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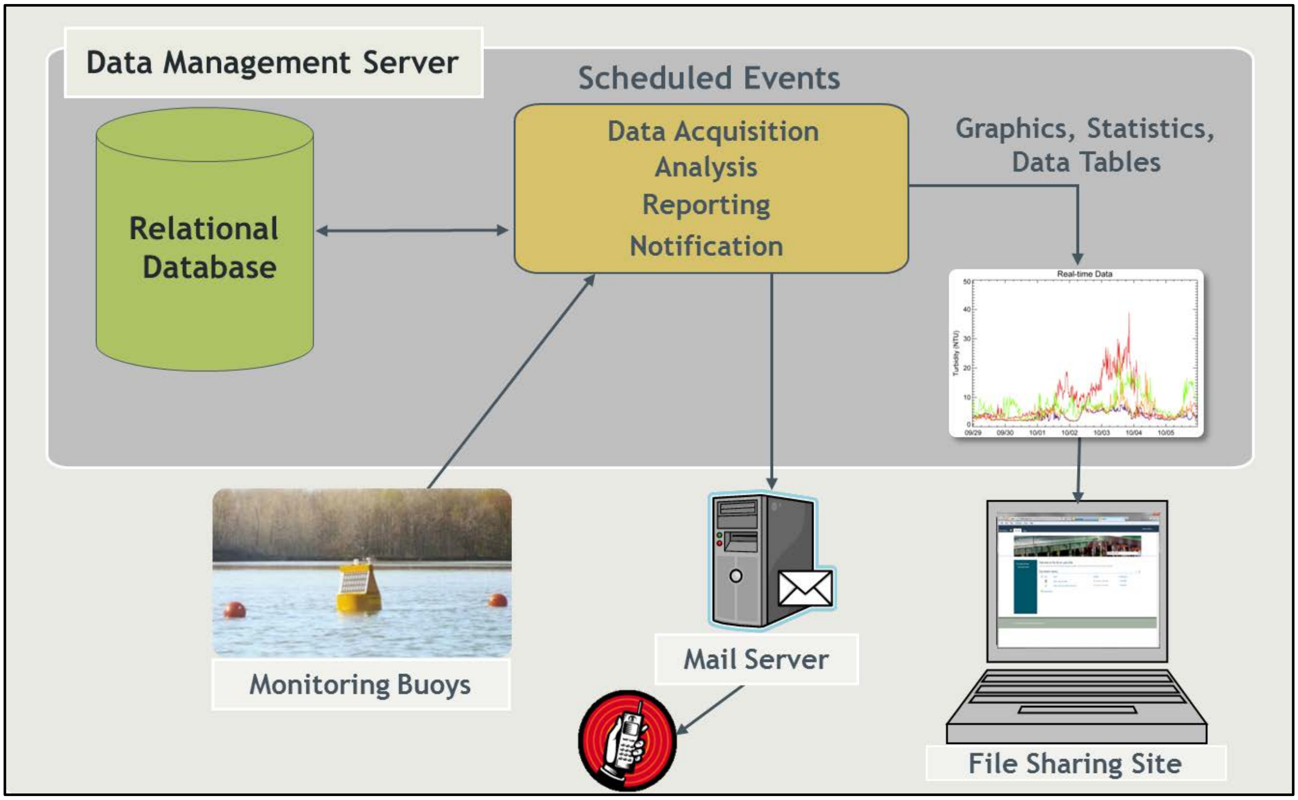

Automated Water Quality Monitoring System at Onondaga Lake, New York
(Photo courtesy of Honeywell, Anchor QEA, and Upstate Freshwater Institute)

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The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects, and case studies.

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WEDA Journal of Dredging, Vol. 15, No. 1

EVALUATION OF DREDGING INDUCED WATER QUALITY TRENDS AT ONONDAGA LAKE, NEW YORK

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William Hague[8], and Larry Somer[9]

