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A Novel Suspended-Sediment Sampling Method: Depth-Integrated Grab (DIG)

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Abstract: Measuring suspended sediment in fluvial systems is critical to understanding and managing water resources. Sampling suspended sediment has been the primary means of understanding fluvial suspended sediment. Specialized samplers, sampling methods, and laboratory methods developed by select U.S. Federal Agencies are more representative of river and stream conditions than commonly used grab sampling and total suspended solids (TSS) laboratory methods but are not widely used because they are expensive, time consuming, and not required as part of water quality standards in the United States. A new suspended-sediment sampling method called a depth-integrated grab (DIG) was developed by combining certain elements from both grab and depth-integrating sampling methods and suspended-sediment concentration (SSC) laboratory methods. The goal of the DIG method was to provide more accurate results than Grab-TSS while being easier and cheaper to sample than specialized samplers and methods. Approximately 50 paired comparison samples were collected at 9 sites in Minnesota from 2018 through 2019. Results showed no significant difference between the DIG and specialized sampling methods and a significant difference between both methods and the Grab-TSS method. The DIG-SSC provided an improved alternative to the Grab-TSS method, but additional research and testing is important to evaluate if this method is appropriate in different conditions than were observed in this study.

Keywords: sediment transport; suspended sediment; suspended-sediment concentration; isokinetic; depth-integrating; grab sampling; total suspended solids; water quality; Minnesota; Wilcoxon test

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1. Introduction

Scientists, engineers, and natural resource managers have a need for fluvial suspended sediment data because they are not always available at locations of interest. Using suspended-sediment samplers has been the primary method for collecting fluvial suspended sediment data, but not all sampling and laboratory methods are representative of a river's suspended-sediment characteristics. Sediment may not be well mixed horizontally across the river cross section, especially when a tributary enters with different sediment characteristics [1]. Fluvial suspended sediment and its grain size distributions are rarely distributed uniformly in a river's cross section and can vary with depth [2], especially when sand-size particles (0.0625 to 2 millimeters [mm]) are present [3]. The occurrence and concentration of sand is often greater near the streambed, and it can be transported as bedload and/or suspended in the water column. Sand is more likely than fines to be deposited in the channel or floodplain when the river's velocities decrease. Fine-sized particles, which consist of silt and clay (less than 0.0625 mm), are more homogenously mixed in the river's cross section and can stay in suspension longer than sand.

Grab sampling does not represent the horizontal and vertical distribution of sediment because it only incorporates the top of the water column (less than 0.5 meters [m]), and only one location in the cross section is sampled (Figure 1c). Additionally, the total suspended solids (TSS) laboratory method [4], which is often used to analyze grab samples, provides additional errors [5–9]. The TSS laboratory method involves subsampling the original water sample, so the amount of suspended sediment in the subsample can be filtered and measured [4]. The TSS laboratory method is not representative of the whole water sample because sand can settle during the subsample extraction given Stokes's law. Several studies have shown that Grab-TSS is not as accurate as using specialized samplers and laboratory methods developed by the Federal Interagency Sedimentation Project (FISP) and the U.S. Geological Survey (USGS) because Grab-TSS fails to measure sand [5–9]. Even though this knowledge exists, Grab-TSS is widely used by water quality agencies and organizations as a water quality standard [10] for rivers and streams, such as in Minnesota where this study took place. There needs to be a less expensive and feasible alternative that is more representative of river conditions than Grab-TSS yet easier and cheaper than specialized samplers and methods.

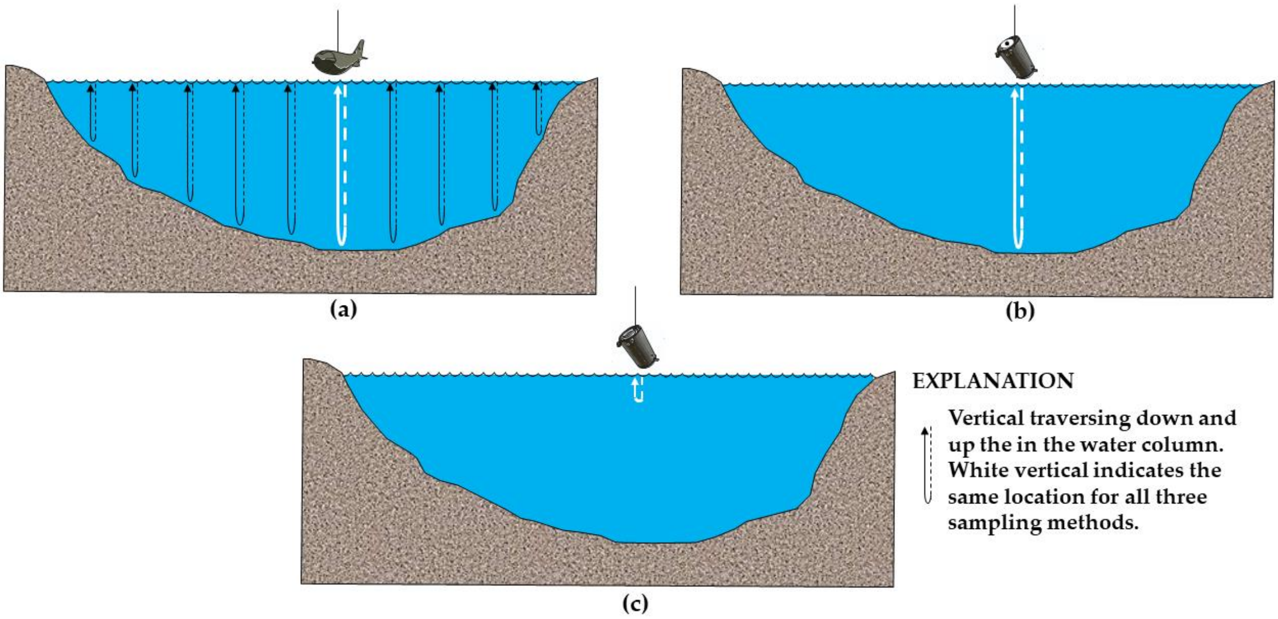

Figure 1. Three suspended-sediment sampling methods: (**a**) equal-width increment (EWI) suspended-sediment sampling method with 10 verticals and a D-74 suspended sediment sampler; (**b**) depth-integrated grab (DIG) suspended-sediment sampling method with 1 vertical and a US WBH-96 suspended sediment sampler with a hole in the bottle's cap; (**c**) Grab suspended-sediment sampling method with 1 vertical (near surface) and a US WBH-96 suspended-sediment sampler with an open-mouth bottle.

