A Comparative Study of Sediment Sorting in Unidirectional and Bidirectional Depositional Systems

Abstract

Different sediment transport and depositional processes result in distinct sediment sorting patterns. Comparing depositional environments through grain size analysis is essential for a better understanding of paleoenvironments. This study focuses on unidirectional fluvial and bidirectional wave-influenced depositional processes in the Potomac and Rappahannock Rivers. Six sediment samples were collected, three from each river, and analyzed for grain size to evaluate how these processes affect sediment characteristics. The unidirectional flow of the Rappahannock River produced a wider range of grain sizes, whereas the bidirectional wave action in the Potomac River resulted in more consistently sorted sediments.

Introduction

Studying sediment transport and depositional environments is important because it helps us understand Earth's past, predict environmental changes, and manage coastal systems. In order to study sediment transport, we must first research grain size, because grain size is a fundamental indicator of depositional energy and transport dynamics (Parker et al., 2024). The specific environments of interest in this study are beach and river estuaries, where contrasting unidirectional and bidirectional regimes contribute to the development of complex sedimentary textures. Chen et al. (2025) found that beach sediments in southern China exhibit moderate to well sorting, influenced by wave dynamics and coastal morphology. In contrast, Guerit et al.

(2018) observed uniform grain size distribution in gravel-bed rivers, suggesting consistent transport energy in braided fluvial systems.

There is a lack of studies comparing these environments using statistical grain size analysis. While the USGS provides extensive coastal sediment data, direct statistical comparisons across depositional environments remain limited (Poppe et al., 2005). The objective of this study is to measure and characterize the hydraulic regimes of the Rappahannock and Potomac estuaries in order to identify differences and similarities and to gain a better understanding of natural sedimentological processes. This study focuses on the Chesapeake Bay estuary system, specifically the Rappahannock River and the Potomac River. The Rappahannock River serves as the unidirectional, fluvial regime, while the Potomac River represents the bidirectional, wave-influenced regime. By understanding modern sedimentation processes, we will be better equipped to interpret deposits from similar paleoenvironments. Understanding grain size dynamics in nearshore and estuarine settings can inform both coastal management and interpretations of past depositional systems (Pradhan et al., 2024).

Methods

This study focuses on quantitative sediment data from two specific sites: the Potomac River and the Rappahannock River. The objective is to measure and characterize the hydraulic regimes of these estuaries—contrasting unidirectional (fluvial) and bidirectional (wave) systems—through the analysis of grain size, grain sorting, and grain roundness.

The selection method for the samples was systematic. Each sample was chosen based on its proximity to and regular submersion by the water body—either the Potomac or the

Rappahannock River. In total, six sediment samples were collected: three from the Rappahannock River and three from the Potomac River.

A flow meter, measuring stick, and tape measure were used during sample collection. In the lab, RoTAP equipment, an oven, and a mass balance were used to process the samples. Microsoft Excel was used for data analysis.

The first set of samples was taken from the Rappahannock River. One person held the end of the tape measure at the river's edge while others extended it across the river. Samples were collected at 28 feet, 151 feet, and 203 feet from the river's edge—all from submerged sediment. At each collection point, water depth and velocity were recorded using a measuring stick and a flow meter. The next set of three samples was collected from the Potomac River using the same procedure. The samples were taken at distances of 4 feet, 10 feet, and 30 feet from the shoreline.

Once collected, all samples were returned to the lab for preparation and analysis. First, the samples were oven-dried to remove any remaining moisture. They were then weighed using a mass balance. After weighing, the samples were processed through RoTAP equipment to separate grains by size. Each grain size fraction was then weighed again.

After separation, the following data were recorded for each sample: total sediment mass, mass of each grain size, individual weight percent, and cumulative weight percent. These values were entered into Microsoft Excel, which generated two graphs per sample: Individual Weight Percent vs. Phi, and Cumulative Weight Percent vs. Phi. Mean, median, skewness, and kurtosis were calculated for each sample.