ABSTRACT

The Onondaga Lake construction monitoring program has enabled an environmentally protective dredging and capping project, spanning 5 years. Prior to the start of construction, a baseline water quality assessment was conducted over 2 years resulting in the development of a tiered compliance program. Alert and action levels have been established at 25 and 50 nephelometric turbidity units above background to enable early investigation and response to water quality issues attributed to construction. Real-time monitoring and data management strategies were envisioned early in project planning, and have ensured that there is close coordination between operational, field, and data management activities. Custom software was developed and integrated with field monitoring equipment, including continuously recording devices, to support field activities and deliver monitoring data to project personnel in real time, 24 hours a day, 7 days a week. Automated data integration, quality control, and assessment have enabled project managers to achieve full compliance with the regulatory monitoring and reporting requirements. The customized system design is highly flexible and enables managers to create data relationships that capture evolving project requirements. This flexibility has been a key factor in maintaining project productivity while complying with demanding monitoring requirements. The results of the monitoring program after 3 years of dredging and capping show consistency with the results of the baseline monitoring program. Turbidity levels have remained largely within the range of ambient conditions seen due to natural forcing conditions. Surface water chemistry results remained below the applicable New York State (NYS) Aquatic (Acute) surface water quality standards. Thus, the water quality monitoring program, through design and implementation, helped preserve the Lake-wide water quality in relation to the conditions observed prior to the start of construction.

Keywords: Turbidity, contaminated sediments, construction quality assurance, tiered performance standards, water quality monitoring

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INTRODUCTION

A multi-year dredging and capping restoration project began in 2012 on Onondaga Lake to address sediments, surface water, and biota impacted by mercury and 22 additional chemical parameters of interest (CPOIs) consisting of chlorinated benzenes, volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls. Onondaga Lake ("the Lake") is a 3,000-acre lake located northwest of Syracuse, New York (Figure 1). Construction activities on the Lake have been focused in five remediation areas (Figure 1). Dredging was conducted for 3 years (2012 through 2014) and resulted in the removal of an estimated 2 million cubic yards of sediment from the littoral zone of the Lake. Capping continues on the Lake and is scheduled to be completed in 2016. When complete, the remedy will include capping of 580 acres in both the littoral and deeper sections of the Lake (Parsons and Anchor QEA 2012a).

In-water construction activities have been implemented under a comprehensive water quality management program that protects against potential release of contaminants through sediment resuspension. Resuspension controls, both physical (i.e., silt or turbidity curtains) and operational (e.g., minimizing cutterhead rotation speed and other best management practices [BMPs]) are used to mitigate potential resuspension. To ensure that these control measures achieved the desired protectiveness, a monitoring program based on real-time turbidity, coupled with discrete water column sampling for chemistry, was used to monitor the water quality impacts of dredging and capping. In 2014, Haffey et al. (2014) described the development and implementation of the water quality monitoring program, focusing on the mechanics of the automated data management system used to assess compliance with the program. This manuscript reiterates the development of the water quality monitoring program and provides a continuation of the previous work by presenting the results of the water quality data (both turbidity and chemistry) collected during dredging and capping and by evaluating observed trends.