The US Federal agencies (USGS, U.S. Army Corps of Engineers, Bureau of Reclamation, and U.S. Department of Agriculture) that make up the FISP have specialized samplers, sampling methods, and laboratory methods to accurately represent fluvial suspended sediment in a river's cross section given that suspended sediment is not always uniformly distributed in fluvial systems due to the presence of sand. The primary suspended-sediment sampling and laboratory methods include equal-width increment (EWI; Figure 1a) or equal-discharge increment (EDI) sampling [11–13] and suspended-sediment concentration (SSC) laboratory methods [14,15]. These standard methods (EWDI-SSC) provide the best measures of suspended sediment because they depth-integrate nearly the entire water depth (except the bottom ~ 10 centimeters (cm) if the sampler touches the river's bed), measure the river's cross section at multiple verticals, and sample isokinetically. Isokinetic sampling is when water and sediment particles enter the sampler's nozzle at the same velocity as the stream velocity outside the sampler's nozzle. The SSC laboratory method measures the entire water-sediment mixture without a subsample extraction used with the TSS method. However, these samplers and methods are not widely used due to being more expensive, time consuming, and requiring more specialized equipment and training than grab sampling and TSS laboratory methods. For example, a weighted bottle sampler [16], commonly used for grab samples, is approximately 7 percent of the total cost of a US D-74 isokinetic sampler [17].

Technology and methods involving turbidity, acoustics, and laser diffraction (called surrogates) have shown great potential for accurately and cost-effectively estimating SSCs and particle sizes [18–20]. These methods and technology allow for increased spatial and/or temporal resolution in fluvial suspended sediment data and, once relations are developed, allow for rapid estimates of SSCs and particle sizes when collecting samples are not feasible or cost effective. However, those methods do not replace physical samples because physical samples are still used to calibrate the sensors.

There is a need for alternative samplers and methods that are more representative of river conditions than Grab-TSS methods but easier and cheaper to deploy than EWDI-SSC methods. The USGS Upper Midwest Water Science Center developed a suspended sediment sampling method that combined the elements from both grab and EWDI-SSC sampling methods. The goal of the new method was to improve the accuracy compared to Grab-TSS and reduce costs associated with EWDI-SSC sampling. The developed sampling method is called a depth-integrated grab (DIG; Figure 1b). It was originally hypothesized that the DIG would not be as accurate as an EWDI-SSC because it only consisted of one vertical measurement and was assumed to be non-isokinetic. However, the results suggest that there was not a significant difference between DIG-SSC and EWDI-SSC.

2. Materials and Methods

2.1. Study Area

The advancement and retreating of glaciers, predominantly the Wisconsinan glaciation occurring 85,000 to 11,000 years ago, has created diverse landforms and surface water conditions across Minnesota [21]. The resulting soil type and topographic relief created 5 sediment regions [22] within the state: southeast, southwest, middle, northeast, and northwest (Figure 2).

Glacial materials older than the Wisconsinan glaciation are found at the surface only in the southeastern and southwestern corners of the state [23]. The southeast region was the only region of the state not covered by the Wisconsinan glaciation, resulting in a lack of glacial till and shallower, poorer topsoil in the region [23]. Rivers in this region have created deep-cut valleys into underlying bedrock, resulting in more efficient drainage systems and more advanced erosion [23].

The southwest region is defined by the present-day Minnesota River valley and was formed from the drainage of glacial Lake Agassiz approximately 10,000 years ago. The tributaries to the Minnesota River flow through highly erodible knickpoints made up of fine-grained till, producing incised valleys throughout the region [24,25].

The middle region in central Minnesota contains a mixture of cultivated crops, pasture, and forests [25]. The middle region is in a transition zone between the agricultural land use of the south and the forested regions of the north [25]. The middle region contains the largest urban developed region in the state, the Minnesota-St. Paul metropolitan area. The northwest has a flat landscape, and the predominant land use is cultivated crops.

The predominantly forested northeast region has shallow bedrock, and steeper gradient rivers flow toward Lake Superior [26,27]. The northwest region contains predominantly cultivated crops, and the landscape is relatively flat compared to the rest of the regions. Overall, Minnesota's low-relief glaciated landscape contains differing sediment transport regimes that vary based on regional vulnerability to erosion, supplies, and controls [22]. The 9 sampling locations selected for this study represent these sediment regions present in Minnesota (Figure 2).

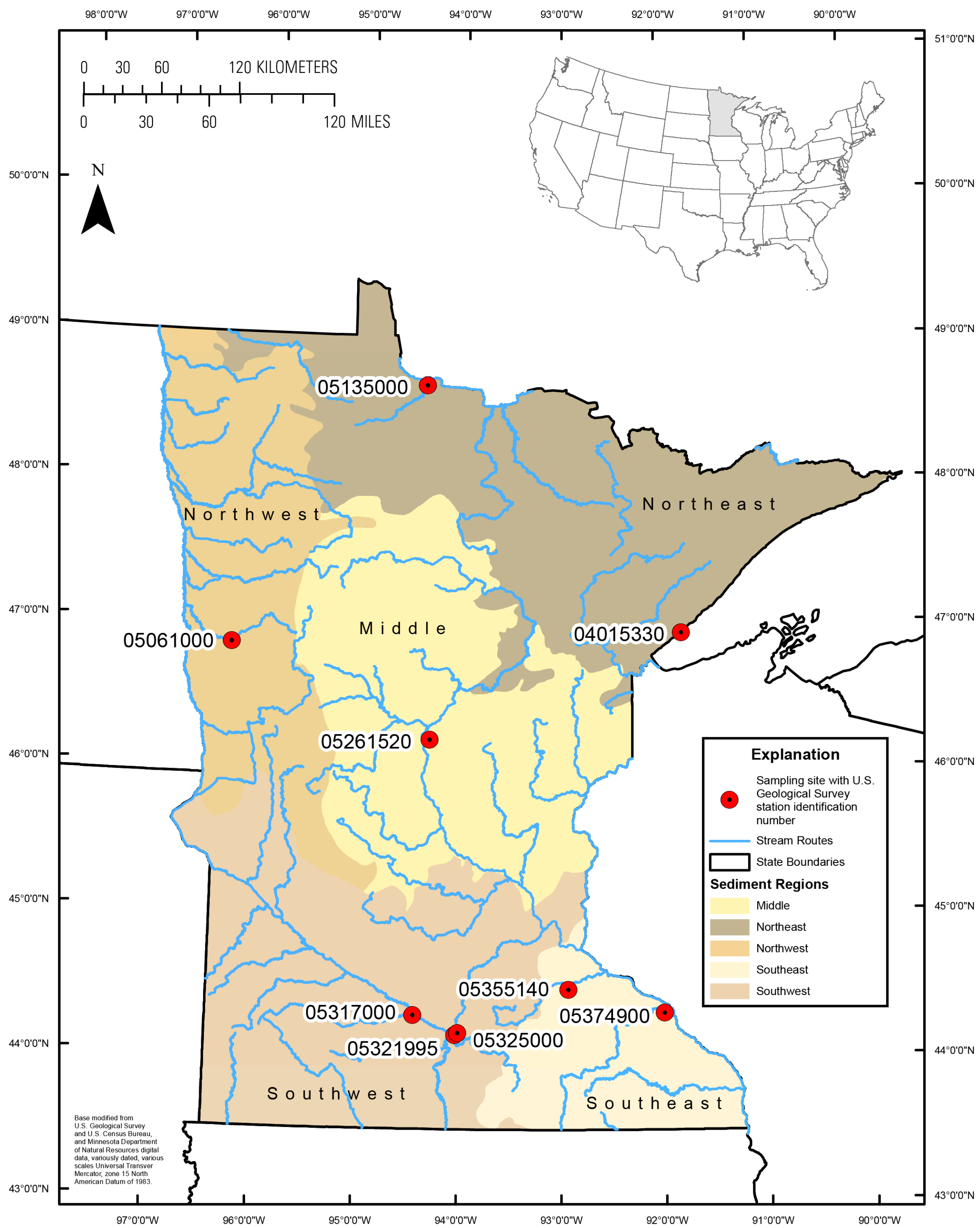

Figure 2. Study area with 9 suspended-sediment sampling sites in Minnesota.

