.2 Motivation

To quantify the loss of fines through the dredging and placement process, information on the sediment characteristics needs to be determined at various locations including (1) the borrow site, (2) the dredge, and (3) the

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[*] Coor, J. L., and J. D. Ousley. (Forthcoming). *Historical Analysis of Fines Lost during Beach Nourishment*. ERDC-CHL Technical Note. Vicksburg, MS: US Army Engineer Research and Development Center.

nourishment site. Each of these locations creates challenging sampling and analysis scenarios, but none more so than the dredge itself. The hopper capacity of trailing suction hopper dredges (TSHDs) can vary on the order of a few thousand to tens of thousands of cubic yards. Germane to this study is being able to sample incoming dredged material in a way that the average value (of some observation) of the population is well represented by the average value determined from a subset of independent samples. To do this requires taking numerous samples throughout the loading cycle due to the fact that (1) sample volumes are very small relative to the total hopper load and (2) the mass flux and/or sediment composition coming into the hopper can vary greatly in time. However, the costs of analyzing so many samples is prohibitive. Instead, the average value could be determined by means of compositing, provided that the errors in compositing samples are acceptably small.

Compositing is a type of physical averaging where multiple independent samples of some process are combined into a single sample. In this way, a single measurement from the composited sample should represent the arithmetically derived average of the individual samples. A primary concern in this approach is unintended bias associated with covarying parameters, such as slurry concentration and slurry flowrate. If the covariance is negative and strong, the arithmetic mean of a single sampled parameter (such as concentration) will deviate from the true average as estimated from the first moment of the covarying quantities. Another important consideration is that a subsample (or aliquot) of a composited sample must be obtained in a way that is representative of the composite, which is possible only through homogenization. As many tens of kilograms of sediment per hopper load are expected, a procedure needed to be developed to homogenize and subsample sediments from the hopper and the inflow. Splitting sediments collected from the inflow is more complicated if the average concentration is also desired, given that this material is in the form of a slurry.

Another consideration is the sampling interval. Errors are introduced when sampling intervals are too coarsely spaced. Thus, it is necessary to know the minimum number of samples required such that a composited sample sufficiently represents the population and the sort of error that might be expected as a function of sample number. Part of this study attempts to answer these questions specific to the study needs.

In summary, the motivation for this study was to develop and test sampling methodologies and analysis schemes within a laboratory setting, and to develop methods for homogenizing and subsampling composited samples. This will help to guide the sampling schemes to be conducted in the field and allow for robust sediment characterization needed to quantify the loss of fines through the dredging and placement process.

1.3 Objectives

Specifically, the objectives of this study were (1) to determine suitable sampling methods for collecting samples at the dredge, (2) to determine whether samples can be composited into a smaller subset of samples, (3) to test a hydraulic means of subsampling large-volume, composited samples, and (4) to determine the appropriate sampling interval required to obtain the minimum number of samples needed to meet a designated error threshold.

1.4 Approach

To achieve Objective 1, a laboratory experiment was designed to simulate the process of hopper filling and subsequent overflow to test different weir sampling methods, as well as methods to sample the hopper directly. The same experiment was used for Objective 2 by comparing composited samples from the overflow to individual samples. For Objective 3, an experiment was designed using a recirculating tank to withdraw aliquots from a known concentration. For Objective 4, a numerical experiment was designed using readily available Dredging Quality Management (DQM) data to determine the potential error associated with sampling frequency. The achievement of each of these objectives is further explained in Chapter 2 Methods of this report.

1.5 Document organization

Chapter 2 of this report discusses the various methods used in this study, including physical sampling and sample analysis. Physical sampling includes sampling of the model weir tank and hopper. A discussion on how the weir tank was constructed and the set up of the entire experiment is included. Sampling (i.e., box, bottle, and tube samplers) and sediment analysis methods for the weir tank experiment and hopper are also discussed. Chapter 2 also includes a discussion of sample analysis methods including a sample splitter experiment and a numerical experiment using

DQM data to determine the sampling frequency required to obtain acceptable sampling error from the dredging process. Chapter 3 presents results from the overflow weir, hopper sampling, sample splitting, and numerical experiment for determining sample frequency. A discussion and conclusions of these results are provided in Chapter 4.

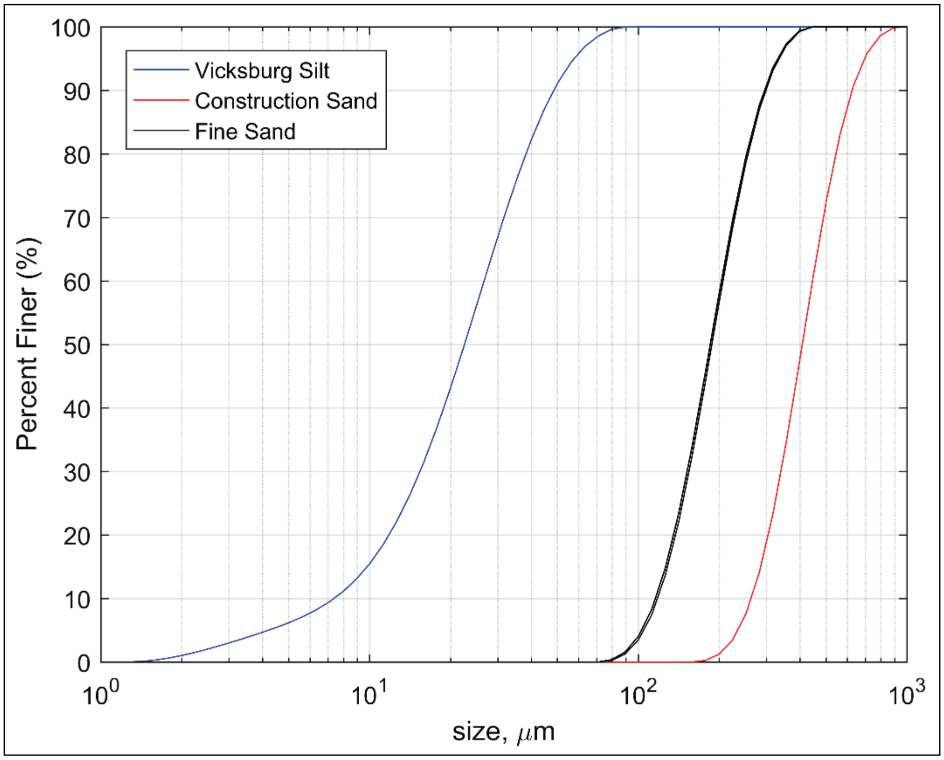
2 Methods

This chapter details the materials, design, and procedures used to test the physical sampling and sample analysis methods. The first section provides details on the sediments used in this study, followed by a section describing the laboratory hopper overflow and subsequent sampling methods. The final sections detail the hydraulic sample splitter tested for sample analysis and an analytical experiment to determine the error introduced by the sampling frequency.

2.1 Materials

Three sources of sediment were used for the laboratory testing. To determine the grain size distribution, samples were analyzed using a Malvern laser scattering instrument. The first sediment was a local sourced loess referred to as Vicksburg silt (VS). The gradation of the VS is given in Figure 1 with a measured d_{50} = 22.6 µm, a d_{10} = 7.4 µm, and a d_{90} = 48.6 µm. The second sediment used was a fine sand (FS) with a d_{50} = 186.3 µm, d_{10} = 117 µm, and a d_{90} = 295 µm. The gradation for the FS is given in Figure 1. A sand used commonly in mortar mix, referred to throughout this document as construction sand (CS), was also used in the laboratory testing. This uniform sand was found to have a d_{50} = 408 µm, a d_{10} = 264 µm, and a d_{90} = 626µm. The grain size distribution for this sand is provided in Figure 1.

Figure 1. Gradation of the VS, FS, and CS.



2.2 Overflow experiments

This section describes the laboratory setup and procedures used for sampling the overflow of a model hopper. The overflow experiments were designed to test different sampling methods and the effectiveness of sample compositing. These experiments were not designed to mimic the flow and sediment dynamics within a prototype hopper. Instead, the only necessary design criteria included scaling the flow rate over the weir and matching the vertical loading rate of the sediment bed, considered in the hopper load parameter, H^*, as defined by van Rhee (2001) in Equation 2-1. The numerator, v_o, is the vertical loading rate calculated by dividing the hopper flow rate by the hopper area. The denominator, w_s is the hindered settling velocity based on the sediment concentration as defined by Richardson and Zaki (1954) in Equation 2-2. Here, w_o is the single grain settling velocity, C is the concentration, and n is an empirical coefficient dependent on grain size.

$$\boldsymbol{H}^* = \frac{\boldsymbol{v_0}}{\boldsymbol{w_s}} \tag{2-1}$$

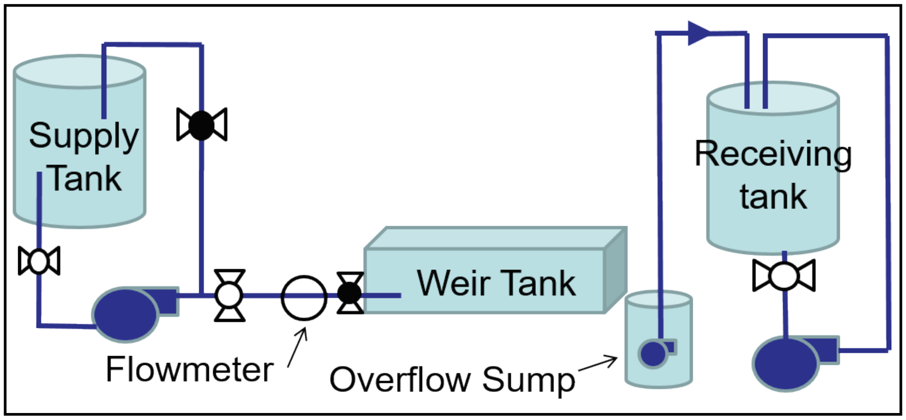
$$w_s = w_0(1 - C)^n \tag{2-2}$$

The experiments conducted in the laboratory were meant to represent a generic dredging event; thus, a typical concentration value of 15% (by volume) was chosen, which corresponds to 400 g/L by mass. This is a reasonable value for inflow concentration, which can vary from 10% to 30% but low enough to pump as a slurry without using special equipment.

2.2.1 Weir overflow

To test the sampling and compositing hypothesis, a model hopper dredge was designed. To build this in a laboratory, three tanks were needed: (1) a supply tank, (2) a weir tank, and (3) a receiving tank. The supply tank holds the sediment mixture and represents the hopper inflow. The weir tank represents the prototype hopper and includes an overflow weir. The receiving tank contains all the contents collected from the overflow and is representative of the outflow from the hopper. Figure 2 provides a schematic of the tanks, valves, instruments, and pumps needed to execute the model hopper dredge.

Figure 2. Weir overflow schematic.

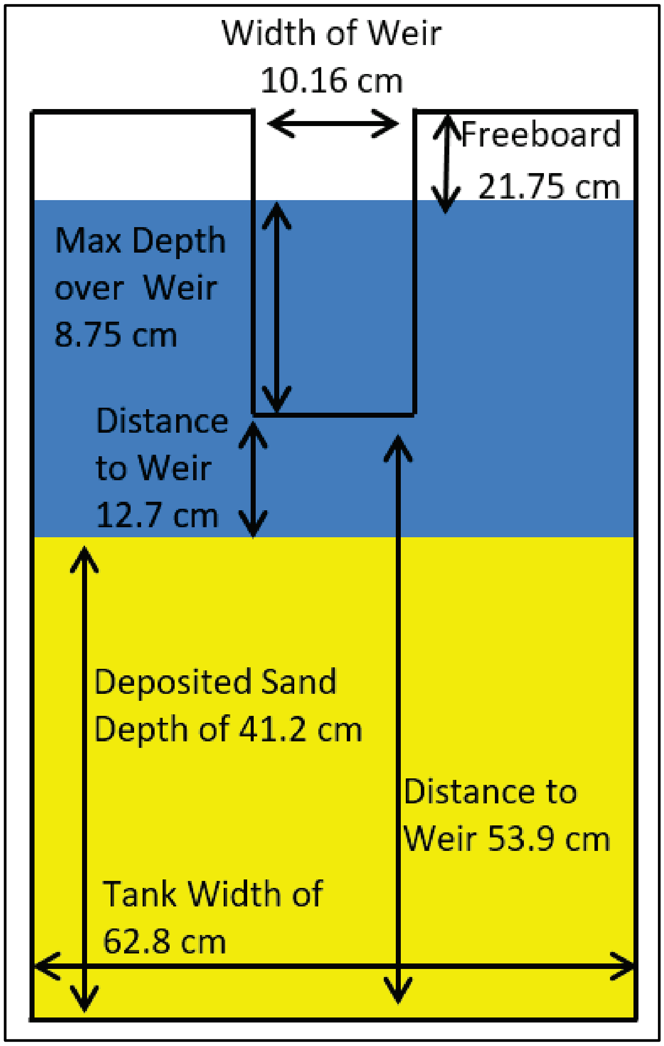


The stainless steel supply tank had a maximum volume of 1,540 L. The bottom of the cylindrical supply tank was beveled and fed into a 10 cm (4 in.) nominal pipe connected to a Honda WT40 gas-powered trash pump capable of handling solids up to 2.54 cm in diameter (Figure 3) and had a maximum flowrate of 28.4 L/s (450 gal/min). To maintain sediments in suspension, the tank also had two mixing paddles located at the tank bottom and mid-depth driven by an electric motor at 120 rpm. A set of ball valves was used to recirculate the mixture from the pump to the supply tank and for transferring to the weir tank. The flow rate of the transferred material was monitored using an in-line Endress+Hauser Proline Promag 50 electromagnetic flowmeter.