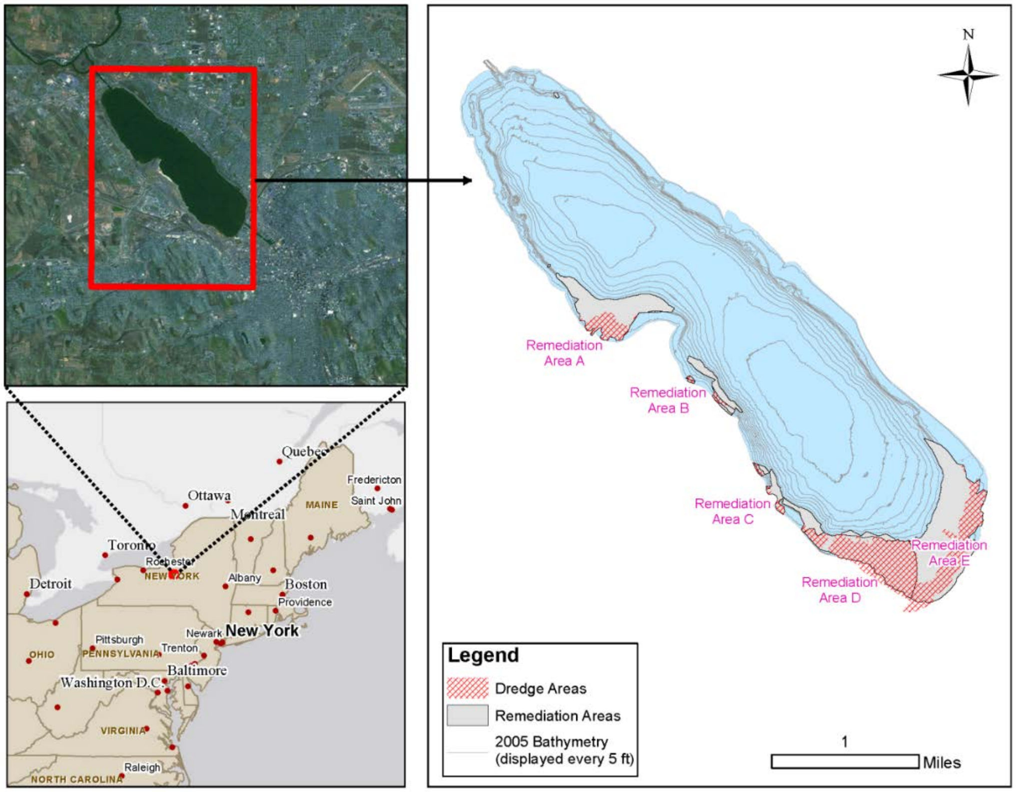

Figure 1. Map of Onondaga Lake Restoration Project

The Baseline Monitoring Program section of this manuscript presents a brief discussion of the observations of baseline water quality that were significant to the design of the monitoring program for comparison with water quality conditions observed during construction. The Water Quality Monitoring Program Design and Implementation section reviews the water quality performance standards and the design of the monitoring program developed to demonstrate compliance, as well as a discussion of how the program was implemented. The Water Quality Trends Observed During Dredging section discusses the results of the monitoring program.

BASELINE MONITORING PROGRAM

Historical water quality monitoring in Onondaga Lake has shown that water quality, and specifically turbidity, within the Lake can vary significantly due to natural events. Meteorological events such as high winds and rainstorms, which impact tributary inflow, can cause increased turbidity within the Lake. Seasonal biological processes (i.e., algal production) also have an effect on water clarity and turbidity levels in the Lake (Parsons and Anchor QEA 2012b). Conversely, on calm days, water clarity can be high.

A baseline monitoring program was performed in 2010 and 2011 to: 1) establish the range and variability of ambient water quality conditions expected to occur during construction; and 2) develop a water quality monitoring program. Findings from this study showed that turbidity measurements collected in 2010 and 2011 generally remained below 10 nephelometric turbidity units (NTUs) throughout most of the monitoring activities. On occasion, turbidity levels rose temporarily to several hundred NTUs. Cumulative frequency distributions of 15-minute turbidity measurements in 2010 and 2011 presented in Haffey et al. (2014) and reproduced herein as Figure 2 illustrate that turbidity was 10 NTUs or less at all locations 75 percent of the time. The frequency of time turbidity exceeded 10 NTUs ranged from less than 1 percent (see location T1 in 2010 and locations A2 and D1 in 2011) to approximately 25 percent at location T4 in 2010. Turbidity was generally higher in 2010 relative to 2011 (Haffey et al. 2014). Inter-annual differences observed can likely be attributed to differences in seasonal conditions, with 2010 having somewhat higher winds and more frequent rainfall than 2011. Differences in sample locations with respect to distance from the tributary inflows may also contribute to the differences (Parsons and Anchor QEA 2012b).