2.2. *Equal-Width Increment or Equal-Discharge Increment (EWDI) Sampling Method*

Based on previous research, the EWDI-SSC was considered the representative measure of SSC and was used as a comparison to other sampling and laboratory methods [5–9]. Suspended-sediment samples were collected with isokinetic and depth-integrating samplers at EWIs or EDIs [12,13]. For the collection of samples, the stream was either divided into 10 EWIs (Figure 1a) or 5 EDIs. Each depth-integrated, isokinetic sample was collected at the centroid of each increment [12]. The EWI method had equal widths while the EDI method's width increments varied depending on the distribution of discharge during the time of sample collection. The EWI method was the primary sampling method used in this study.

Before an EWI sample could be collected, the sampler transit rate had to be determined. Different sampler transit rates (generally, 0.4 times the average velocity in the sampled vertical [12]) were tested by sampling the deepest and fastest part of the river, to ensure the sample container did not overfill during the final sample. The same transit rate was used for all the EWI sample verticals. Depending on the river depth and velocity, a US DH-48 bottle sampler (with a 0.5-L glass bottle), US D-74 bottle sampler (with a 0.5-L glass bottle or 1-L glass bottle) (Figure 3b), or US D-96 bag sampler (with a 3-L bag) [13]. The US D-74 sampler and 0.635 cm sampler nozzle were mostly used in this study.

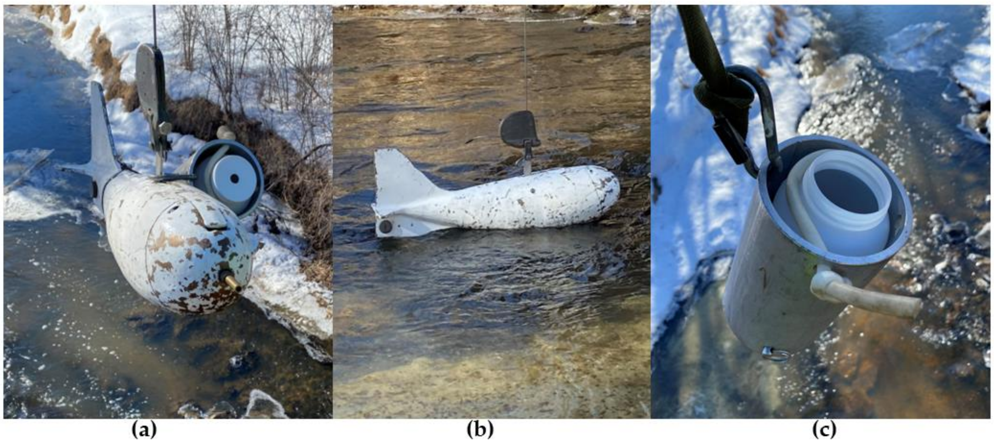

Figure 3. The 3 suspended-sediment samplers: (**a**) depth-integrated grab (DIG) suspended-sediment sampler (US WBH-96 with a hole in the bottle's cap) attached to a D-74 suspended sediment sampler; (**b**) A D-74 suspended sediment sampler near the water surface; (**c**) A US WBH-96 grab suspended-sediment sampler with an open-mouth bottle.

The US DH-48 bottle sampler and US D-74 operate identically with the only difference being that the US D-74 can hold either a 0.5- or 1-L glass bottle while the US DH-48 can only hold a 0.5-L bottle. The US DH-48 and US D-74 have vents which are located on the side of the sampler and point downstream during sample collection. The vent allows air to escape as it is displaced by the sample being collected in the bottle. The US D-96 bag sampler can sample at deeper depths and higher velocities than the US DH-48 and US D-74. The US D-96 does not have a vent but, prior to sample collection, the person sampling collapses the bag with their hands which pushes the air out from the bag and nozzle prior to sample collection.

Contamination can occur when a sampler's nozzle digs into the streambed. A depth-sounding was taken before each sample was collected to determine the water depth. Each vertical was sampled approximately 0.15 to 0.3 m above the streambed to prevent bed contamination. The distance above the streambed varied depending on the estimated height of the river's sand dunes to avoid inadvertently sampling the sand dune. All samples collected from the centroids of the stream transect were composited into one sample and sent to the laboratory for analysis.

2.3. Depth-Integrated Grab (DIG) Sampling Method

A DIG consists of a single depth-integrating vertical. For this study, the location of the DIG sample was the centroid of the river's channel. The location of the DIG sample was always the same location as one of the EWDI verticals and the grab sampling location (white verticals in Figure 1a–c). A depth-sounding was taken before each sample was collected to determine the water depth. Each vertical was sampled approximately 0.15 to 0.3 m above the streambed to prevent bed contamination. The DIG method sampled the same depth of the water column as the one vertical of the EWDI sample.

The DIG deploys a weighted-bottle sampler (US WBH-96) with a 1-L high-density polyethylene plastic bottle secured to the inside of the sampler with a rubber band. For this study, the weighted bottle was attached directly to the isokinetic sampler to obtain a concurrent sample (Figure 3a) that was collected at the same time as 1 of the EWDI-SSC verticals. The one-liter bottle had a cap attached to the mouth of the bottle with a 1.27 cm hole in the center of the bottle cap (Figure 3a). The hole in the cap was created with a drill press. The purpose of the hole in the cap was to prevent the bottle from overfilling while depth integrating. The DIG sampler does not have a separate vent like the US DH-48 and US D-74 samplers, so air escapes from the hole in the cap during sample collection.

A transit rate for the DIG sample was determined at the same time as the EWDI transit rate for the isokinetic samplers (US DH-48, US D-74, or US D-96). It was important to determine a transit rate common to the DIG sampler and isokinetic sampler that prevented overfilling because the sample container's volume and nozzle opening sizes differed between samplers. The same transit rate was used with the DIG sample as the EWDI sample because the samplers were sent into the water column concurrently. After the sample was collected, the bottle was inspected to make sure the sample was not overfilled. This was done by making sure the collected sample was below the shoulder of the bottle. A cap without a hole in it was secured to the bottle and sent to the laboratory for analysis.