Figure 3. Sediment mixing tank.

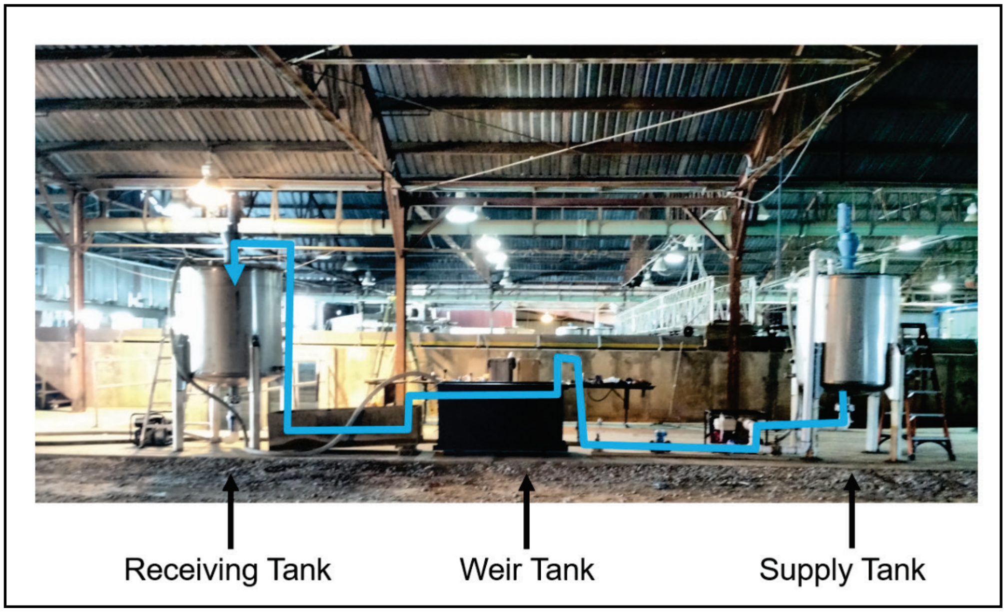
Figure 4 provides a schematic of the designed depth of settled sand, maximum water depth, and freeboard distance. The basin was 88.4 cm deep with an area of 62.8 cm × 152.4 cm. The overflow weir was 53.9 cm from the basin floor with an opening width of 10.16 cm. A target inflow rate of 4.7 L/s was determined to achieve the desired sediment loading rate of 5 mm/s, which was controlled using a gate value immediately upstream of the weir tank. The design volume of sand collected in the tank was 384 L, which equates to bed height of 41.2 cm assuming a uniform distribution with a bulk density of 1,600 kg/m^3. The expected bed height was used to determine the maximum water depth over the weir. The flow rate and exit velocity of the overflow was calculated using the sharp crested weir equation (with a $C_d = 0.6$), which was designed to be similar to that encountered in dredge plants.

Figure 4. Schematic of weir tank. Tank dimensions are shown with design depths of sand, water, and design freeboard. Not to scale.



The overflow discharged from the weir was captured in a separate aluminum basin. At the end of the loading cycle, the material was then transferred to the receiving tank using a nominal 5 cm (2 in.) sump pump. Special attention was taken during testing to move all the overflow material to the receiving tank. The receiving tank was identical to the supply tank except a nominal 5 cm (2 in.) gas-powered semi-trash pump was used to recirculate the contents of the tank. The maximum flowrate of the receiving tank pump was approximately 15.8 L/s (250 gpm). A photograph of the laboratory setup with the process moving from right to left following the blue line is shown in Figure 5.

Figure 5. Photograph of weir overflow laboratory setup. Laboratory setup indicates supply tank, weir tank, and receiving tank. Blue line indicates the path of flow from the supply tank to the receiving tank.



The sediments used for the experiment consisted of three constant volume mixtures created with increasing fines content of 10%, 20%, and 30%. Each mixture was created in triplicate for repeatability and statistical significance. To achieve the 10% fines mixture, 526 kg of CS and 59 kg of VS were combined with 1,241 L of water. Respectively for the 20% and 30% fines mixtures, the masses were 468 kg CS + 117 kg VS + 1,241 L water, and 409 kg CS + 175 kg VS + 1,241 L water. All sediment masses used in the mixture calculations were corrected for moisture content prior to mixing. The testing procedure is provided in Table 1.

Table 1. Overflow testing procedure.

1	Check plumbing.
2	Identify pre-measured sediment bags for test.
3	Prepare sampling bottles and sampling method/equipment.
4	Check that flowmeter/scale are logging.
5	Fill tank 1 with desired amount of water.
6	Turn on recirculation pump and paddles for supply tank.
7	Add CS to supply tank.
8	Add VS to supply tank.
9	Let supply tank mix for 5 min.
10	Take samples from supply tank.
11	Start logging flowmeter and scale data.
12	Begin flow into weir tank and monitor flowmeter.
13	Sample overflow from weir tank every 30 s.
14	Begin pumping overflow in the receiving tank.
15	Turn pump and paddles for the receiving tank.
16	Once empty, turn off pump and paddles for the supply tank.
17	Ensure all overflow is included in receiving tank after overflow stops.
18	Let receiving tank run for 5 min.
19	Take samples from receiving tank.

2.2.2 Sampling methods

The overflow weir (Figure 6) was sampled directly using three different sampling devices to identify any potential biases in sediment concentrations and grain size distributions between sampler types. A total of nine tests (B-J) were conducted, grouped by the percentage fines (< 63 µm) in the sediment mixtures (Table 2). For each test, a sample was collected approximately every 20 s, which yielded approximately 14 samples per test for a 5 min overflow period. Half of these samples were used to determine sediment concentration by mass while the other half were used for grain size analysis and determination of the fraction of fines. Two samples (~ 0.5 L each) were also collected at the receiving tank for comparison against the overflow samples.

Figure 6. Model weir tank in overflow.

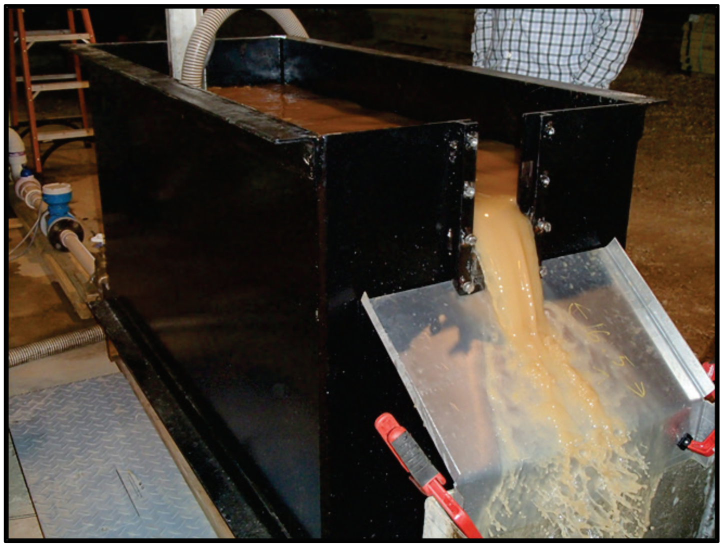
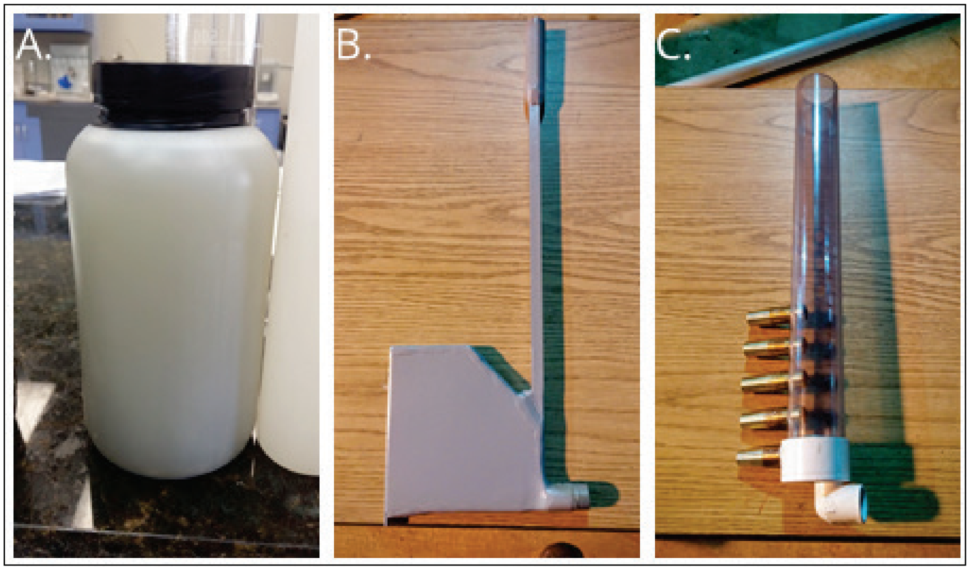


Table 2. Test matrix for weir overflow sampling.

% Fines	Test ID	Sampler Type
0.1	H	Bottle
0.1	I	Box
0.1	J	Tube and Hopper Pipe Sampling
0.2	B	Bottle
0.2	C	Box
0.2	D	Tube
0.2	K	Hopper Pipe Sampling
0.3	E	Bottle
0.3	F	Box
0.3	G	Tube

The sampling devices consisted of a bottle sampler, a box sampler, and a tube sampler (Figure 7). The bottle sampler (Figure 7-A) was simply a 1 L Nalgene bottle that was dipped by hand into the overflow. Care was taken not to overfill the bottle, which could bias the sample; any overfilled bottles were discarded then resampled.

Figure 7. Three weir overflow sampling devices: (a) bottle, (b) box, and (c) tube.



The box sampler (Figure 7-B) was designed to take an integrated sample through a column of the overflow. The narrow design and thin side walls were meant to minimize turbulence and allow for isokinetic (undisturbed flow) sampling of the design flow velocity. A bottle was used to collect samples from the outflow port as flow was continuously passed through the sampler for the duration of overflow. The tube sampler (Figure 7-C) consisted of a vertical array of metal ports that were tapered and thinning in the direction of incoming flow. The ports directed flow into a vertical tube with an outflow port at the bottom for sample collection. Like the box sampler, the tube sampler rested on the lip of the weir allowing flow to pass through continuously while samples were taken at the outflow port.

2.2.3 Dredge hopper

A significant challenge of the project was to capture representative sediment samples from the hopper. While sampling the hopper bed during the loading cycle, special attention was necessary to minimize bias introduced from any sampling technique used.

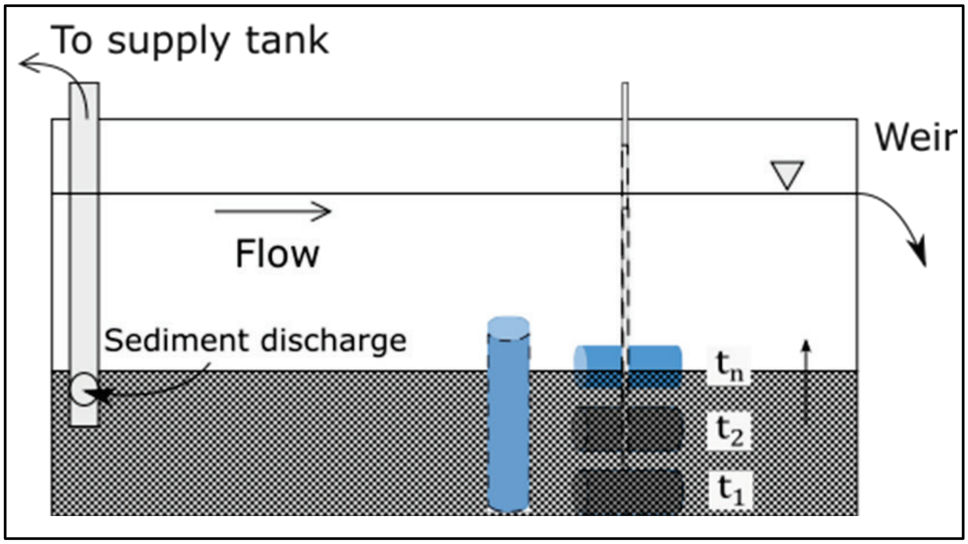
Three general techniques were proposed to capture representative hopper samples: (1) collect samples via vibracoring once dredging had ceased, (2) collect samples from the collapsing side wall of sediment during pump-out operations, and (3) collect samples from the rising bed surface during the loading cycle. The vibracoring Option 1 was eliminated based on safety concerns of conducting such an operation on the dredge deck, as well as concerns about achievable penetration depth. Option 2 was considered viable, but the question of the number of samples needed, and the distribution of sample locations to achieve sample representativeness, remained. Thus, Option 3 was decided to be safer than the vibracoring method while providing the benefits of collecting data spatially across the hopper. For these laboratory experiments, two custom devices were tested: (1) a pipe sampler and (2) a plate sampler. Laboratory tests were designed and conducted to evaluate the effectiveness of the samplers, and are described in detail below.