Results

The six samples used in this study were collected from the Potomac River and the Rappahannock River, three from each. Table 1 shows which river each sample was collected from, along with the distance from the shore, the mean, sorting, skewness, and kurtosis of each sample as well.

The Mean grain size values suggest that the Potomac has slight variability, with two fine-grained samples ($\Phi > 0$) and one coarse-grained ($\Phi = -1.09$). The Rappahannock includes both fine ($\Phi = 1.75$) and very coarse samples ($\Phi = -3.67$). The coarsest sample overall came from Rappahannock at 151 feet. The Sorting (σ) values suggest that Sorting is generally better, with a lower σ value, in the Potomac (0.66σ–1.87σ) rather than in the Rappahannock (0.68σ–2.52σ). The Rappahannock sample at 151 feet had the poorest sorting of the six (2.52σ). Potomac samples show slightly negative to near-symmetrical skewness, suggesting relatively balanced distributions. Rappahannock samples range more widely, including a strong positive skew of 0.93.

This data is supported by Figures 1-12, showing individual and cumulative weight percentage histograms for all six samples. Potomac samples show a slight variety in individual weight percentages compared to their size in phi. Whereas the Rappahannock samples show a wider variety of individual weight percentage compared to their size in phi.

The data is simplified in Table 2, where it is shown that the Rappahannock River displays a larger variety in grain size and generally poorer sorting, consistent with unidirectional fluvial transport. In contrast, the Potomac, which is characterized by bidirectional wave action, exhibits more consistent and better-sorted sediments overall.

Discussion

The Rappahannock samples show a wider range of grain sizes (from -3.67 to 1.75 Φ), while the Potomac samples are more narrowly distributed (0.85 to -1.09 Φ). This reflects the more variable and episodic energy of the Rappahannock's fluvial regime, where sediment transport can change rapidly during high-energy events. In contrast, the Potomac's bidirectional, wave-influenced setting likely promotes grain homogenization and favors the deposition of finer material. This interpretation is supported by Guerit et al. (2018), who observed that unidirectional river systems like the Rappahannock often carry coarser sediment with consistent energy. Chen et al. (2025) further support this by noting that bidirectional wave-dominated environments such as the Potomac tend to produce moderate to well-sorted sediments.

Overall, the Potomac samples were better sorted (as low as 0.66σ), while the Rappahannock included very poorly sorted material (up to 2.52σ). This difference likely reflects the influence of wave reworking in the Potomac, which promotes selective transport and consistent grain sizes. On the other hand, the Rappahannock's poor sorting may result from irregular high-energy events like floods, which can move a mix of grain sizes without much sorting. These patterns suggest that the Potomac experiences lower but more consistent bidirectional energy, while the Rappahannock is shaped by higher-energy, unidirectional flow that varies more over time.

Skewness values also show a clear distinction. Potomac samples tend to be symmetrical or negatively skewed, while the Rappahannock includes positively skewed samples. The most positively skewed Rappahannock sample of 0.93 likely contains a fine tail, pointing to periods of suspension settling during low-energy conditions.

Distance from shore did not follow a simple trend, but some patterns were still noticeable. The Rappahannock's coarsest and most poorly sorted sample came from the mid-channel site (151 feet), suggesting it may be a primary high-energy transport zone. In contrast, the Potomac's best-sorted sample was collected closer to shore (10 feet), which may be influenced by wave swash zone dynamics that repeatedly rework sediments near the shoreline.

The modern implications of this study are relevant for estuarine and coastal management. Understanding sorting and grain size variability can help inform dredging strategies and shoreline restoration projects. In a broader context, these results can be applied to interpreting ancient depositional environments. Recognizing the differences between wave-dominated shorelines and fluvial point bars or channels can help geologists make more accurate paleoenvironmental reconstructions. As noted by Pradhan et al. (2024), sediment depositional behavior in river systems is essential for geologic and environmental understanding.