2.4. Grab Sampling Method (Grab)

A grab sample was collected using the same type of 1-L HDPE plastic bottle as the DIG but had no cap attached (open-mouth) to the bottle (Figure 3c). The plastic bottle was secured to the inside of a weighted-bottle sampler (US WBH-96) with a rubber band (Figure 3c). The grab sample was collected from the centroid of the river channel (same location as DIG and one EWDI vertical) at a depth ranging from directly below the water surface to less than approximately 0.5 m below the water surface, depending on water velocities (Figure 1). If water velocities were higher, the sampler was not able to go that far below the surface. The exact depth was not measured each time. A Grab-TSS sample was collected directly before (sequentially) and within minutes of when the DIG and EWDI samples were collected. The grab sample was not collected at the same time as the EWDI and DIG because only 1 weighted-bottle sampler was available during the sampling events. After the sample was collected, the bottle was secured with a cap and sent to the laboratory for analysis.

2.5. Suspended-Sediment Concentration Labratory Method (SSC, Fines, and Sands)

The SSC laboratory analyses consisted of two methods. Suspended-sediment samples collected with EWDI and DIG sampling methods were both analyzed for SSC following method D3977-97 [14,15] by the USGS Sediment Laboratory in Iowa City, Iowa. SSC is measured by measuring the dry weight of sediment from a known volume of a water-sediment mixture. SSC measures the entire water-sediment mixture. Percentages of fines (%Fines) were also determined from SSC samples at the same laboratory by wet sieving [14]. SSC and percent fines results are available in the USGS National Water Information System [28].

The suspended-sand concentration (Sands) was calculated from Equations (1) and (2) while the suspended-fines concentration (Fines) was calculated from Equation (1). First, %Fines was multiplied by the corresponding SSC value and dividing the product by 100 to obtain the Fines. Second, the calculated Fines (Equation (1)) was subtracted (minused) from the corresponding SSC to calculate Sands (Equation (2)).

$$\text{Fines} = (\%\text{Fines} \times \text{SSC})/100 \quad (1)$$

$$\text{Sands} = \text{SSC} - \text{Fines} \quad (2)$$

2.6. Total Suspended Solids Laboratory Method (TSS)

Suspended sediment samples collected with the grab sampling method were analyzed at the Minnesota Department of Health Laboratory in St. Paul, Minnesota for TSS following method 2540 D [4]. The results from the TSS laboratory analyses are available from the Water Quality Portal [29].

2.7. Data Analysis

Data analysis included summary statistics, visual inspection of the data, bootstrapped median and percentile values, and the Wilcoxon signed rank test [30]. The R statistical environment was used to produce the bootstrapped median and percentile values and perform the Wilcoxon signed rank tests [31].

3. Results

A total of 9 rivers were sampled in 2018 and 2019 (Table 1). The sampling campaign resulted in 48 pairs of EWDI-SSC and DIG-SSC with all but 2 of those pairs having Grab-TSS being collected at nearly the same time (sequential).

Table 1. Summary of sampling sites and number of samples collected.

Station Name	Station Number	Date from (yyyymmdd)	Date to (yyyymmdd)	Number of Samples
KNIFE RIVER NEAR TWO HARBORS, MN	04015330	20180531	20190415	3
BUFFALO RIVER NEAR HAWLEY, MN	05061000	20190401	20190716	6
NOKASIPPI RIVER NEAR FORT RIPLEY, MN	05261520	20190402	20190923	8
COTTONWOOD RIVER NEAR NEW ULM, MN	05317000	20190418	20190904	2
BLUE EARTH RIVER AT HWY 169 AT MANKATO, MN	05321995	20180608	20180921	2
MINNESOTA RIVER AT MANKATO, MN	05325000	20180421	20190529	9
LITTLE CANNON RIVER NEAR CANNON FALLS, MN	05355140	20190323	20190702	3
ZUMBRO RIVER AT KELLOGG, MN	05374900	20180422	20180921	4
EAST FORK RAPID RIVER NEAR CLEMENSTON, MN	05135000	20190424	20190710	11

Abbreviations: MN, Minnesota.

The rivers' sizes ranged from 12–126 m in width and 1–10 m in depth (Table S1; Supplemental Materials). The 9 rivers' streamflows ranged from 3–1823 cubic meters per second during sample collection (Table S1; Supplemental Materials). The range of EWDI-SSC measured was 4–1690 milligrams per liter (mg/L). The percentage of suspended sand in the EWDI-SSC samples ranged from 0–56 percent. The range of EWDI-Fines concentrations ranged from 2–1487 while the EWDI-Sands concentrations ranged from 0–278 mg/L (Table 2).

Table 2. Summary statistics for sampling and laboratory methods and river conditions.

	EWDI-SSC (mg/L)	DIG-SSC (mg/L)	EWDI-Sands (mg/L)	DIG-Sands (mg/L)	EWDI-Fines (mg/L)	DIG-Fines (mg/L)	Grab-TSS (mg/L)	Water Depth (m)	Stream Width (m)	Q (cms)
Min.	4	3	0	0	2	2	3	1	12	3
Max.	1690	1690	278	629	1487	1572	1600	10	126	1823
Mean	267	279	52	60	215	219	221	3	49	277
Med.	90	80	13	15	65	52	76	2	37	16
SD	362	400	71	113	307	320	317	3	39	517

Abbreviations: Min., minimum; Max., maximum; Med., median; SD, standard deviation; EWDI, equal-width or -discharge increment; SSC, suspended-sediment concentration; mg/L, milligrams per liter; DIG, depth-integrated grab; TSS, total suspended solids; m, meters; Q, streamflow; cms, cubic meters per second.

EWDI-SSC, EWDI-Sands, and EWDI-Fines were considered the representative measures of suspended sediment and were the primary samples to which the other methods were compared. Sediment sample distributions by sampling methods are shown in Figure 4. Sediment sample distributions and median concentrations of SSC, TSS, Fines, and Sands varied among rivers and the 3 sampling methods, EWDI, DIG, and grab (Figure 4). The highest measured EWDI-SSC, -Fines, and -Sands were in the southwestern and southeastern sediment regions of Minnesota at the Blue Earth River at Mankato (05321995), the Cottonwood River near New Ulm (0531700), and the Zumbro River at Kellogg (05374900). The northeastern sediment region site East Fork Rapid River near Clemenston (05135000) and middle sediment region site the Nokasippi River near Fort Ripley (05261520) had the lowest median SSC, Fines, and Sands values, regardless of sampling method. The Grab-TSS concentrations were lower than those obtained by EWDI and DIG methods at most of the sites (Figure 4).