2.2.3.1 Hopper pipe sampler

The pipe sampler was a nominal 7.6 cm (3 in.) diameter polyvinyl chloride (PVC) pipe, 15.3 cm long, and closed at one end with a total volume of approximately 1.5 L. The pipe sampler was attached to a pole and lowered to the sediment surface for 15 s (Figure 8), which would fill the sampler based on a typical vertical bed rise velocity of 5 mm/s within a prototype hopper. After each collection, the contents of the sampler were emptied into a bucket and composited to obtain a bulk size distribution and percentage of fines that should represent the average composition in the tank. Two trials were conducted using the pipe sampler (Table 2, Tests J and K). For each trial, three to four samples were collected and composited for grain size analysis.

For comparison, the weir tank was also cored using a 10 cm diameter polycarbonate tube. The composition of this core was treated as being closer to the *true* representation of the sediment. Surface fines retained in the core were discarded to make a proper comparison.

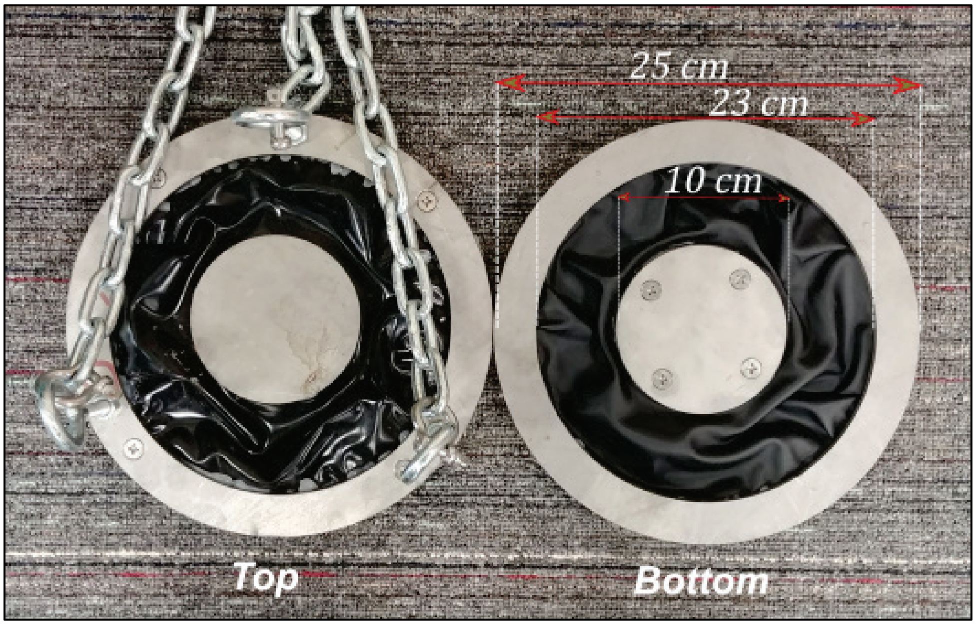
Figure 8. Schematic cross-sectional view of the weir tank with bed samplers. Samples were taken during the overflow period as the bed developed and raised, which filled the sampler. A core was taken adjacently once the surface water had drained.



2.2.3.2 Plate sampler

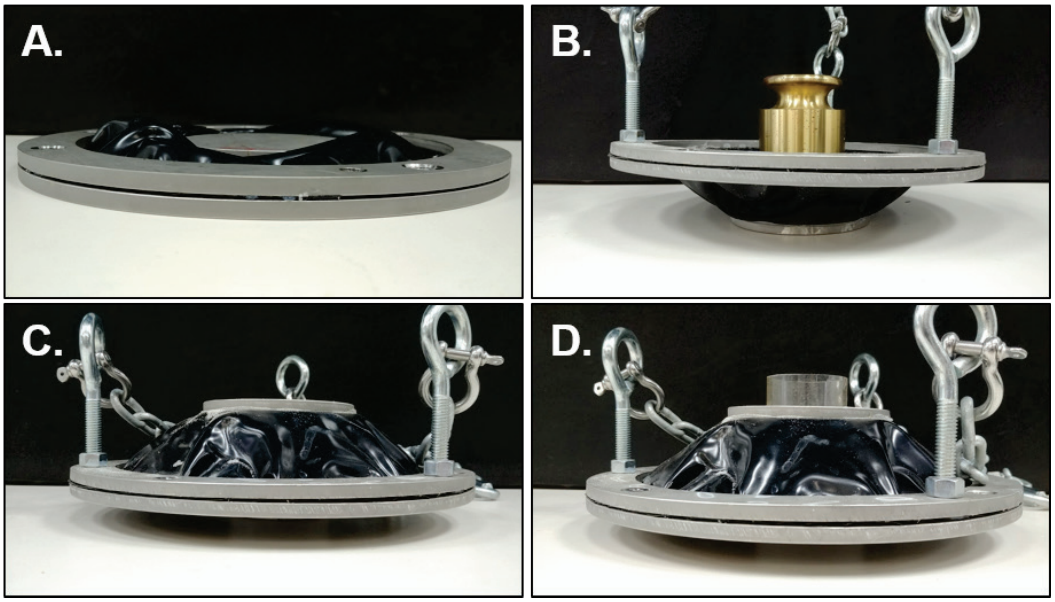
The plate sampler consisted of an inner, 10 cm diameter aluminum disk and an outer 25 cm diameter ring. Each disk and ring was fabricated in two parts that sandwich a strong, flexible, vinyl membrane (Figure 9).

Figure 9. Plan view of the plate sampling device. The fully constructed version with chain bridling is shown on the left.



The operational aspects of the sampler are illustrated in Figure 10A-D. The low-profile design was intended to eliminate sheltering effects by resting flat on the sediment bed until retrieval (A). Under load, the membrane flexed and created a shallow bowl to retain the sediment sample (B). The contents were exposed for sampling by pushing the plate onto a riser (C). Finally, a subsample was taken by pushing a short core with known volume to refusal above the center plate (D).

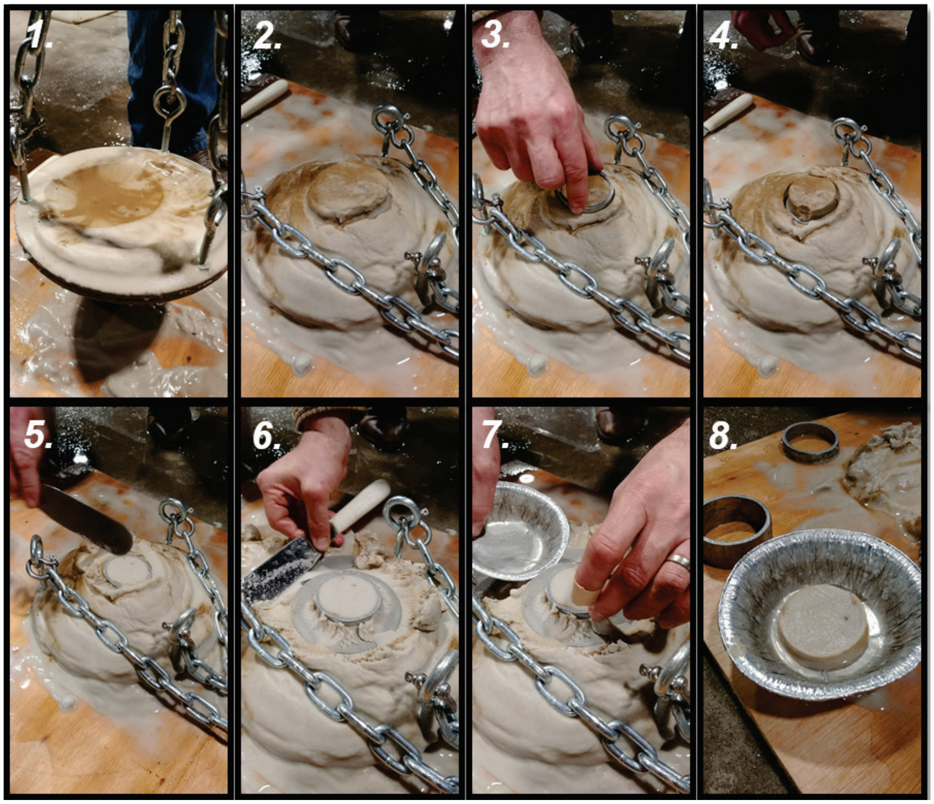
Figure 10. Generalized operational aspects of the plate sampler. Rest position (A), under load upon retrieval (B), and sample recovery position (C and D).



Chain bridling was attached to the sampler to facilitate deployment. The sampling technique consisted of lowering the sampler to the hopper bed, waiting a specified period for burial, and then retrieving. Upon retrieval, the membrane flexed and created a shallow bowl when full to protect the sample from washing out during retrieval (Figure 11). Any remaining surface fines that would otherwise cause a positive bias were discarded during the subsampling procedure using the short core, which is illustrated in detail in Figure 12.

Figure 11. Deployment (left) and retrieval (right) of the plate sampler in the model hopper tank.

Figure 12. Image sequence showing the sample recovery process. (1) The sample was retrieved, and (2) the inner disk was allowed to rest on a riser that exposed the sediment collected on its surface. (3) A short core was inserted to refusal (4), and sediment above and around the short core was cleared away (5 and 6). The sample was then slid off the disk into a container and then composited (7 and 8).

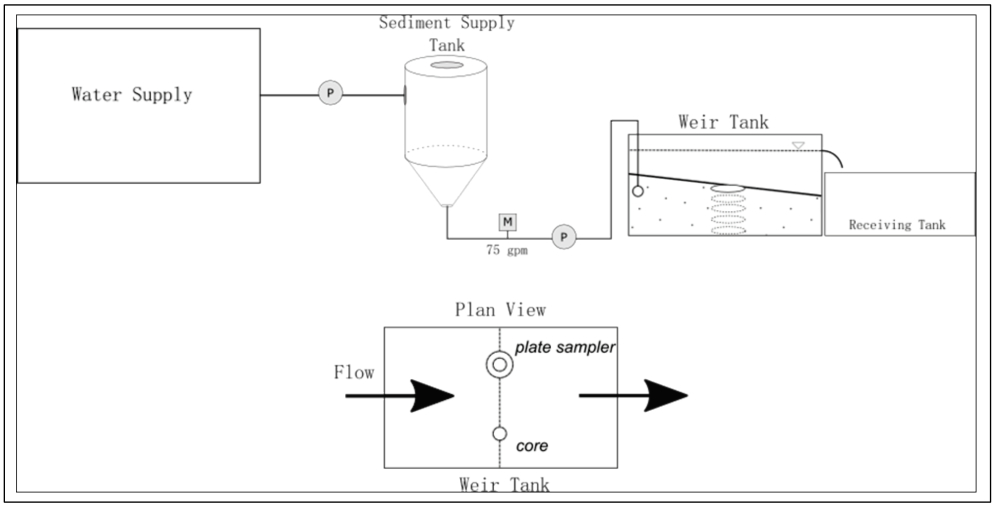


The plate sampler experiments were conducted independently of the previous tests and therefore used a slightly different experiment setup which is described below.

Two test mixtures were created using silt/sand ratios of 0.10 and 0.30 using the VS and FS sediments. Each mixture was batched to approximately 635 kg total weight divided into thirty-two 5 gal buckets.

A schematic diagram of the experiment setup is shown in Figure 13. The system was designed for continuous flow while maintaining hydraulic head in the sediment supply tank. Water was supplied to the sediment tank using a small gas powered 5 cm (2 in.) intake semi-trash pump, which was then transferred to the weir tank using a similar pump. Flow to the weir tank was monitored using an electromagnetic flow meter. Flow rate to the weir tank and head within the sediment tank was maintained by adjustment of a series of gate valves.