Conclusion

This study compared grain size characteristics in two contrasting estuarine environments. The unidirectional, fluvial regime of the Rappahannock River and the bidirectional, wave-influenced regime of the Potomac River. The results show clear differences in grain size distribution, sorting, and skewness between the two systems. The Rappahannock River samples, samples 4-6, displayed a wider range of grain sizes and poorer sorting overall, with one

mid-channel sample showing both the coarsest grains and the highest degree of sorting variability. Potomac samples, samples 1-3, were finer, better sorted, and more symmetrical, likely due to the consistent reworking of sediment by wave action.

These findings support previous research on sediment transport and depositional processes. The Rappahannock data reflect variable and episodic transport conditions, consistent with fluvial dynamics and flood-driven events. The Potomac data align with studies showing that wave-dominated environments tend to produce more uniform sediment textures.

The implications of this study go beyond academic comparison. Estuarine management practices, including dredging and shoreline restoration, should take into account the natural variability in sediment textures and transport energy. These results also contribute to our understanding of ancient depositional environments by helping distinguish between wave-influenced shorelines and fluvial channel deposits. By studying modern estuarine systems, we are able to gain useful insight into both current coastal processes and the sedimentary record they leave behind.

Fig.1, Fig.2, Fig. 3: Individual weight percentage histograms for samples 1-3 (Potomac)
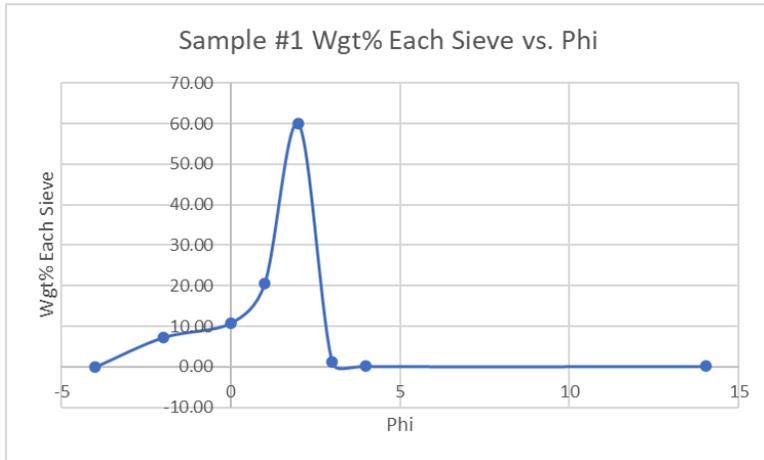
Figure 1: Shows sample number one's weight percentage for each sieve compared to the size of the grain in Phi. This graph shows a well-sorted sample, due to a small distribution of weight throughout the different sieves. 60% of the weight of this sample was in the 2 Phi range.
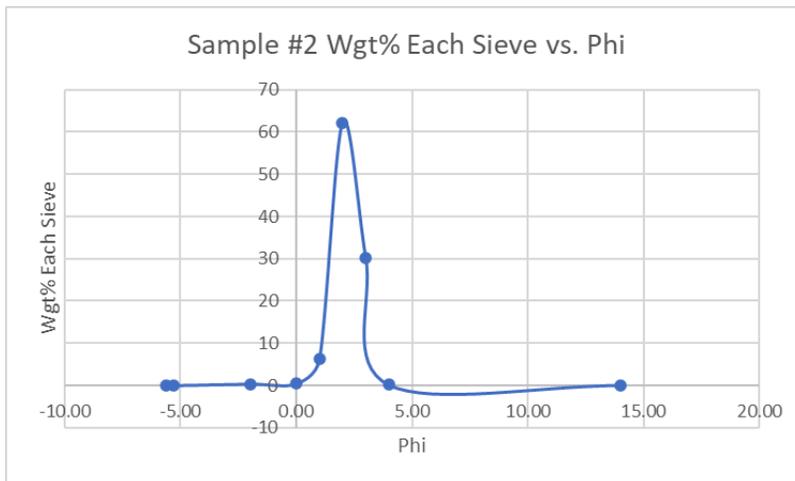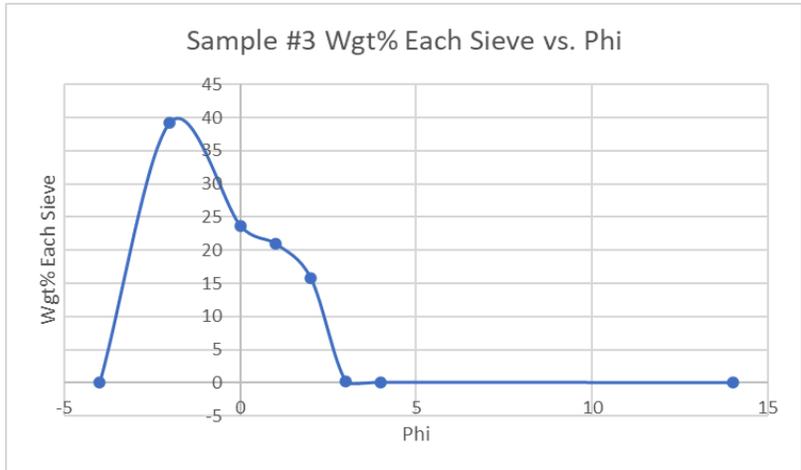