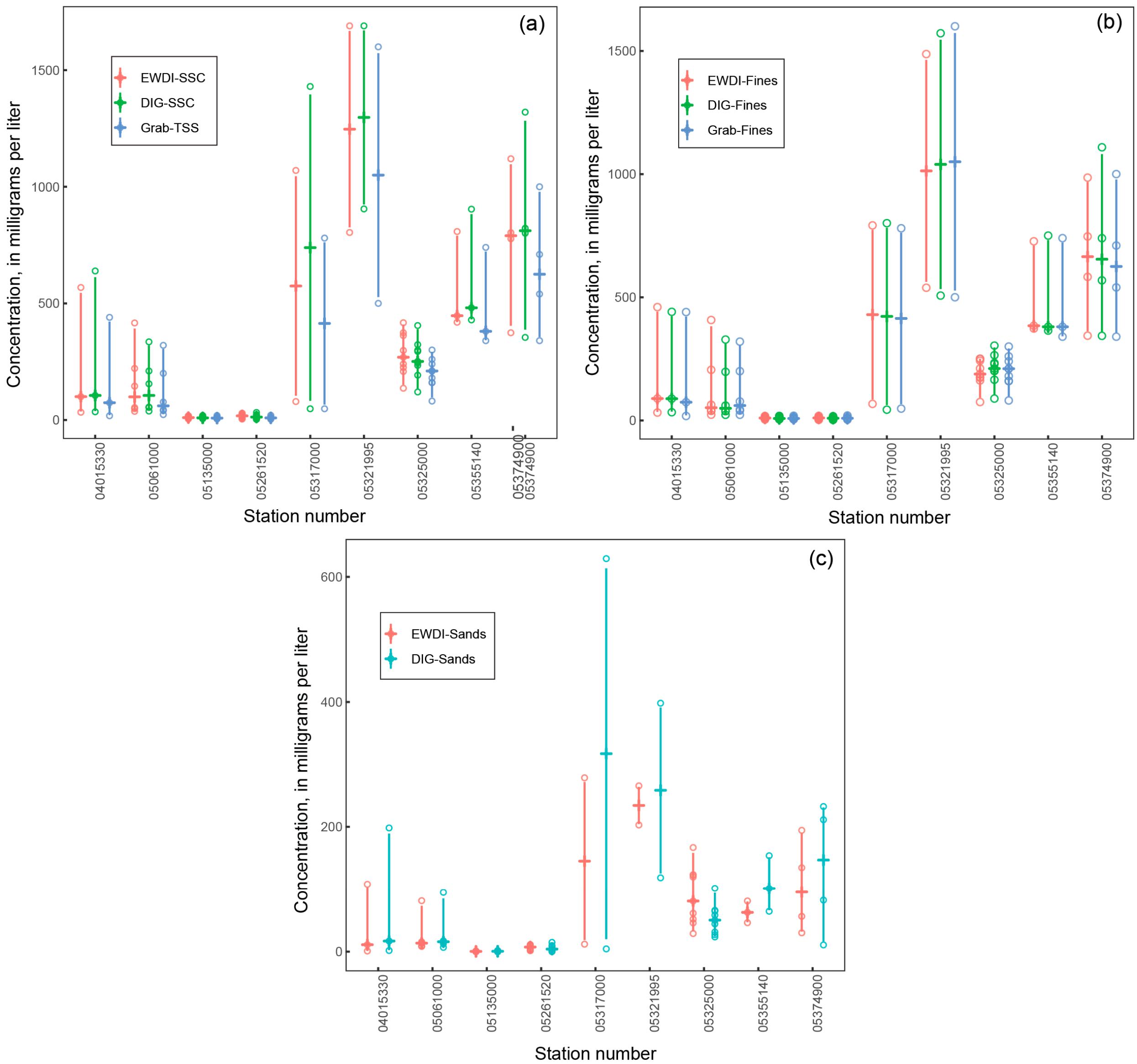

Figure 4. Bootstrapped median values (horizonal line) and the 2.5th and 97.5 percentiles (vertical line), and measured values (open circle) for sampling (equal-width or -discharge increment [EWDI], depth-integrated grab [DIG], and Grab) and laboratory methods at each of the 9 sampling sites: (**a**) Suspended-sediment concentration (SSC) and total-suspended solids (TSS) laboratory methods; (**b**) Suspended-fines concentration (Fines) laboratory method; (**c**) Suspended-sands concentration (Sands) laboratory method.

Visual inspection of the SSC data showed close agreement between EWDI and DIG sampling methods (Figure 5). Most of the data plotted near or on the 1:1 line. The paired data from site 0531700 which deviated the furthest from the 1:1 line was at 1070 mg/L on the x-axis (EWDI-SSC) and 1430 mg/L on the y-axis (DIG-SSC). This paired data had the greatest discrepancy due to there being much higher Sands in the DIG sample (629 mg/L) than the EWDI sample (278 mg/L) when compared to the whole dataset. These paired samples had the highest measured Sands observed during the study. This discrepancy in measured Sandse between the two methods could be due to only measuring one vertical with the DIG method and measuring it at a location with potentially higher sand transport. The location of the DIG samples was at the centroid of the channel which is generally the deepest and fastest part of the river because it was the same location where transit rates were tested and determined.

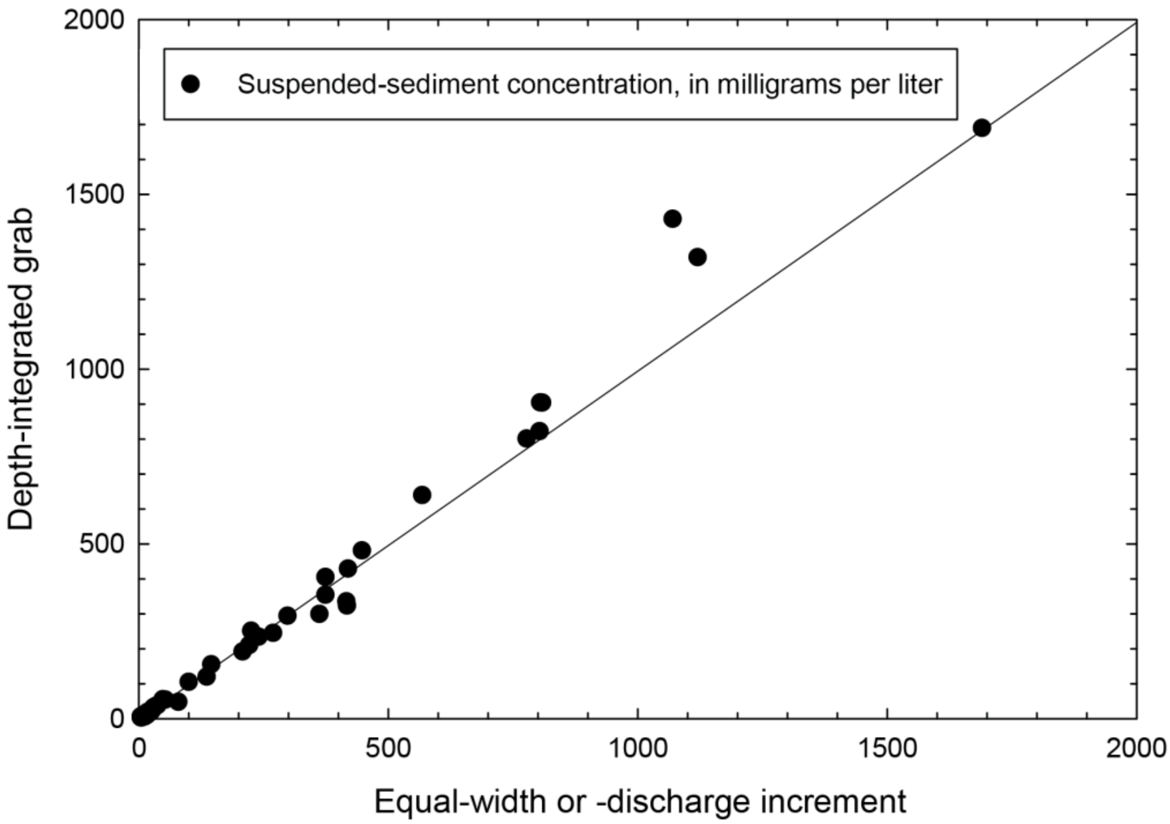

Figure 5. Relationship between depth-integrated grab (DIG) and equal-width or -discharge increment (EWDI) sampling methods using the suspended-sediment concentration (SSC) laboratory method. The black line is the 1:1 line.