Figure 13. Schematic diagram of the plate sampler experiment design.



Once the target flow rate (75 gal/min) and desired head were achieved, sediment was introduced to the supply tank at a rate of 40 lb/min. The plate sampler was then lowered to the bed, and a sample recovered for every four buckets of material introduced (enough to be assured the sampler was buried). Thus, a total of eight samples were recovered for each test. Samples were recovered at the same position midway of the tank (Figure 13, plan view). Once all the sediment was introduced, flow was stopped and a 5 cm (2 in.) diameter core was taken at the opposite side of the plate sampler (Figure 13, plan view). The contents of the core were emptied into a bucket, except for the upper 5 cm at the sediment-water interface to avoid biasing the sample with fines from the overlying water column (Figure 14). Core recovery for test 1 (10% fines) was approximately 90%, while for test 2 (30% fines) core recovery was approximately 60%.

Figure 14. Recovered core used to compare against composited bed samples.

2.2.3.3 Sample analysis

The sediment from the composited bed samples and core was dried in a 50°C oven for 24 hr, then prepared for mechanical sieving. Observations of the dried sediment noted the presence of aggregated silt. As a consequence, it was necessary to mechanically agitate the samples using a rubber-tipped pestle to break apart the aggregates until they were no longer observed. The sediment was then split using a riffle splitter to a target mass of approximately 50 g and mechanically sieved at the sand/fine boundary using a no. 230 (63 µm) sieve. The percentage by weight passing the no. 230 sieve was taken as the percentage of fines in the sample. The composition of the core was treated as the true but unknown value from which to compare the composited bed samples and determine the percentage error.

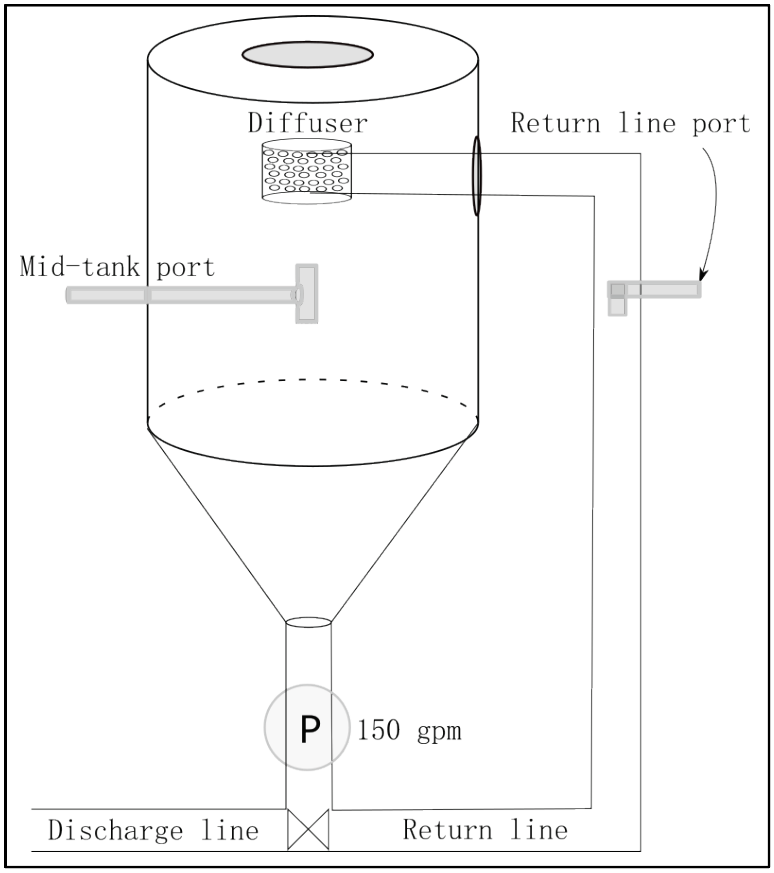
2.3 Hydraulic splitting of sediment-water mixtures

This section considers the use of a large recirculating tank for the purpose of splitting sediment-water mixtures. Inflow and/or weir sampling could involve the capture of 30 to 60 L of slurry per load that would then have to be reduced (via sample splitting or subsampling) to a manageable volume or mass for laboratory analysis. Existing hydraulic means (such as cone or churn splitters) for splitting of suspended sediment samples containing sand are prone to bias associated with the rapid settling of sand. Further, they are not practical for splitting large volumes at high sediment concentration. These tests explored whether or not subsamples extracted from the tank would be reliably characteristic of the population contained within.

2.3.1 Recirculating tank system

The recirculating system consisted of a 377 L (100 gal) semi-conical tank outfitted with a flexible nominal 5 cm (2 in.) suction line attached to a trash pump with a flow capacity of 9.5 L/s (150 gal/min) (Figure 15). The suction line ran from the bottom of the tank to the return line, which was a vertical section of 5 cm (2 in.) diameter PVC pipe that was routed back into the tank via a through-wall connector. Attached to the terminating end of the return line was a metal diffuser to disperse the sediment mixture. Two ports were installed from which to draw samples, one off the middle of the tank and one off the return line. The intake side of the mid-tank port ran to the center of the tank and had an open-ended tee attachment to restrict the sampling zone and minimize sample bias. The return line port was located in the vertical section of the return line. The placements of the sampling ports were based on locations of high turbulence to allow for increased mixing efficiency. The flow rate was monitored using an in-line electromagnetic flow meter.

Figure 15. Recirculating tank schematic for hydraulic sample splitting.



2.3.2 Sediment mixtures and schedule

Sediments used in the tests consisted of CS, FS, and VS sediments (Table 3). Grain size characteristics for these three sediments were provided in Section 2.1. A total of six tests were conducted. The sediment mixtures for tests 1–3 were the construction sand (CS) and silt (as previously described) with silt content of 0.10, 0.20, and 0.30, respectively. The mixtures for tests 4–6 were comprised of the same sand/silt ratios but used FS in place of CS. Five replicate samples were collected for each test. The target dry sediment mass introduced to the system was 19 kg to obtain an average sediment concentration by mass in the tank of 50 g/L. Care was taken to ensure that the sediment concentration in the tank was accurately quantified. As such, sediment masses were weighed to the nearest gram, and for each sediment type the average moisture content was obtained by evaporation to account for the additional water volume. Water volumes pumped into the tank system were measured to the nearest gallon (with accuracy of +/-1%) using the flow meter.

Table 3. Sample splitting test matrix.

Test No.	Test ID	Sand type	% Sand / %Silt	Sample method
1	A1	CS	90/10	Mid tank spigot
	A2	CS	90/10	Tank return line
2	B1	CS	80/20	Mid tank spigot
	B2	CS	80/20	Tank return line
3	C1	CS	70/30	Mid tank spigot
	C2	CS	70/30	Tank return line
4	D1	FS	90/10	Mid tank spigot
	D2	FS	90/10	Tank return line
5	E1	FS	80/10	Mid tank spigot
	E2	FS	80/20	Tank return line
6	F1	FS	70/30	Mid tank spigot
	F2	FS	70/30	Tank return line

Note: CS refers to construction sand. FS refers to fine sand (see text for median size information).

2.3.3 Splitting procedure

First, the recirculating tank was filled with a known water volume, 370 L. While at maximum flow (150 gal/min; 9.5 L/s), the target sediment mass at the assigned sand/silt proportion was then slowly added. Silt was introduced first and mixed for 3 min before the sand was slowly introduced. Once the sand was added, the slurry was allowed to mix for an additional 5 min to optimize mixture homogeneity. This allowed for approximately 7–8 full-volume mixing cycles based on the tank evacuation time of 0.66 min. Next, samples were withdrawn from the mid-tank port followed by the return line port, each being received into a 1 L bottle. For each test, five independent samples were collected at each port for repeatability and error analysis. A minimum volume of 0.5 L was collected for analysis, and care was taken not to overfill bottles to prevent sample biasing (any overfilled samples were noted as such, mostly for a few samples at the return line due to its high discharge velocity). Finally, the remaining slurry was pumped out of the system, and the tank was cleaned and prepared for the next test.

2.3.4 Analysis methods

Samples were analyzed for sediment concentration and grain size distribution. Sediment concentrations were determined by evaporation according to ASTM standards (ASTM 2019). Once the concentrations were determined, samples were re-slurried to a minimum volume of 250 mL and split using a fluorocarbon cone splitter with 10 discharge ports (Capel and Larson 1995; Wilde et al. 2014). Aliquots from 3 of the 10 ports were retained for grain size analysis using a Malvern laser scattering instrument.

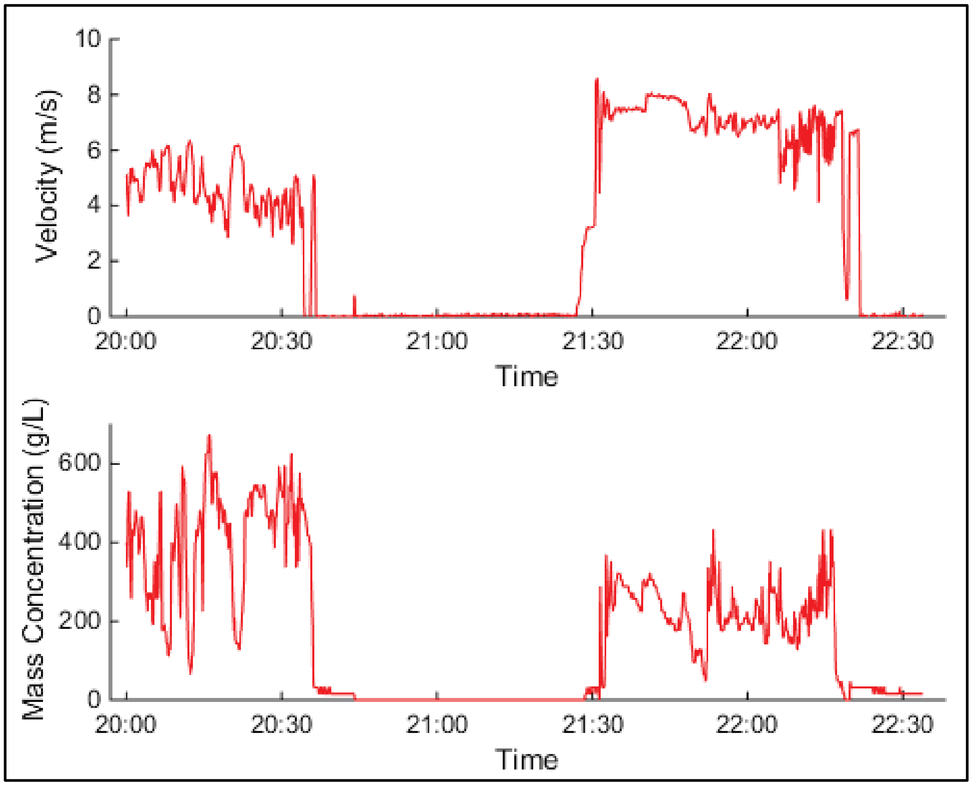
2.4 Composite sampling of hopper inflow

A numerical experiment was conducted to determine the appropriate discrete sampling interval of hopper inflow to achieve a representative mean.

2.4.1 Data source

The data for this analysis were taken from the DQM system for a TSHD plant operating along the Florida coast in 2014. The records for 147 loads were used for this analysis starting with load 1 on 19 November 2014 and ending with load 147 on 28 December 2014. DQM data were recorded on average every 7.8 s. While over 30 data metrics are reported, this analysis used only the date, time, starboard inflow specific gravity, and starboard inflow velocity. The inflow specific gravity was used to calculate the mass concentration (g/L). Figure 16 provides the inflow velocity and mass concentration for load 93, a typical load based on observation. The dredge made two passes on this load with a pause in dredging identifiable by the inflow velocity falling to nearly zero and specific gravity equal to unity between 20:45 and 21:20. No information was provided in the DQM system for sediment gradation; thus, this analysis only considered the concentration into the hopper.

Figure 16. Recorded starboard velocity and specific gravity for hopper load 93.



2.4.2 Analysis methodology

For each load, the total sediment input, *M*, into the hopper through the starboard inflow was found by numerically integrating the mass flux. The sediment mass flux was calculated as the product of the instantaneous volume flux, *Q*, and mass concentration, *C*, (estimated from slurry density). This numerical integration used the trapezoidal rule as shown in Equation 2-3, and assumed the volume flux, *Q*, was equal to the DQM reported port inflow velocity.