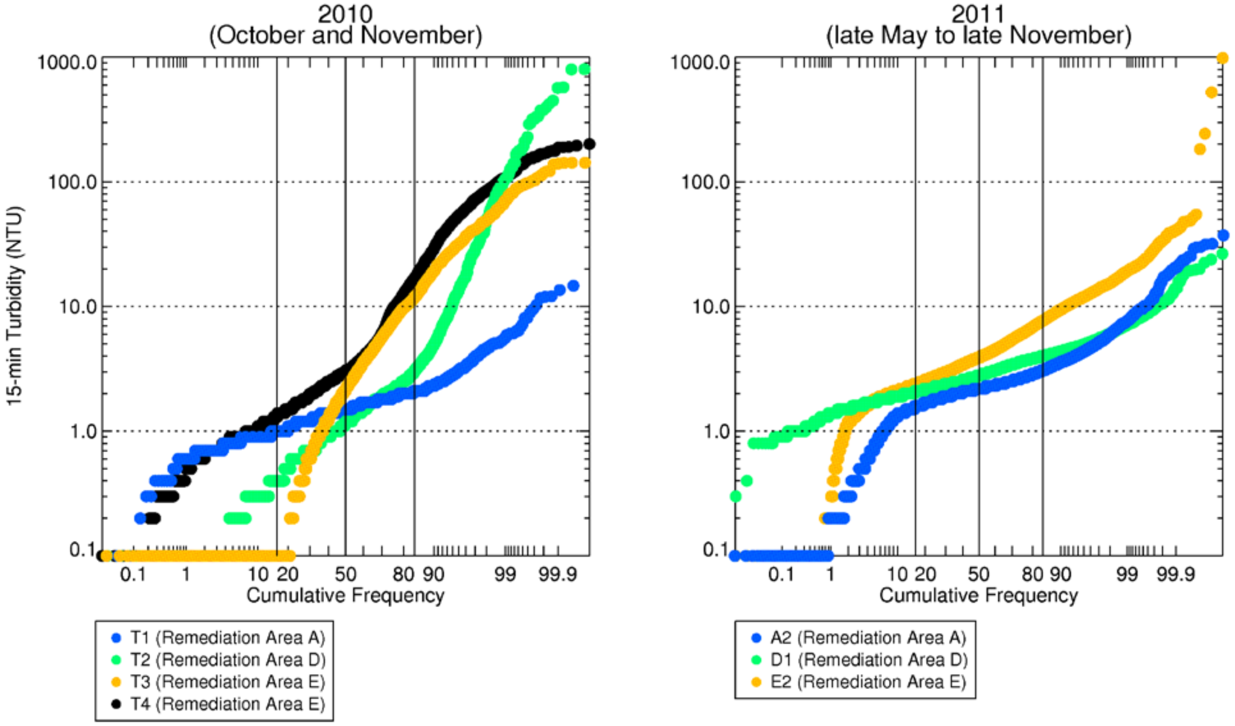

Figure 2. Summary of Continuous Baseline Turbidity Monitoring Data

The relationships of turbidity to natural forcing conditions were further investigated by plotting a time series of continuous turbidity alongside a contemporaneous time series of nearby tributary inflows, wind speed, and precipitation. Evaluation of these plots revealed that short-term increases in turbidity generally coincide with increases in wind, precipitation, and/or flow in nearby tributaries (Parsons and Anchor QEA 2012b). The complete time series plots developed to analyze the baseline monitoring data are available in the *Water Quality Management and Monitoring Plan* (WQMMP; Parsons and Anchor QEA 2012b).

Surface water chemistry samples collected during the baseline monitoring program were analyzed for and compared to the suite of applicable NYS Class B/C Aquatic (Acute) surface water quality

(SWQ) criteria. Based on the results of the baseline monitoring program, as well as all additional data available dating back to the first rounds of sampling from the Remedial Investigation in 1992, the only observed exceedances of the applicable SWQ criteria described above were a few limited samples for PAH compound (benzo(a)anthracene) collected in 2010 (Parsons and Anchor QEA 2012b).

WATER QUALITY MONITORING PROGRAM DESIGN AND IMPLEMENTATION

As described in Haffey et al. (2014) and restated here, a water quality performance standard and construction monitoring program based primarily on real-time turbidity with supplemental discrete water column sampling for chemistry was developed for the Onondaga Lake dredging and capping project to protect against resuspension of sediments and associated potential release of sorbed contaminants. Because turbidity is in large part a measure of particulate matter that may contain sorbed phase chemicals, this monitoring program allowed for rapid response to potential adverse water quality conditions related to a release of contaminated sediments.

The standard employed monitoring in both the immediate vicinity of construction operations (i.e., near field) and in the larger, Lake-wide environment (i.e., far field), and incorporated two-tiered criteria that consist of both alert and action levels. This approach allowed for early identification of elevated turbidity in the near field and enabled mitigation of water quality issues through adjustments to control measures before the greater Lake environment is impacted.

Table 1 lists the tiered turbidity criteria and describes the locations at which they were applied. These criteria are based on analysis of ambient turbidity measurements (see Appendix B of the WQMMP [Parsons and Anchor QEA 2012b]), and thus, are tailored to Onondaga Lake in particular and are not based solely on regional state or federal water quality regulations. The monitoring locations were targeted and at times varied due to turbidity control structure movement from wave action or adjustments to accommodate traffic and tail pipe movement.

Table 1. Tiered Performance Standard

Level	Criterion (NTU)	Location
Alert	25	200 feet from the edge of the turbidity control structure
Action	50	500 feet from the edge of the turbidity control structure

The alert level was assessed at near-field monitoring locations termed performance monitoring (PM) stations. This PM station was designed to provide an early warning mechanism that could alert project personnel to potential water quality impacts before they affected the greater, Lake-wide system. As illustrated by the discussion in the Baseline Monitoring Program section, the range of ambient turbidity in the Lake is generally under 10 NTUs but can temporarily increase to several hundred NTUs due to tributary runoff and/or high winds. Therefore, a turbidity alert level of 25 NTUs above background at the PM stations was considered appropriate to provide a sufficient indication of water quality impacts due to construction-related activity. The action level was applied in the far field at monitoring locations referred to as compliance monitoring (CM) stations and was designed to be protective of the Lake-wide environment. During construction operations, each active remediation area was monitored by a monitoring operation consisting of three simultaneously operating PM stations configured to capture the upcurrent, downcurrent, and crosscurrent conditions. Each monitoring operation had a single CM station positioned further out into the Lake. A schematic of this monitoring configuration is shown in Figure 3. Monitoring was conducted from automated buoy platforms set to record turbidity every 15 minutes. Stations were at times shared between monitoring operations when two adjacent remediation areas were simultaneously active. During the peak of dredging and capping operations, 13 data buoys were operating simultaneously throughout the Lake.