When comparing the Fines and Sands between EWDI and DIG sampling methods, the range of Sands was generally less than the Fines. The maximum measured Sands was 629 mg/L (DIG) while the maximum measured Fines was 1572 mg/L (DIG). There was a closer agreement between the EWDI-Fines and DIG-Fines than the EWDI-Sands and DIG-Sands (Figure 6). Most of the Fines data plotted near or on the 1:1 line (Figure 6). There was more variability around the 1:1 line for Sands data. The same sample that deviated the furthest from the 1:1 line in Figure 5 also plotted the furthest above the 1:1 line, with the DIG sample having an additional 351 mg/L of Sands than the EWDI sample.

A paired Wilcoxon test, also known as the Wilcoxon signed-rank test, was used to compare samples collected by 2 different methods [30]. The paired test takes the sample differences from each collection method and tests the null hypothesis that the median difference is equal to zero. Distributions of paired samples are shown in Figure 7. The results from the paired Wilcoxon test are shown in Table 3.

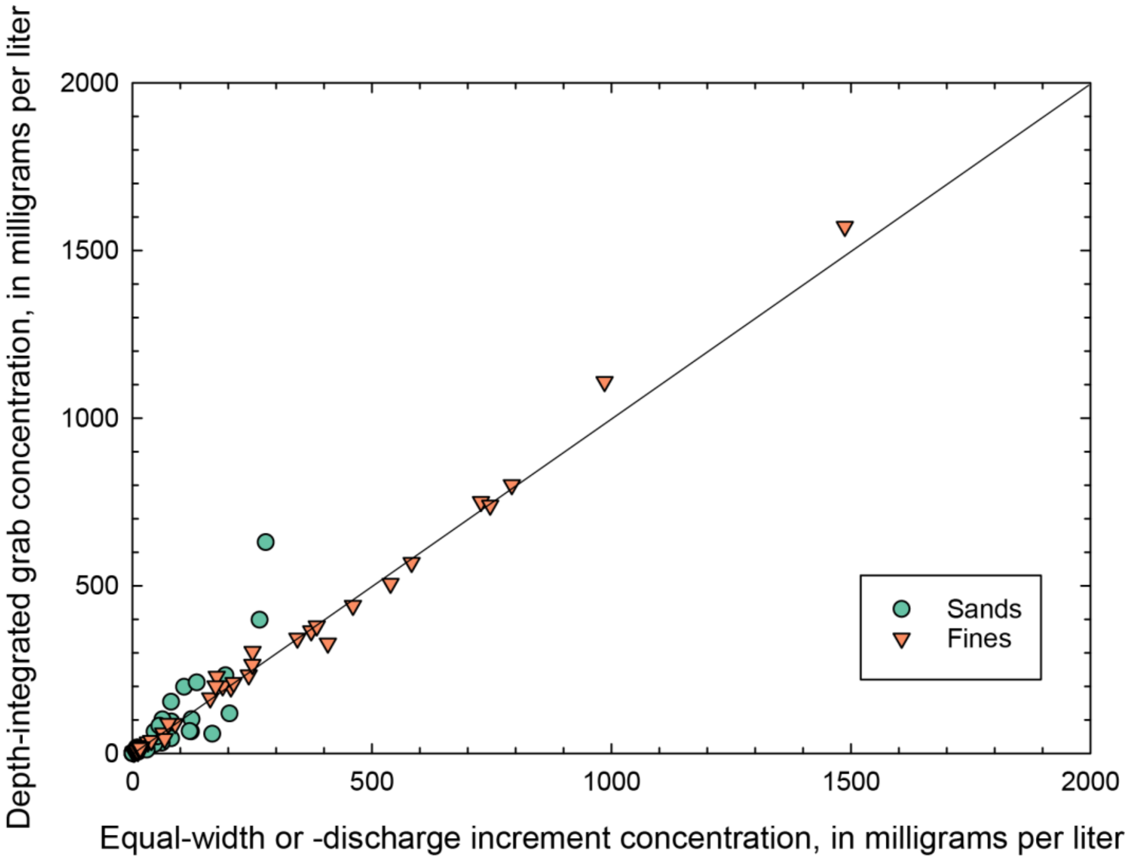

Figure 6. Relationship between Sands and Fines concentrations for equal-width or -discharge increment (EWDI) sampling method (x-axis) and depth-integrated grab (DIG) sampling method (y-axis). The black line is the 1:1 line.

Table 3. Results from the paired Wilcoxon test [30].

First Method	Second Method	Median	*p*-Value
EWDI-SSC	DIG-SSC	0	0.68
EWDI-SSC	Grab-TSS	28	<0.01
DIG-SSC	Grab-TSS	15	<0.01
EWDI-Sands	DIG-Sands	0.09	0.96
EWDI-Sands	Grab-TSS	−33	<0.01
DIG-Sands	Grab-TSS	−47	<0.01
EWDI-Fines	DIG-Fines	0.65	0.42
EWDI-Fines	Grab-TSS	1.72	0.06
DIG-Fines	Grab-TSS	1.67	<0.01

Abbreviations: *p*-value, probability value; <, less than; EWDI, equal-width or -discharge increment; SSC, suspended-sediment concentration; DIG, depth-integrated grab; TSS, total suspended solids.

Statistically significant (*p*-value less than 0.05) differences were not found between EWDI and DIG methods for any sediment type (SSC, Sands, and Fines; Table 1). There was not a statistically significant difference between EWDI-Fines and Grab-TSS (Table 3). Conversely, there were statistically significant differences between all the other comparisons (EWDI-SSC-Sands and DIG-SSC-Fines) and Grab-TSS. The Grab-TSS samples were generally lower than EWDI and DIG methods. The median difference between EWDI-SSC and Grab-TSS was 28 mg/L, and the median difference between DIG-SSC and Grab-TSS was 15 mg/L (Table 3). For Fines, the median differences were 1.72 and 1.67 between EWDI-Fines and Grab-TSS, and DIG-Fines and Grab-TSS, respectively (Table 3).