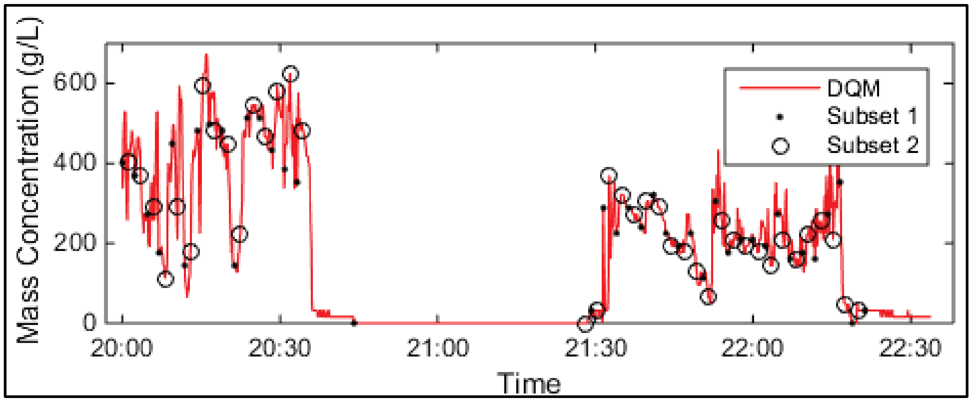
$$M = \sum_{1}^{n} \frac{(Q_{n-1} \times C_{n-1}) + (Q_n \times C_n)}{2} \Delta t \qquad (2\text{-}3)$$

Any DQM data point where the inflow velocity was less than 30.5 cm/s was not included as this indicated the dredge was not actively dredging. Finally, the average sediment mass concentration for the entire load, $\overline{C}$, was found by dividing the integrated sediment mass, *M*, by the integrated volume, *V*. The integrated volume was found using Equation 2-4.

$$V = \sum_{1}^{n} \frac{(Q_{n-1}) + (Q_n)}{2} \Delta t \qquad (2\text{-}4)$$

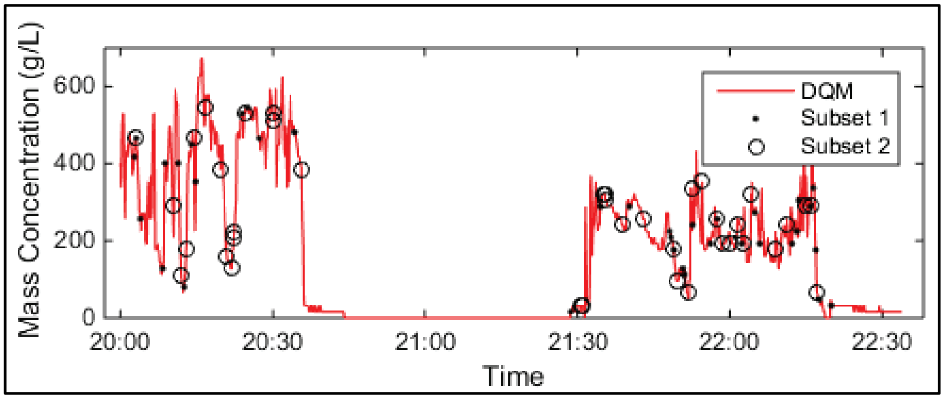
The first methodology assumed samples were taken at specific intervals. For example, starting with the first sample and choosing every 20th sample results in a time interval of 156 s. These selected samples were then averaged to compute an average concentration without any consideration of the flowrate. However, an additional comparative dataset can be found by starting at the second sample and choosing every 20th sample, akin to applying a phase shift. Figure 17 shows this sampling strategy being applied to load 93 with the sampled points for no phase shift (Subset 1) and a phase shift of 10 (Subset 2) with a sampling interval of 156 s, or every 20th sample. Thus, this methodology found the average mass concentration for a load for every possible interval up to 600 considering every possible phase shift, and is referred to as “fixed interval” in results.

Figure 17. Example of subset sampling Load 93. A fixed sampling interval with no phase shift (Subset 1) and a phase shift of 10 (Subset 2).



The second methodology assumed random sampling intervals. For example, a sample size of 20 may have been chosen for a load that takes 20 min to dredge. These samples were pulled randomly but not uniformly in time. The average sampling interval was the length of dredging record divided by the number of samples, or in this example, 60 s. These randomly sampled concentration measurements were averaged and compared to the correct average concentration. As with the previous sampling method, no consideration for the associated flowrate for each sample was given. However, one random sampling does not provide a strong comparative point, but it is possible to randomly sample the set creating many realizations. Figure 18 is an example of two subsets for load 93 using this methodology. This methodology finds the average concentration for a load for 100 random perturbed realizations for every average sampling interval up to 600 s and is referred to as “random interval” in the results.

Figure 18. Example of two subset samplings of load 93. Two random sampling realizations with average sampling interval of 156 s. Note that the samples are pulled randomly, not at a fixed sampling interval.



The averages of the sampled concentrations were compared to the correct average mass concentration given by using Equation 2-3 and 2-4, and the percent error, E, was calculated using Equation 2- 5.

$$E = 100 \times \frac{\left|\bar{C}_{sampled} - \bar{C}_{correct}\right|}{\bar{C}_{correct}} \tag{2-5}$$

This procedure was repeated for many realizations of each sampling strategy over 147 hopper loads of data, resulting in a probabilistic estimate of the expected errors associated with each sampling and compositing strategy. The mean absolute error, $\bar{E}$ for all 147 loads for a given time interval, was calculated by taking the average percent error from each load for each sampling interval.

$$\bar{E}(t) = \frac{1}{n} \sum_{n=1}^{147} E_n(t) \tag{2-6}$$

The bias was calculated by the same method as above for the relative error instead of the percent error. Additionally, for a given sampling interval all the errors were used to populate a lognormal distribution that was used to calculate the 95% standard error for a given load. A lognormal distribution was chosen because the percent error could never be negative whereas a normal distribution would allow for some percentage of the results to have a negative percent error. Two parameters are needed to quantify a lognormal distribution: (1) the mean, μ, and (2) standard deviation, σ, of the variable's natural logarithm. The variance, or square of the standard deviation, can also be used. These values were combined from each load to define a lognormal distribution that represented the absolute error for each sampling interval. This was achieved by taking an average of the lognormal distribution means, μ, and combining the variances, σ^2.

3 Results

This chapter presents the results of laboratory and numerical testing, and analysis aimed at addressing the sampling and analysis plan for conducting field sampling to address sediment sorting and separation during hopper dredging and placement operations.

3.1 Physical sampling

3.1.1 Weir overflow results

The sediment passing the overflow weir consisted mostly of fines, which comprised 95.5% ± 1.3% (mean ± standard deviation) of the total sample averaged across all tests. The fines content for each test was analyzed to discern differences between sampling devices, as well as differences between the numerically averaged overflow samples and composited receiving tank samples.

Figure 19 shows there was little difference between the average percent fines from individual weir samples and the composited value obtained from receiving tank samples (95.9% ± 0.2%), which also showed little variability irrespective of initial fines content of the starting mixture (10%, 20%, 30%). Likewise, there was little variability in the fines percentage between sampling devices (Figure 19).

Results from the analysis of sediment concentrations for all experiments are summarized in Table 4. Sediment concentrations showed little variability between sampling devices (Figure 20). The largest uncertainty in concentration (mean ± standard error of the mean) between sampling devices occurred for the tests using 30% fines, which increased slightly from 124±4, 128±3, and 133±2 g/L for bottle, box, and tube methods, respectively. Since the percentage of fines over the weir was nearly uniform at 95%, the measured concentrations tended to increase proportionally to the percent fines of the starting mixture from the supply tank, also with little variability between the overflow and receiving tank (Figure 21).

Except for the box sampler, no systematic trend in concentration was detected between sampling methods with increasing fines content of the mixtures (Figure 22). The standard deviation in concentration of the box sampler increased with increasing fines content, from 1.6 to 5.2 to 8.4 g/L for mixtures with 10%, 20%, and 30% fines, respectively.

Figure 19. Results of weir sampling tests, average percent fines between weir overflow samples and receiving tank samples. Sampling method only refers to the overflow weir.

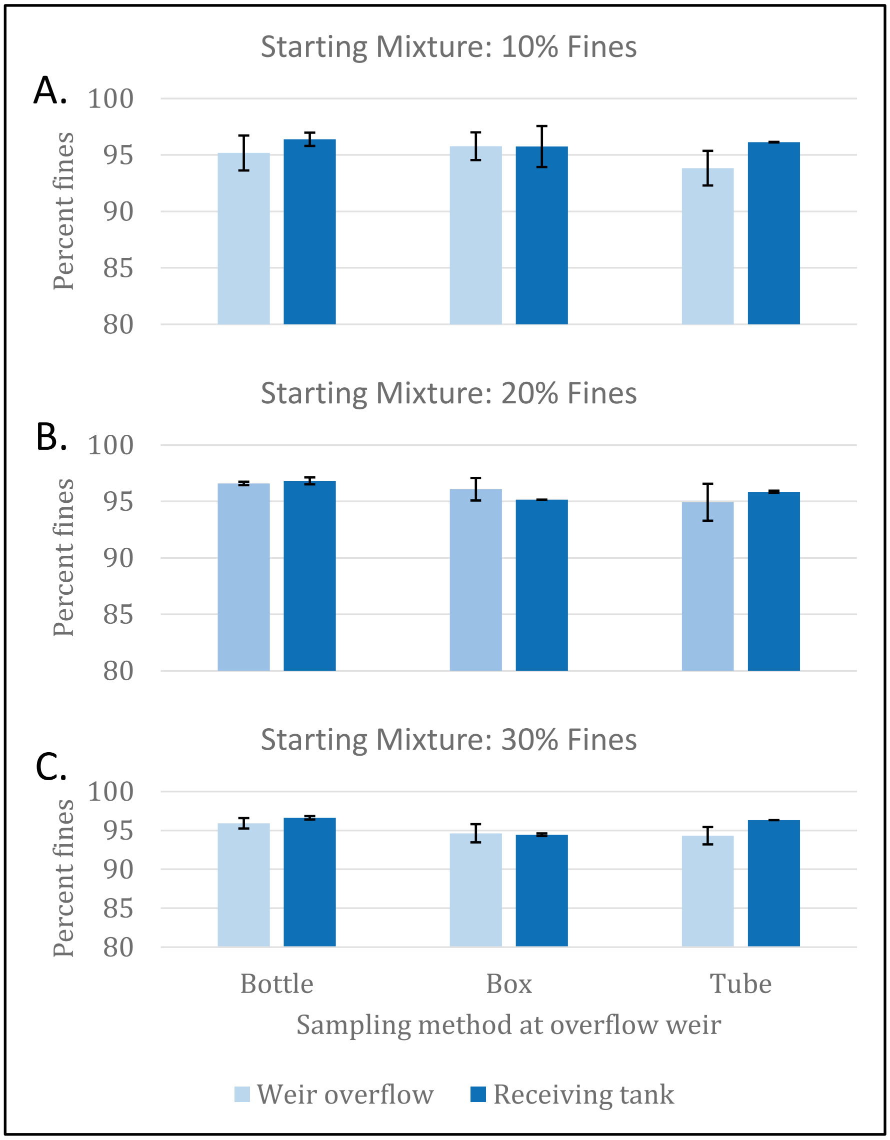


Table 4. Summary table of sediment concentrations for each experiment. Experiment IDs annotated with R refer to receiving tank samples while those with W refer to weir tank samples. Std Dev refers to standard deviation, and Std Error refers to the standard error of the mean.

Experiment ID	n samples	% fines	Sampling method	Mean C (mg/L)	Std Dev	Std Error
BR	2	20%	Bottle	85.24	1.28	0.90
BW	6	20%	Bottle	82.39	4.86	1.99
CR	2	20%	Box	88.64	1.16	0.82
CW	7	20%	Box	85.86	5.23	1.98
DR	2	20%	Tube	87.96	0.11	0.07
DW	6	20%	Tube	82.49	18.03	7.36
ER	2	30%	Bottle	125.54	0.35	0.25
EW	7	30%	Bottle	123.99	9.66	3.65
FR	2	30%	Box	131.36	0.65	0.46
FW	6	30%	Box	127.52	8.37	3.42
GR	2	30%	Tube	130.77	0.77	0.55
GW	6	30%	Tube	132.52	5.93	2.42
HR	2	10%	Bottle	42.46	0.71	0.50
HW	7	10%	Bottle	38.83	10.12	3.83
IR	2	10%	Box	40.79	0.64	0.45
IW	6	10%	Box	42.02	1.62	0.66
JR	2	10%	Tube	43.67	0.91	0.65
JW	6	10%	Tube	44.32	2.78	1.13

Figure 20. Average concentration for the different methods of weir overflow sampling and receiving tank.