Figure 2: Shows sample number two's weight percentage for each sieve compared to the size of the grain in Phi. This graph shows a well-sorted sample, due to a small distribution of weight throughout the different sieves. Over 60% of this sample was found in the 2 Phi range.

Figure 3: Shows sample number three's weight percentage for each sieve compared to the size of

the grain in Phi. This graph shows a well-medium sorted sample. 40% of this sample is in the

-1.5 phi range, 24% of this sample is in the 0 phi range, 21% of this sample is in the 1 phi range,

and 16% of this sample is in the 2 phi range.

Fig. 4, Fig. 5, Fig. 6: Individual Weight Percentage Histograms for samples 4-6 (Rappohannock)
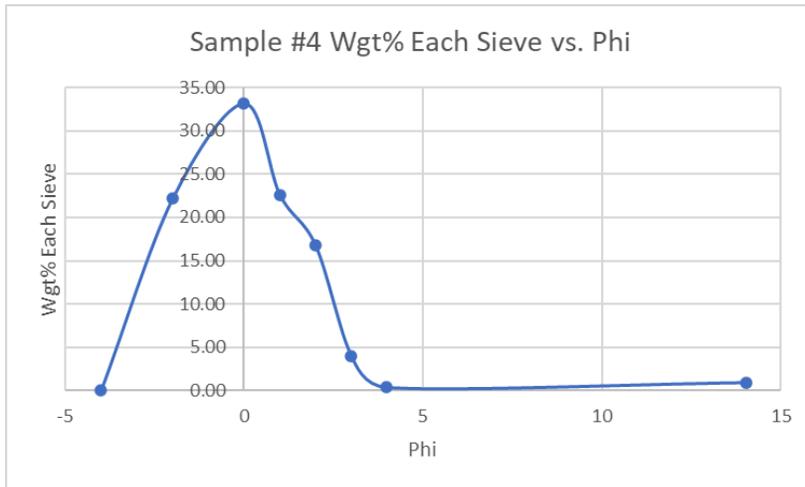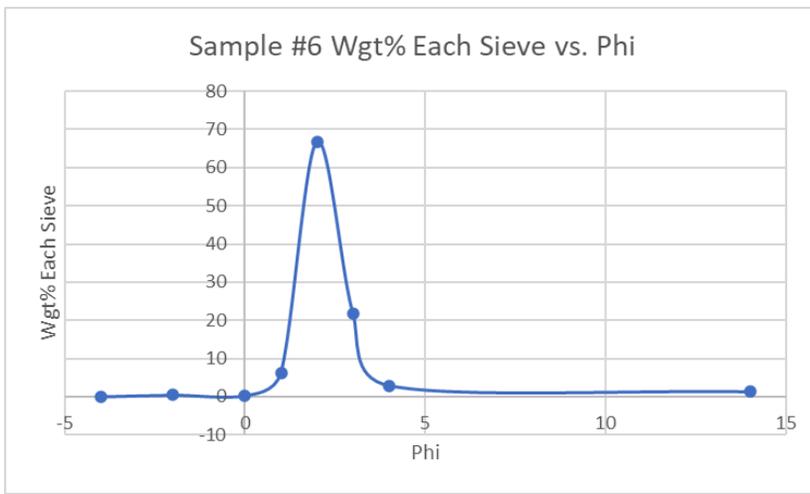