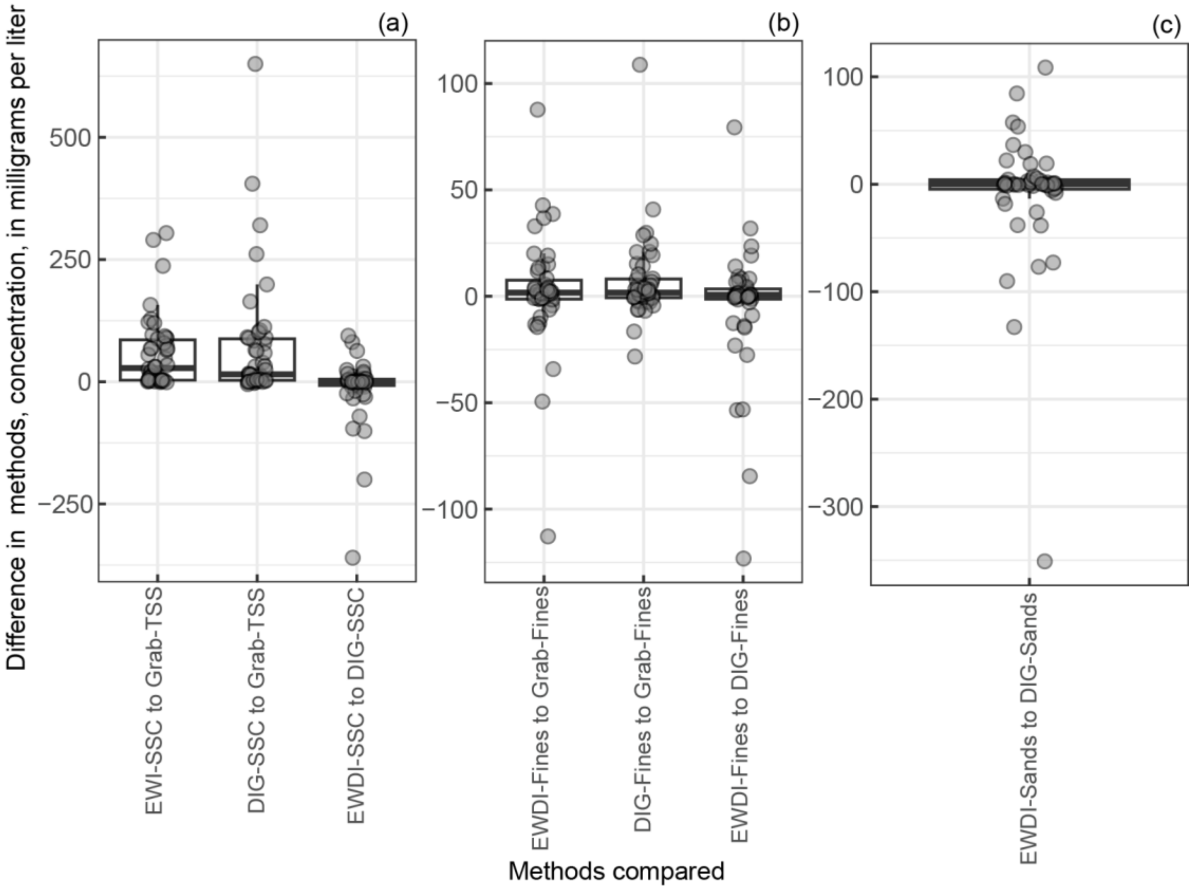

Figure 7. Box plots depict the minimum, first quartile, median, third quartile, and maximum, with measured values depicted as single points, and show the difference in the paired values between each sampling (equal-width or -discharge increment [EWDI], depth-integrated grab [DIG], and Grab) and laboratory method for a particular sample: (**a**) Suspended-sediment concentration (SSC) and total-suspended solids (TSS) laboratory methods; (**b**) Suspended-fines concentration (Fines) laboratory method; (**c**) Suspended-sands concentration (Sands) laboratory method.

4. Discussion

Since there was not a statistically significant difference between the EWDI-SSC and DIG-SSC sampling methods, the DIG-SSC shows promise as a more representative method than Grab-TSS. Furthermore, the DIG-SSC is easier and cheaper to use in the field than EWDI-SSC. However, the DIG-SSC was only tested at 9 sites within a specific range of river and suspended-sediment characteristics (Table 2). The DIG-SSC method would benefit from testing at other rivers with different streamflow and suspended-sediment characteristics that were not represented in this study. Additional results could help validate or challenge our study's results.

The close agreement between EWDI and DIG methods may be explained by the rivers in this study being relatively well mixed horizontally. The main limitation with the DIG method occurs when a river is poorly mixed horizontally. If deploying the DIG method and the river is poorly mixed horizontally, possible solutions would be to go further downstream where the river is fully mixed horizontally or modify the DIG method to sample at multiple verticals by using EWDI methods with the DIG sampler.

The DIG-SSC method would benefit from testing at sites with higher concentrations of sand than what was observed in this study. Sand caused greater variability when comparing EWDI and DIG sampling methods. The variability might be explained by the DIG method only sampling one vertical while the EWDI method sampled multiple verticals. Furthermore, the sample location of the DIG method was at the deepest and fastest part of the river, which probably had the highest concentrations of sand, and greater than the other EWDI sampling locations. This could be tested by comparing the same location and the same number of verticals with both the DIG and isokinetic samplers. This would make the sampling methods comparable to see if the variability seen in this study is from the different number of verticals used by DIG and EWDI methods.

It would also be beneficial to test if the DIG sampler is isokinetic or not. The measure of isokinetic sampling is defined as the ratio of the velocity through the nozzle entrance (Vn) to the ambient stream velocity (V):

$$\text{Isokinetic} = \text{Vn}/\text{V} \quad (3)$$

where Vn and V are averaged over the sample time and depth for each specific sample. This could be another possible explanation of the variability between EWDI and DIG methods. If additional sampling data were to be collected in the future, it would be beneficial to determine the DIG sampler's intake efficiency (IE) which is a measure of isokinetic sampling [32]. Equation (4) contains K which is indexed to the nozzle opening, volume (Vol), duration, and stream velocity (SV).

$$\text{IE} = \text{K} \times (\text{Vol}/\text{D})/\text{SV} \quad (4)$$

The average IE should fall within $0.75 < \text{IE} < 1.25$ [32]. Moreover, IE could be compared with temperature [33] and depth which would help determine the operational specifications of the DIG sampler. Furthermore, future research could entail testing the DIG sampler in a tow tank to see if it samples isokinetically and(or) by performing 3-dimensional (3D) modeling to see if the DIG samples isokinetically. Since there is no significant difference between the DIG-SSC and EWDI-SSC, the DIG-SSC could be isokinetic; however, the results in this study cannot confirm this without additional testing and evaluation.