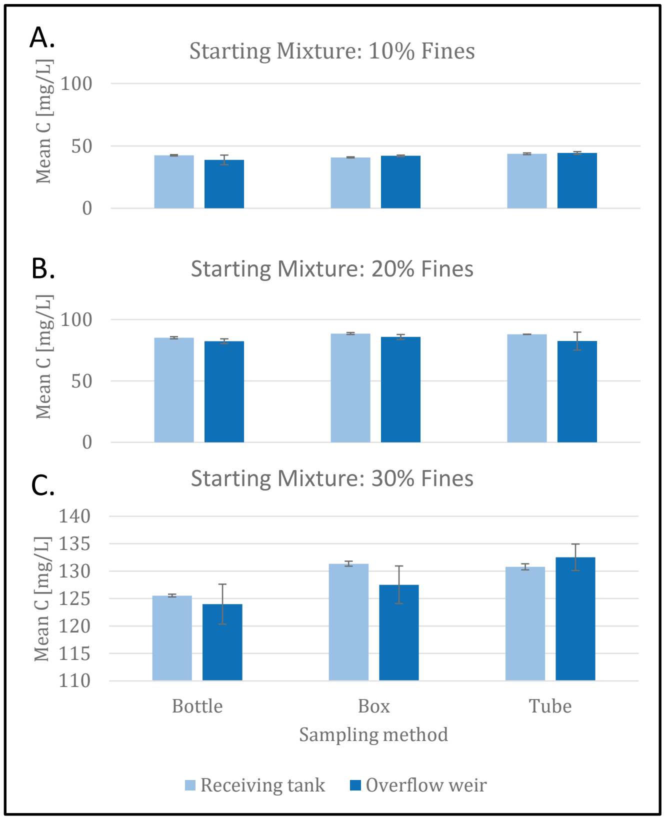


Figure 21. Mean concentration for all sampling methods for weir overflow and receiving tank samples.

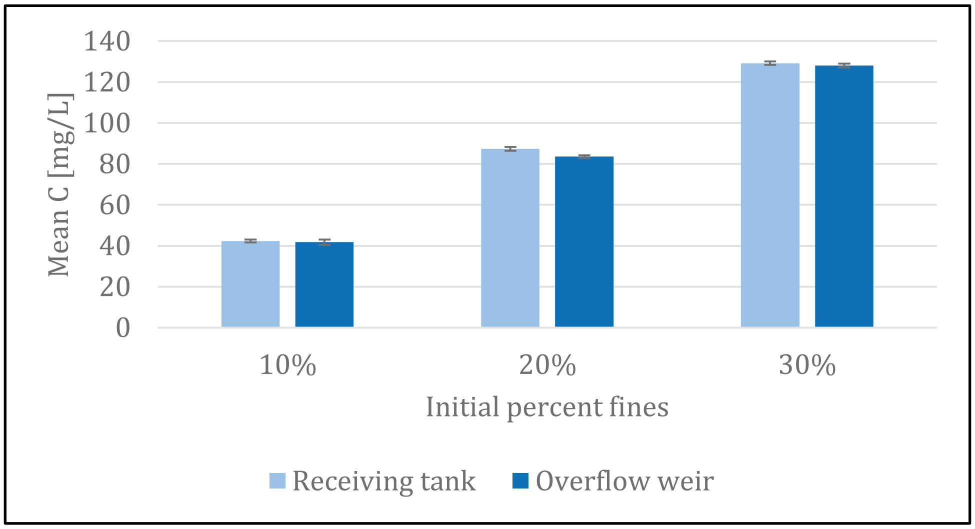
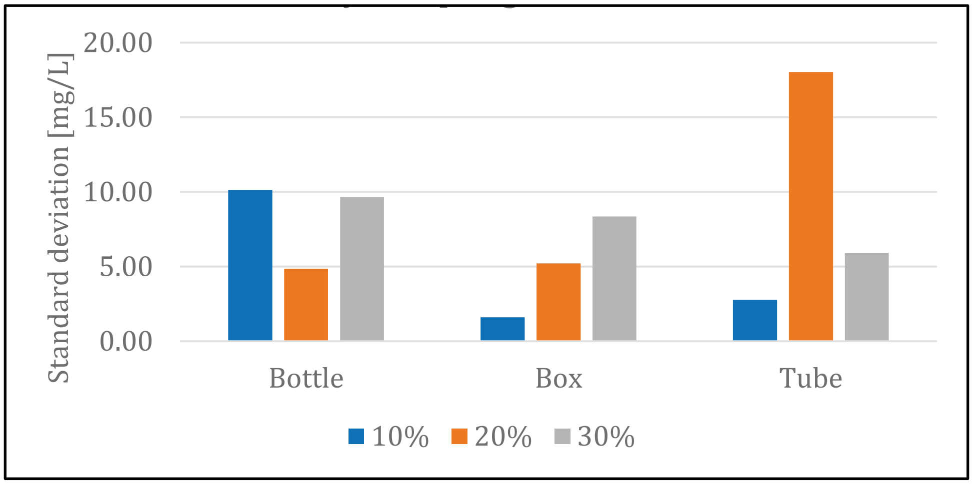


Figure 22. Variability of concentration for each weir overflow sampling method.



Relative errors (RE) between sample mean concentrations and receiving tank concentrations are provided in Table 5. Here, the tank mean was considered the true or expected value. The RE of any sampler was within 10%. On average the concentrations from the weir samples were lower than expected (6 out of 9 cases). Computing the mean relative error (MRE) for each sampler (Table 5) shows that the bottle sampler had the greatest deviation from the expected value (-4.4%) compared to the box and tube samplers that had MRE of -1.0% and -1.1%, respectively.

Table 5. Summary table comparing the RE in concentrations between the weir samples and the mean value in the receiving tank for all sediment mixtures and sampling devices.

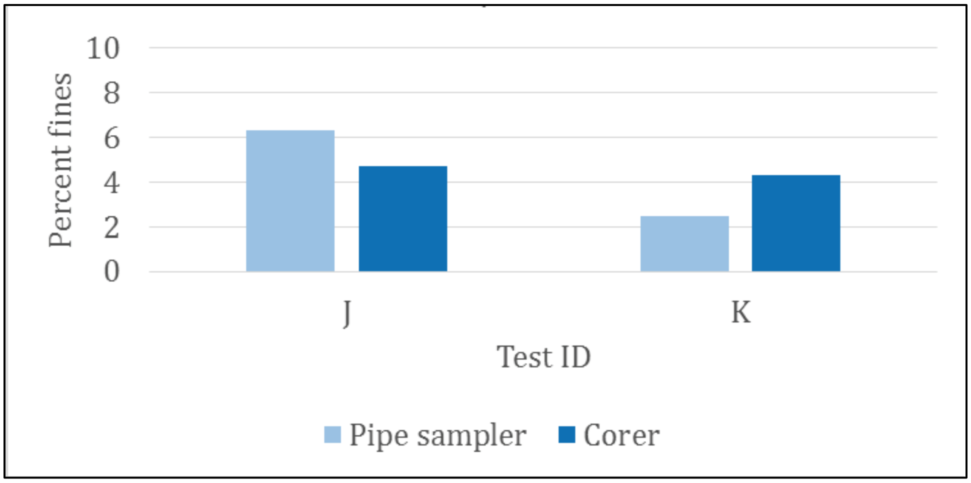
Test % fines	Method	Tank mean (g/L)	N	Weir mean (g/L)	N	MRE (%)
10	Bottle	42.46	2	38.83	6	-8.6
10	Box	40.79	2	42.02	6	3.0
10	Tube	43.67	2	44.32	7	1.5
20	Bottle	85.24	2	82.39	6	-3.3
20	Box	88.64	2	85.86	7	-3.1
20	Tube	87.96	2	82.49	6	-6.2
30	Bottle	125.54	2	123.99	7	-1.2
30	Box	131.36	2	127.52	6	-2.9
30	Tube	130.77	2	132.52	6	1.3

Method	MRE (%)
Bottle	-4.4
Box	-1.0
Tube	-1.1

3.1.2 Hopper sampling

The percentage fines of sediment retained in the hopper was compared between the pipe sampler and corer for two starting mixtures (10% and 20%). For each case, the composited sediment collected by the pipe sampler was unable to match the fines content measured by the core sample. The fines content was overestimated by 111% for the starting mixture of 10% fines and underestimated by 57% for the starting mixture of 20% fines. (Figure 23). The sediments collected by the corer are considered the true composition; however, note that the percent fines from Tests J and K did not double despite a doubling of fines of the starting mixture from 10% to 20%. Similarly, the percent fines captured by the pipe sampler were similar between tests (3.5% and 3.2%) despite a doubling of fines of the starting mixture.

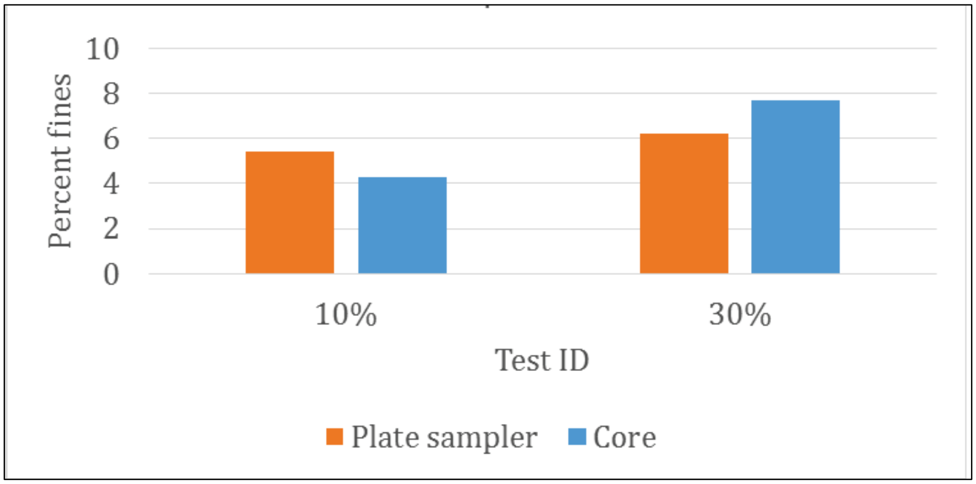
Figure 23. Comparison of the percentage fines retained in the hopper tank collected by the pipe sampler and a core for two test cases.



3.1.3 Hopper sampling via plate sampler

The percentage fines captured by the plate sampler was 5.4% for the 10% silt mixture and 6.2% for the 30% silt mixture (Figure 24). That is compared to 4.3% and 7.7% fines captured by the cores for the same mixtures, respectively. Therefore, the plate sampler slightly overestimated the fines content for the 10% silt mixture while it slightly underestimated the fines for the 30% silt mixture. This represents an absolute error of 20%–25%. However, statistical significance cannot be established due to the limited number of experiment runs.

Figure 24. Results comparing the percentage fines captured using the plate sampler and a 2 in. diameter coring device.



3.2 Hydraulic sample splitting

Results from the sample splitting experiments were used to determine if the sediment characteristics (concentration and size distribution) of hydraulically withdrawn aliquots from a recirculating tank are representative of the known concentration and composition of a slurry mixture (Table 3). The sediments used in the experiments (CS, FS, and VS) are the same as previously described. See Section 2.1 for percentile sizes and gradation curves.

3.2.1 Sediment composition

A summary of the sediment size characteristics, percent sand, and percent mud for each test is provided in Table 6. From examining the ratios of the sand-to-mud content before and after sample collection, the mud contents are often similar or over-represented in the CS tests and under-represented in the FS tests.

Table 6. Averaged sediment characteristics of samples collected from the mid-tank port (T) and the return line port (R). Initial mud/sand ratios represent the starting sediment mixture for a given test followed by ratios after sampling. IDs appended with C refer to construction sand tests and with F refer to fine sand tests.

ID	Sand Type	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	Sand %	Fines %	Initial Mud/sand	Final Mud/sand
T10C	CS	25	339	619	81.1	18.9	0.11	0.23
R10C	CS	199	387	665	90.1	9.9	0.11	0.11
T20C	CS	18	293	574	70.0	30.0	0.25	0.43
R20C	CS	33	341	603	82.7	17.3	0.25	0.21
T30C	CS	11	127	493	48.1	51.9	0.43	1.08
R30C	CS	20	357	625	76.5	23.5	0.43	0.31
T10F	FS	110	194	322	96.4	3.6	0.11	0.04
R10F	FS	122	210	351	98.0	2.0	0.11	0.02
T20F	FS	92	182	313	93.1	6.9	0.25	0.07
R20F	FS	104	186	312	95.4	4.6	0.25	0.05
T30F	FS	27	162	307	83.1	16.9	0.43	0.20
R30F	FS	43	178	328	88.2	11.8	0.43	0.13

Averaged sediment characteristics of samples collected from the mid-tank port (T) and the return line port (R). Initial mud/sand ratios represent the starting sediment mixture for a given test followed by ratios after sampling. IDs appended with C refer to construction sand tests and with F refer to fine sand tests. Percentile grain diameters in red highlight significant deviation from the average.