Figure 4: Shows sample number four's weight percentage per each sieve compared to grain size in phi. This graph shows a medium-sorted sample. 34% of this sample is in the 0 phi range, 22.5% in the -2 phi range, 22.5% in the 1 phi range, and 16% in the 2 phi range.
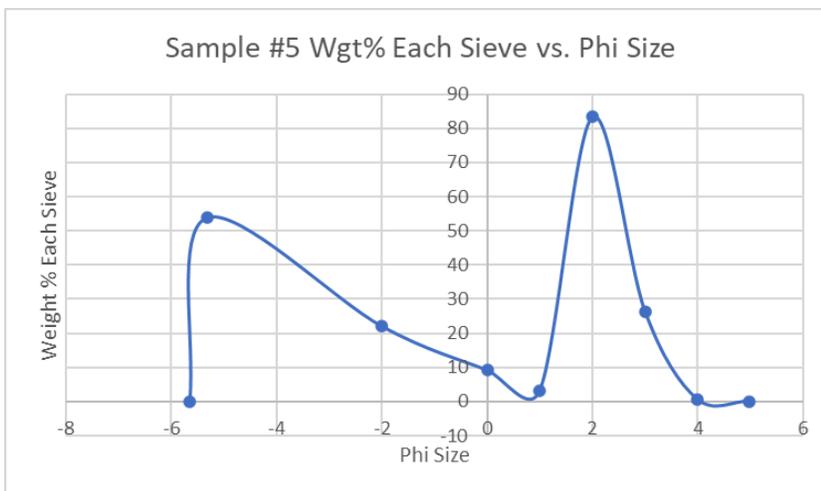
Figure 5: Shows sample number five's weight percent for each sieve compared to the grain size in phi. This graph shows a poorly-sorted sample from phi sizes ranging from -5.5 phi to 5 phi.

Figure 6: Shows sample number six's weight percentage for each sieve compared to grain size in phi. This graph shows a well-sorted sample, with 68% of this sample in the 2 phi range.

Fig. 7, Fig. 8, Fig. 9: Cumulative Weight Percentage Histograms for samples 1-3 (Potomac)
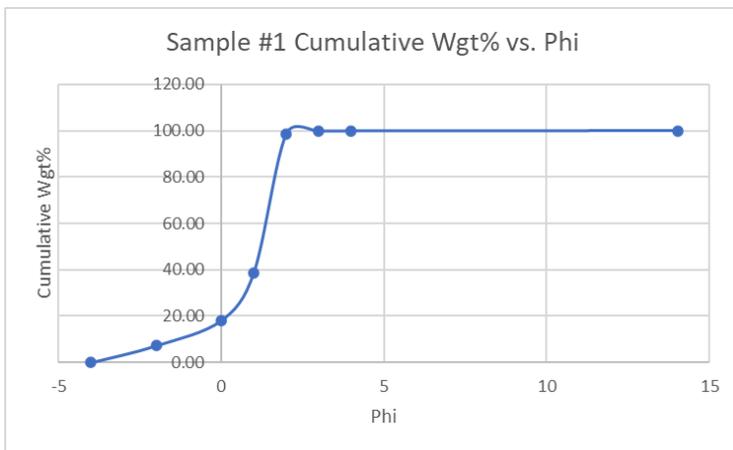