The DIG-SSC might not be applicable everywhere but does provide a more representative estimate of suspended sediment than Grab-TSS due to its ability to capture and measure sand with sampling and laboratory methods. Even though the comparison of EWDI-Fines and Grab-TSS was only marginally above the threshold of significance, another study showed the similarity between EWDI-Fines and Grab-TSS [9]. Since there are nominal differences between Grab-TSS and measured Fines with EWDI methods, Grab-TSS might only be used as an estimate of Fines and may not be considered a complete measure of Sands and Fines.

When deploying the DIG method in future studies, there are some important considerations. Since the DIG method uses one vertical, it might only be used at rivers that are well mixed horizontally. If a river is poorly mixed horizontally, EWI and EWDI methods can be used with the DIG sampler. Before the final sample is collected, an independent transit rate should be determined, so the bottle is not overfilled. At higher water velocities, additional weight may be required to maintain position in the water column during the lowering and raising of the sampler (Figure 8a,b). A weight can be attached to the bottom of a weighted bottle sampler (Figure 8a,b). A reel and bridge board can assist in raising and lowering the sampler and weight to help maintain a consistent transit rate when operated correctly (Figure 8b,c).

The DIG method could replace grab sampling at lower flows and velocities when sampling conditions are non-isokinetic. FISP samplers are designed to sample at velocities equal to or greater than 0.457 meter/second [m/s; 13], and the DIG method allows for depth-integrating sample collection at velocities less than 0.457 m/s. Even though it is assumed there is no sand in transport at lower velocities, the DIG-SSC method would be able to capture any potential sand in suspension. At lower river velocities, a rope could be used to raise and lower the weighted-bottle sampler by hand (Figure 8d).

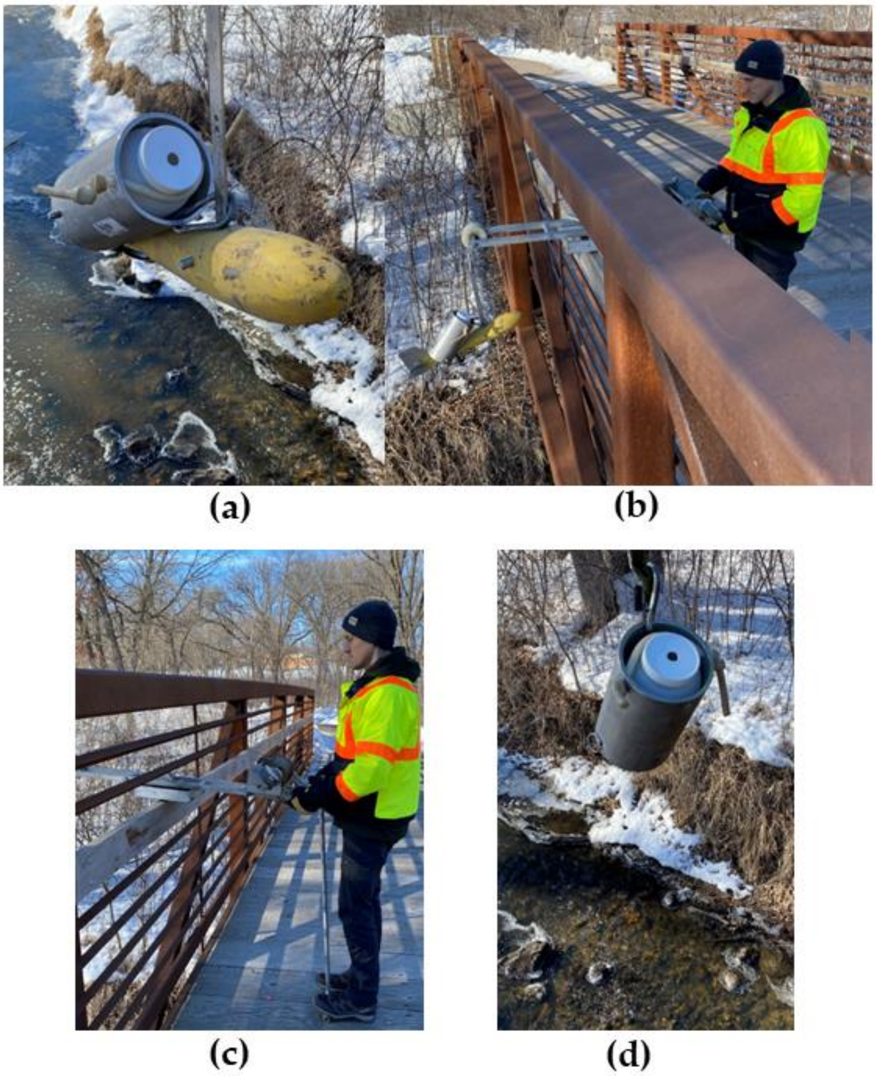

Figure 8. Suggested depth-integrated grab (DIG) suspended-sediment sampling setup for high (**a**,**b**) and low (**d**) stream velocities: (**a**) Depth-integrated grab (DIG) suspended-sediment sampler (US WBH-96 with a hole in the bottle's cap) attached to a sounding weight; (**b**) A bridge board, A-55 sounding reel, US WBH-96 with a hole in the bottle's cap attached to a sounding weight, and a person sampling from a bridge; (**c**) A bridge board, b-reel, and a person sampling from a bridge; (**d**) Depth-integrated grab (DIG) suspended-sediment sampler (US WBH-96 with a hole in the bottle's cap) attached to a rope.

5. Conclusions

Even with the advancement of technology, sampling suspended sediment still remains the primary means of understanding fluvial suspended sediment. The novel DIG-SSC sampling method provided more accurate results than Grab-TSS, and results showed there was no significant difference between the DIG and EWDI methods. The DIG method is easier and cheaper to sample than with isokinetic samplers and EWDI sampling methods. However, DIG-SSC was only tested at 9 sites (48 sample pairs) within a range of river and suspended-sediment characteristics, so this method would benefit from further testing at other rivers with different river and suspended-sediment characteristics not represented in this study.

Additional data collection could entail comparing the same number of verticals from EWDI and DIG. Collecting additional data to determine the IE, tow tank testing, and 3D modeling may help answer if the DIG sampler is isokinetic or not. Comparing the same number of verticals and isokinetic testing may help determine the cause of variability between EWDI and DIG methods observed in this study. Answering these questions could help potential users know if this method could be applied at rivers beyond this study area.

In addition to there being benefits of additional data collection, since this is a new sampling method, here are some important considerations when using the DIG method:

(1). The DIG method does not replace isokinetic samplers and EWDI methods but shows promise as an alternative if users are unable to use isokinetic samplers and EWDI sampling methods.
(2). The DIG method may only be used at sites that are well mixed horizontally. If a site is poorly mixed horizontally, EWDI methods with a DIG sampler can be used.
(3). Grab sampling often occurs at lower velocities as isokinetic samplers are not recommended. The DIG-SSC method could replace grab sampling at lower velocities.

If users are unable to use the DIG-SSC method, here is one important consideration when using the Grab-TSS method:

(1). Grab-TSS may only be used as an estimate of suspended fines.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13137844/s1, Table S1: All sampling-method comparison and river condition data for 9 river sites in Minnesota, 2018–2019.

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