3.2.2 Sediment concentration

Sediment concentrations between the mid-tank port and return line port were markedly different. Figure 25 shows a bar graph of the average concentrations for each mixture and sampling port. The dashed line designates the known system concentration of 50 g/L. For each test, concentrations showed little variability (N = 5) at either sampling port, though the standard error of the mean (SEM) was slightly higher for samples collected at the return line; values ranged from 0.4-0.8 g/L at the mid-tank port and from 1.1-3.1 g/L at the return line port.

The data are further reduced in Figure 26 and provide a good summary of the results. Overall, sediment concentrations collected at the mid-tank port averaged 40 ± 2 g/L for the coarse sand tests and 45 ± 1 g/L (mean ± SEM) for the fine sand tests and were therefore closest to the known concentration of 50 g/L. Still, these values represent respective errors of 19% and 11%. In contrast, sediment was much more concentrated in the return line port, which averaged 117 ± 5 g/L and 75 ± 4 g/L (mean ± SEM) for the coarse and fine sand tests, representing errors of 134% and 50%, respectively.

Figure 25. Sediment concentrations averaged by test. Error bars represent the SEM. T = tank port, R = return line port, F = fine sand, and C = construction sand. Dashed line shows the known system concentration.

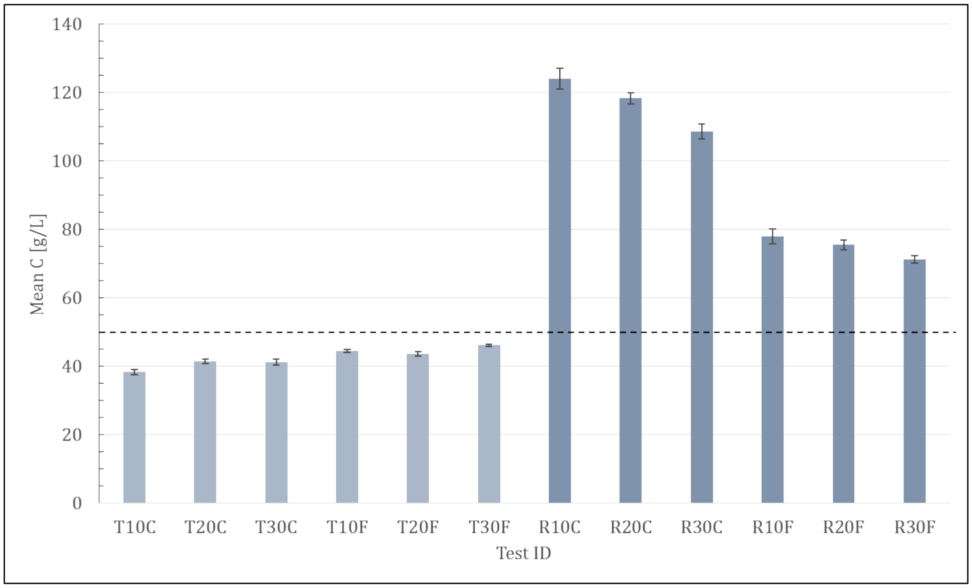
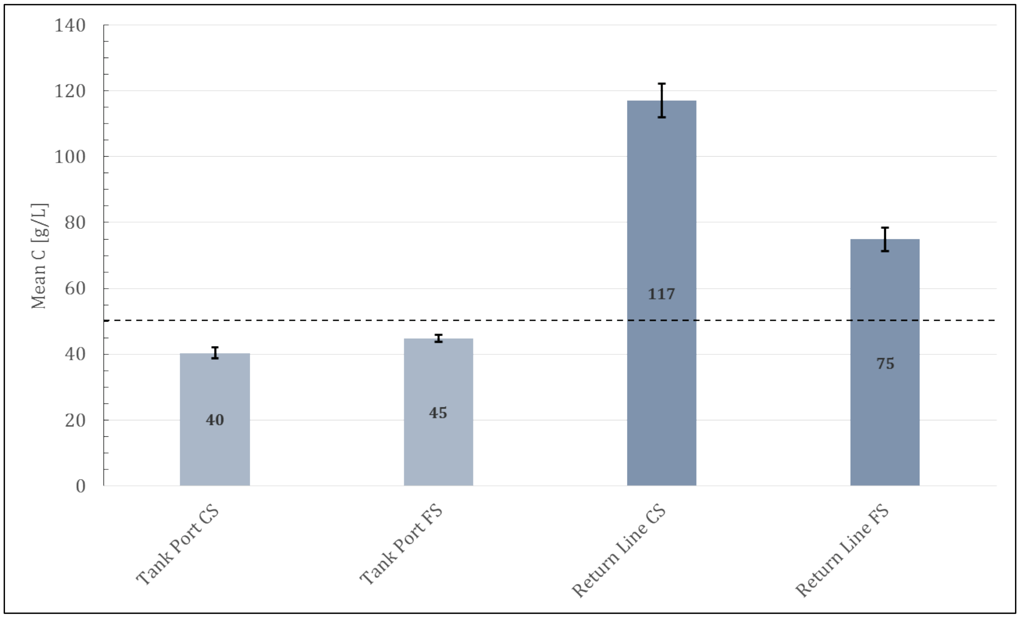
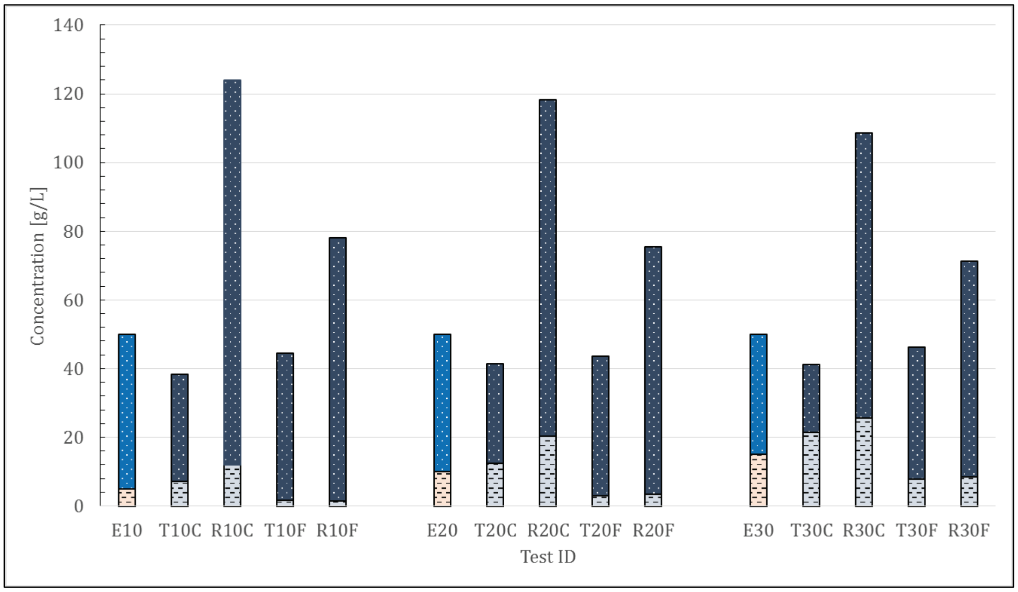


Figure 26. Sediment concentrations averaged by sampling port and sediment type. Error bars represent the averaged SEM. Dashed line shows the known system concentration.



Sand and mud concentrations were determined by multiplying the mean concentration of a given test by its fraction of sand or mud (Figure 27). The sampled concentrations from each test can then be compared to the expected concentrations of sand and mud (Figure 27; E10, E20, and E30). Due to sand's settling velocity, the concentration of sand was expected to be slightly higher in the rising flow of the return line and slightly lower in the descending flow of the tank. The relative magnitude of these concentration variances increased with settling velocity and decreased with flow speed in the return line. For the testing configuration, the sand concentration biases were expected to be on the order of a few percent. Due to the slow settling velocity of fine sediment, the concentration of fine sediment was expected to be very close to equal in the return line and tank. The results presented in Figure 27 show much more variation in both total concentration and fractional concentration than expected. The total concentration in the return line was much higher than expected, and the mid-tank total concentrations were similarly lower than expected. These observations suggest that there could be inadequate mixing by the tank diffuser and, perhaps, gravity flow down the tank walls that bypasses the mid-tank sampling position. This flow down the tank walls would also concentrate sediment at the bottom of the conical tank and increase sediment concentration in the return line. The variations from expected values in mud concentration are likewise unexpected. The measured mud concentrations vary by more than a factor of two, both higher and lower, from the expected values.

Figure 27. Averaged concentrations of mud (dashed pattern) and sand (dotted pattern) for each test grouped by initial mud content (10%, 20%, 30%). T = tank port, R = return line port, C = construction sand, and F = fine sand. For comparison, the expected concentrations of sand and mud are also plotted (E10, E20, E30).



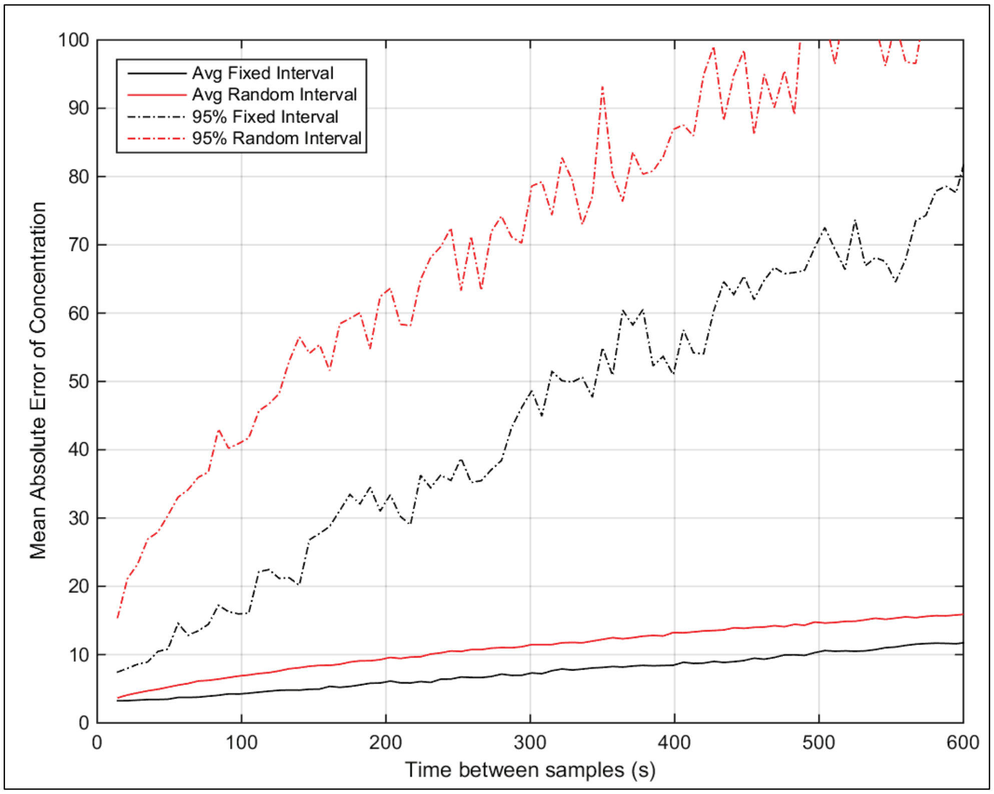
The underlying principles of the large-volume hydraulic splitter are sound. The testing results presented here highlight the difficulty in splitting suspended sediment samples, particularly those with fast-settling particles. Further testing of the concept in the future is recommended with particular attention given to redesign of the flow diffuser in the upper portion of the tank, and sample analysis methods for the sand/fine split. Alternatively, samples with fast settling particles can be dewatered and split in a moist state.

3.3 Numerical experiments

To determine appropriate sampling methods and intervals for the dredge inflow, a numerical experiment was undertaken. Figure 28 provides the mean and 95% confidence intervals of the absolute relative error in mass concentration for both fixed and random interval sampling. The mean absolute RE of the mass concentration was approximately 3% smaller for the fixed interval sampling versus the random interval sampling. The 95% interval error was approximately 15% larger for the random interval sampling versus the fixed sampling for any average sampling interval over

200 s. At a sampling interval of 60 s, a 4% error was introduced with the fixed interval sampling compared to 7% for the random interval sampling. Both sampling methods showed a mean absolute error of less than 10% with a sampling interval less than 200 s. Even at sampling intervals less than 30 s, error was present on the order of 4%. This error was the result of the difference between the first moment of mass flux (the true measure given by Equation 3) and the arithmetic mean (an approximation of the true measure). Additionally, the fixed interval and random interval methods produced a relative bias of -1.36% and -1.23%, respectively, for the calculated average concentration.

Figure 28. Results of numerical experiment of inflow sampling interval, showing the mean absolute error and the 95% interval percent error for both the fixed and random interval sampling.