Figure 7: Shows sample number one's cumulative weight percentage compared to grain size in phi. This graph shows a well-sorted sample, with the graph that has a steep slope until plateauing at around (2.5 phi, 100 %).
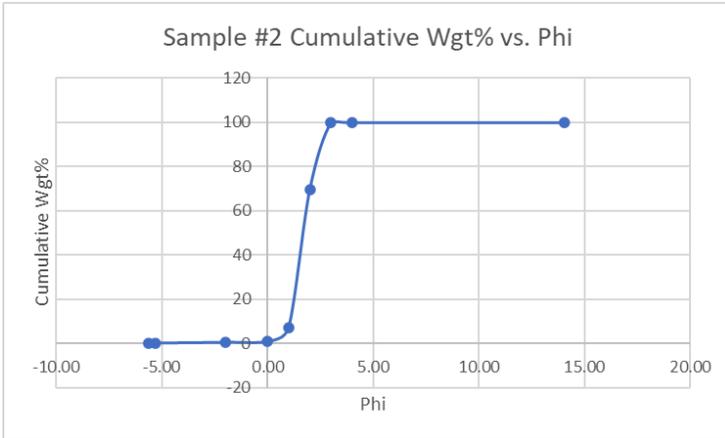
Figure 8: Shows sample number two's cumulative weight percentage compared to grain size in phi. This graph shows a well-sorted sample with a steep slope until plateauing at around (2.5 phi, 100%)
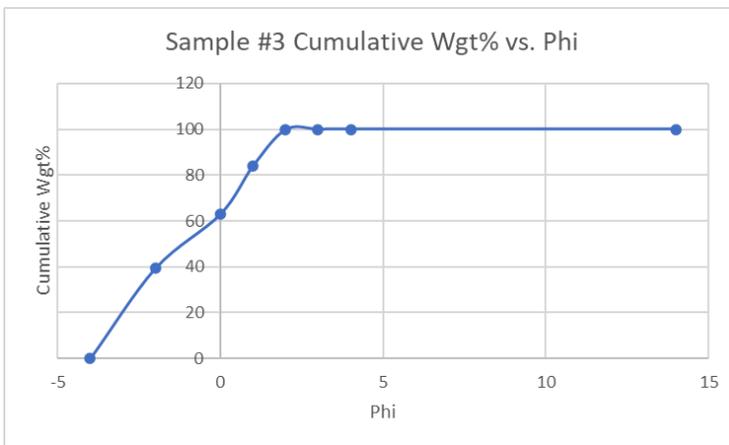

Figure 9: Shows sample number three's cumulative weight percentage compared to grain size in phi. This graph shows a medium-sorted sample with a steady slope from (-4 phi, 0%) to (2.5 phi, 100%) and then plateaus.

Fig. 10, Fig. 11, Fig. 12: Cumulative Weight Percentage Histograms for samples 4-6 (Rappohannock)
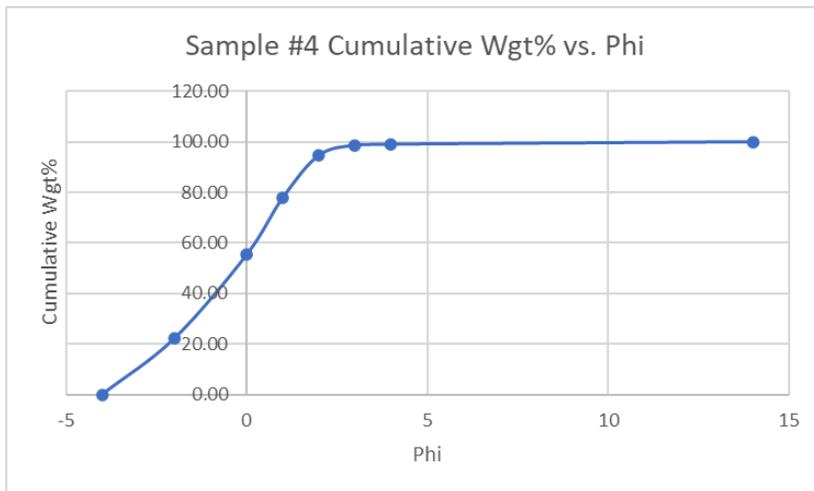