4 Discussion and Conclusions

The goal of this study was to evaluate specific sediment sampling and measurement techniques to be applied on TSHDs to determine the fraction of fine sediments present at various stages of the dredging process. Several specific sampling-related topics were explored, including the following:

- determining whether samples from the TSHD can be composited (or combined) to form physically averaged samples
- testing a hydraulic means of subsampling large-volume, composited samples
- determining suitable sampling methods for collecting samples within the dredge from the inflow slurry, the hopper sediment bed, and the hopper overflow
- determining the appropriate sampling interval for the hopper inflow.

These research topics were evaluated through a set of laboratory and numerical experiments described in previous sections. A discussion of the results of the laboratory and numerical experiments is provided in this section. Particular emphasis in the discussion is given to recommendations for a field data collection campaign to quantify the separation of sediments during the dredging and beach placement processes.

4.1 Sample compositing

Sample compositing (or physical averaging) is a method by which samples are collected in time, space, or both, and physically mixed to form an *averaged* sample. An inherent assumption in arithmetic averaging is the uniform weighting of samples (all samples are equally valued). For the proposed field study, sample compositing is considered for hopper inflow sampling, hopper bed sampling, and beach coring.

A primary concern with compositing hopper inflow samples is that the covariance of hopper inflow rate and slurry concentration can contribute to sample bias. Bias is introduced by arithmetic averaging (physical or numerical) of inflow concentration, instead of from the first moment of the inflow sediment mass flux. A numerical experiment was conducted to determine the error introduced by compositing samples, including the effects of sampling interval and regularity. The numerical experiment resampled data of hopper inflow rate and slurry density with two sampling schemes and a range of sampling intervals, for the purpose of determining the difference between the arithmetic mean of slurry concentration and the true value of mean slurry concentration (as estimated by the first moment of sediment mass flux). The results of the numerical experiment indicated a small mean error (or bias) on the order of -1%. (In this case, negative bias means that the arithmetic mean of the composited sample is less than the true value estimated from the first moment of sediment flux.) The small bias indicated by the analysis suggests that compositing of the physical inflow samples for concentration and size analysis is appropriate.

4.2 Sample splitting

Sample compositing often results in sample volumes or masses that are too large for the intended laboratory sample analysis methods. In these instances, the sample must be split in a representative manner without introducing bias. There are well-documented procedures for splitting of dry and moist soil and sediment samples. However, suspended sediment samples present particular challenges since the settling velocity of coarse sediments such as sand and gravel is sufficiently large to interfere with complete and unbiased hydraulic mixing of the sample. Inadequately mixed suspensions generally result in bias, as the sample may be withdrawn either from a sediment-rich or sediment-poor portion of the suspension and will not be representative of the population.

This study attempted to configure a hydraulic sample splitter for the purposes of splitting composited hopper bed, hopper overflow, and/or hopper inflow samples. The hydraulic splitter was tested with mixtures of sand and silt. The results of the hydraulic sample splitter indicated that coarser sediments are inadequately mixed by the present design. The biases in the return line sample are suspected to be associated with inadequate mixing of the sample by the flow diffuser in the upper tank, and consequent gravitational settling and concentration of the coarser sediments in the bottom section of the conical tank. Concentration of the sample in this location resulted in increased concentration in the return line and relatively sparse concentration of coarse sediment near the mid-tank withdrawal point. The conclusion of this work is that the present design of this system is inadequate for the requirements of the present study, and alternate approaches will be more appropriate.

The preferred approach for the field study is to settle and decant water from any suspended sediment samples from the composited samples and quantify sediment mass in the decanted water. Suspended solids would be quantified by filtering decanted water through large glass-fiber filters. The settled sediments could then be subsampled in a moist or dry state, which is much less prone to particle-settling-related biases.

4.3 Sampling methods

Sampling methods were tested for acquiring samples from the hopper outflow weir, the hopper sediment bed, and the hopper inflow.

4.3.1 Hopper overflow weir sampling

Three sampling devices (bottle, box, tube) were tested to determine applicability for sampling at hopper overflow weirs. Each device was tested in a controlled laboratory experiment aimed at quantifying the suspended sediment concentration and size fractionation of a sediment suspension passing with similar depth and flow velocity as a prototype hopper overflow weir. These tests served to identify advantages and disadvantages of one design over another and to anticipate potential issues that might arise when deployed on a dredge.

All three sampling devices provided very similar estimates of average concentration and mud content when compared to samples from the recovery tank. These favorable evaluations suggest that, when the flow depth and flow velocity of the weir are comparable to the testing conditions, any of the sampling methods would be appropriate. For deeper depths of flow, the bottle sampler may be prone to overfilling and, therefore, bias. The box and tube samplers are readily scalable to provide sampling over the full depth of overflow. While the preference for one sampler over another may only depend on the unique operating logistics of a dredging vessel, there is reason to think that pump-sampling (via the box or tube sampler) may offer significant advantages. For example, Kerssemakers (2004) used custom bottle and flow-through samplers to collect samples from a standpipe-style overflow weir aboard the TSHD *Cornelia*. This work clearly demonstrated the challenges of collecting overflow samples. It was uncertain whether their devices were capturing representative samples due to either overfilling (in the case of the bottle sampler) or sampler positioning within the weir. With the box and tube samplers, there is no concern of overfilling, and both are more likely to capture a depth-integrated sample of the overflow (especially the box sampler) than the bottle sampler. Additionally, a sample could be drawn continuously by attaching a suction line to the discharge outlet from which to draw samples. This would allow for greater flexibility in setting sampling intervals, which is an important consideration for compositing purposes.

4.3.2 Hopper sediment bed sampling

The preliminary design for a hopper sampler consisted of pipe with one capped end resting on its side (pipe sampler), as described in Section 3.3. During testing, it was noted that sampler orientation had a marked effect on sediment capture. Sediment was captured sufficiently only when the sampler was oriented parallel to the primary direction of flow (Figure 8). Results from two independent tests indicated a sampling bias by preferential collection of fine sediments relative to that collected by an adjacent core from the bed. The suspected cause of the bias was attributed to (1) a sheltering effect by the pipe that allowed suspended fine sediments to settle within the sampler and/or (2) sub-maximum filling of the sampler that allowed suspended fines to be collected in the overlying water within the sampler during retrieval. The limited testing of the pipe sampler indicated that its characteristics were unsuitable for sampling the hopper bed.

Given the unsatisfactory performance of the pipe sampler, a plate sampler was designed and constructed to address sample bias from sheltering effects. The operational concept was proven in the laboratory experiments and suggests that bed samples from a dredge hopper can be reliably obtained in a consistent manner.

The apparent bias in the fraction of fines obtained using the plate sampler was both positive and negative compared to cored samples. These differences cannot be explained with any statistical significance given the constraints on the number of trials conducted. However, the results showed much better agreement compared to those derived using the pipe sampler. Although more trials would be necessary to fully evaluate the plate sampler, it remains a viable option for collecting representative hopper samples from the dredge. Other devices considered (though not tested here) to collect samples from the hopper bed were surface grab devices and gravity corers.

The Ponar sampler is a clamshell-style gravity sampler that has opposing jaws to take surficial sediment samples to a depth of approximately 10 cm. They are often equipped with top-facing rubber flaps to allow water to pass through upon descent. They are easy to operate, but the major disadvantages envisioned are (1) potential for premature closing in high turbulence environments, (2) loss of sample due to incomplete closing (usually with sandy, coarse sediments), and (3) high propensity of biasing during retrieval (not completely shielded). Grab samplers are particularly susceptible to washout of fine-grained sediment (FieldsCapri and Schumacher 2004). Based on these factors, the Ponar sampler was eliminated as a viable sampling option.

Gravity core samplers are weight-assisted coring devices used to take vertical profiles of the sediment. The sediment is contained within a polycarbonate tube equipped with a core catcher to aid in sample recovery. They are most often used for soft, loosely consolidated fine-grained sediments. However, the sandy sediment within the upper layers of the dredge hopper bed may be fluidized enough to allow for sufficient penetration, and therefore the gravity core sampler remains a viable sampling option.

4.3.3 Hopper inflow sampling

Collecting samples from the hopper inflow would be achieved using a pump sampling device. The intake of the sampling hose would be positioned directly within the inflow discharge. Slurry would be withdrawn from the dredge inflow with an engine-driven trash pump. Samples would be collected from the trash pump discharge on a periodic basis from the trash pump effluent. Proper testing of a sampler for this purpose was not feasible in the laboratory due to the large discharge volumes expected at the dredge inflow.

Primary concerns of inflow sampling are the potential biasing of inflow samples by compositing of samples and excessive error introduced by inadequate sampling of the inflow. The sample compositing concern was addressed through a numerical analysis (discussed above). The numerical experiment also examined appropriate sampling intervals of the inflow. Sampling theory indicates that sample approximation of the population improves with increased sample size. The numerical experiment indicated an improved estimate of the true mean slurry concentration with reduced sample interval (equivalent to increased numbers of samples). Regular sampling in time was clearly better than random sampling in time, reducing the mean absolute error by approximately 5% and the upper limit of absolute error by 10% to 20%. The gains of regular sampling are presumably due to the inherent time variability in the inflow rate and slurry concentration. Regular sampling over the entire loading cycle would also be important for capturing variations in sediment composition during the loading cycle. A mean absolute error less than 10% can be obtained with composited samples collected at regular intervals of 120 s or less. If the sampling interval is further reduced to 90 s, the mean absolute error reduces to less than 5%. These sampling intervals are physically feasible with the proposed pump sampling. Additionally, the results of the numerical experiment can be applied as an estimate of the expected error for the actual sampling intervals performed in the field.

4.4 Conclusions

The findings of the laboratory and numerical evaluations described in this study lead to the following conclusions related to field studies:

1. The three devices (box, bottle, and tube samplers) used to measure the sediment properties of the hopper overflow generated estimates of suspended sediment concentration and size distribution that were, on average, within 4% or less relative to samples obtained from the recovery tank. The choice of sampling device to apply in a field setting is most likely dependent on access to the hopper overflow location and characteristics of the overflow such as depth of overflow, velocity of overflow, and weir geometry.
2. Numerical evaluation of inflow data for 147 hopper loads indicated that compositing of the hopper inflow samples will result in low bias and acceptable accuracy. Sample compositing is also acceptable for increased sampling of the hopper bed, hopper suspended load, and beach coring activities.
3. A hydraulic sample splitter to reduce the volume of composited hopper inflow samples was evaluated and found to be unacceptable in its capacity to mix sand-sized sediment. All sample splitting for the field study should be accomplished by moist or dry sample splitting according to established standards and procedures. Suspended sediment samples should be settled and decanted prior to sample splitting to avoid hydraulic separation and bias.
4. The numerical experiments of the inflow data provided guidance for the necessary sampling interval to accurately describe the

concentrations. A fixed interval between samples had less error than a random interval, demonstrating the need for regular sampling over the entire filling operation. Sampling intervals of 90 to 120 s contribute sampling errors less than +/- 5% to 10%, respectively.

5. Sampling the deposited sediment in the hopper requires that the method not create a shelter from the flow and turbulence. Sheltering increases the percent fines of the sample, thus biasing the results. Other important concerns are likelihood of sample recovery, ease of use, and safety. Based on these concerns, vibracores, pipe samplers, and surface grabs were eliminated as sampling options in the hopper. Therefore, the two options considered here that provide the best chance of collecting representative hopper samples are the gravity corer and the plate sampler.

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Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
microns	1.0 E-06	meters
miles (nautical)	1,852.0	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
ounces (mass)	0.02834952	kilograms
ounces (US fluid)	2.957353 E-05	cubic meters
pounds (mass)	0.45359237	kilograms
quarts (US liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

Acronyms and Abbreviations

CS	construction sand
DQM	Dredging Quality Management
FS	fine sand
MRE	mean relative error
PVC	polyvinyl chloride
RE	relative error
SEM	standard error of the mean
TSHD	trailing suction hopper dredges
VS	Vicksburg silt
SAND	Sediment Assessment and Needs Determination
SD	standard deviation

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14. ABSTRACT
Hopper dredging operations for beach and nearshore placement typically include periods of overflow, which produces some degree of separation between the size fractions of the dredged sediment. The degree of separation and the controlling factors are presently poorly known. This report focuses on laboratory experiments aimed at determining (1) suitable sampling methods on a dredge, (2) composite sampling techniques to reduce analysis cost, (3) associated sampling intervals to achieve suitable sediment representation of a hopper load, and (4) a hydraulic means of sample splitting. Results showed that no statistical difference exists among the three methods used to sample the hopper weir overflow. The method used to sample deposited hopper sediment identified a bias in the percent fines that resulted from flow sheltering. Further, it was found that composited samples were able to quantify the concentration and percent fines accurately, although an analytical data experiment showed that the accuracy of a composited sample is dependent on the sampling intervals. The accuracy of the fines and concentration from a hydraulic sample splitter was found to be dependent on median grain size, with fine sediment being evenly distributed and coarser sediment increasing the error in concentration and grain size distribution.

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