Figure 10: Shows sample four's cumulative weight percentage compared to grain size in phi. This graph shows a medium-sorted sample with a steady slope from (-4.5 phi, 0%) to (3.5phi, 100%), then plateauing.
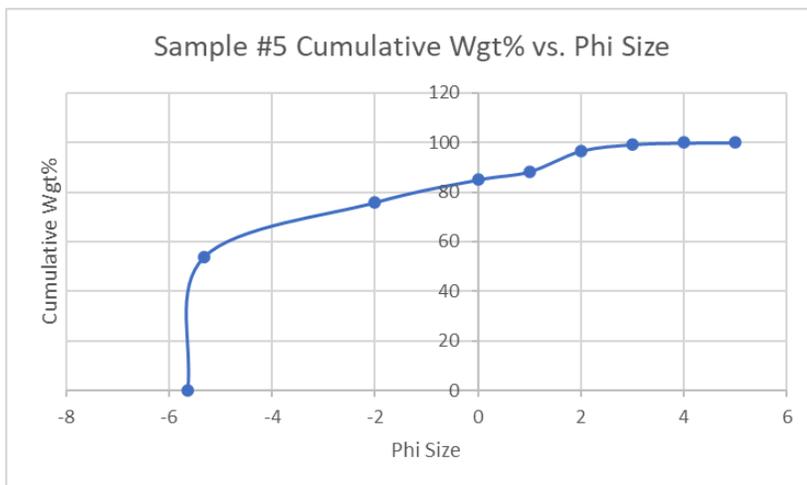

Figure 11: Shows sample five's cumulative weight percentage compared to grain size in phi. This graph shows a poorly-sorted sample with a slope from (-5.75 phi, 55%) to (3 phi, 100%), then plateauing.
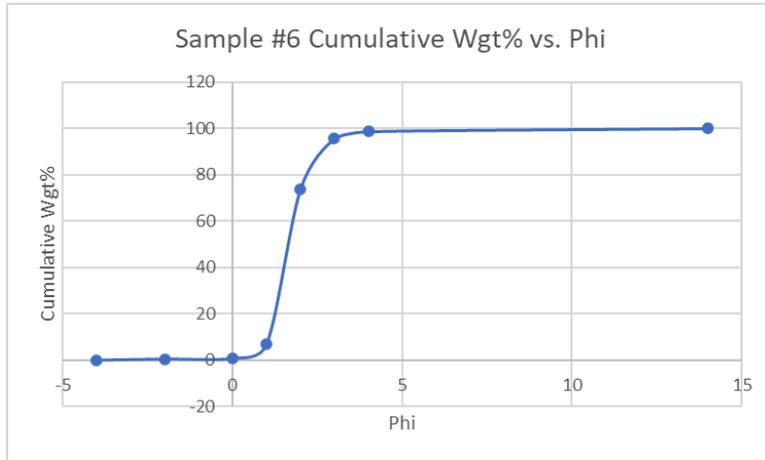
Figure 12: Shows sample six's cumulative weight percent compared to the grain size in phi. This graph shows a well-sorted sample with a steep slope from (0 phi, 0%) to (4.5 phi, 100%) and then plateaus.

Table 1: Grain Size Statistics

	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Sample #6
River	Patomac	Patomac	Potomac	Rappahannock	Rappahannock	Rappahannock
Distance from shore	4 feet	10 feet	30 feet	28 feet	151 feet	203 feet
Mean (Φ)	0.85	1.77	-1.09	-0.50	-3.67	1.75
Sorting (σ)	1.23	0.66	1.87	1.83	2.52	0.68
Skewness	-0.57	0.12	0.01	-0.14	0.93	0.20
Kurtosis	1.47	0.85	0.68	0.86	0.87	1.20

Table 2: River Grain Comparison

Metric	Potomac River	Rappahannock River
Mean Grain Size	0.85 to -1.09 Φ	-3.67 to 1.75 Φ
Sorting	0.66 – 1.87	0.68 – 2.52
Skewness	-0.57 to 0.12	-0.14 to 0.93
Coarsest Sample	-1.09 Φ (30 ft)	-3.67 Φ (151 ft)
Best Sorting	0.66 (10 ft)	0.68 (203 ft)
Poorest Sorting	1.87 (30 ft)	2.52 (151 ft)

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