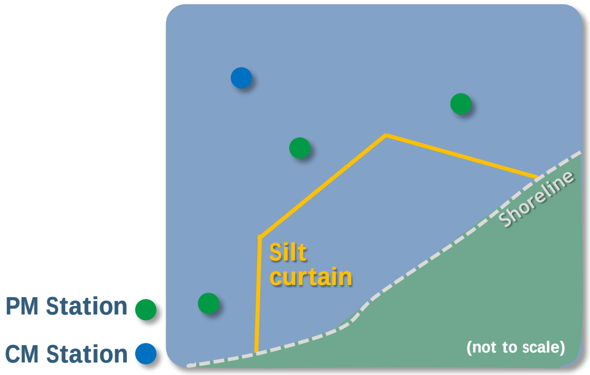

Figure 3. Schematic of the Monitoring Station Configuration

In the event that the alert level was exceeded at a PM station, specific steps were initiated to address the exceedance (Parsons and Anchor QEA 2012b). The first step in the process was to confirm the exceedance with additional measurements including continued assessment of the real-time turbidity data, manual probe measurement, and visual observation of the turbidity plume. If turbidity at the PM station continued to exceed the alert-level criterion for four consecutive measurements, and manual measurement and observation were in agreement, then the cause of elevated turbidity was investigated. Investigative activities included (but were not limited to) inspection of the silt curtain and assessment of the surrounding area for non-project-related causes (e.g., wind-wave activity, visible plume originating from tributary mouth). If the exceedance was deemed to be attributable to construction activities, the operations were evaluated and appropriate operational changes implemented.

Both alert and action levels were evaluated relative to the real-time turbidity at a designated background station and assessed on a 2-hour running average of the real-time turbidity data at the location. The background station was conservatively determined in real time as the PM station within the monitoring operation that had the lowest turbidity value for the given time-step. Evaluating the monitoring data relative to a remediation area-specific, real-time background condition accounts for the fluctuating ambient conditions identified by the baseline monitoring program and reduces the likelihood of generating a non-project-related exceedance, and thus, avoids unnecessary follow-up investigations.

Assessment of the water quality data as a 2-hour running average was done to account for sporadic variability observed in turbidity in the baseline monitoring program, and to eliminate impacts of passing debris, or other short-lived elevated turbidity due to natural causes. These anomalous high values, along with those caused by temporary equipment malfunctions are not indicative of actual changes in water quality; averaging the data over a 2-hour period helps reduce the chance of generating unnecessary exceedances.

In addition to the turbidity monitoring described above, discrete water column grab samples were also collected at CM stations under a supplemental sampling program implemented during dredging and capping operations. The discrete water column grab samples were analyzed for the suite of chemicals provided in Table 2, as well as total suspended solids, total mercury, total phosphorus, total dissolved phosphorus, and soluble reactive phosphorus. For dredging operations, samples were collected daily for an initial "verification period" that spanned approximately the first 14 days of dredging to confirm that the turbidity monitoring and water quality management program were protective. Because no exceedances of the relevant SWQ standards occurred during this verification period, the New York State Department of Environmental Conservation (NYSDEC), the regulatory agency overseeing the remediation, approved a transition of the sampling schedule from daily to weekly (Anchor QEA 2013). Water quality samples continued to be collected at CM stations throughout the duration of dredging activities; however, NYSDEC approved a transition to a turbidity-only monitoring program during capping operations for the remainder of the project as a result of no exceedances observed during the 2012 capping activities (Anchor QEA 2013).

Table 2. Water Quality Monitoring Parameters and Associated Aquatic (Acute) Criteria

Chemical Parameter	New York State Aquatic (Acute) Class B/C Surface Water Quality Standards (µg/L)
Benzene	760
Ethylbenzene	150
Toluene	480
Total Xylenes	590
Acenaphthene	48
Anthracene	35
Benzo(a)anthracene	0.23
Fluorene	4.8
Naphthalene	110
Phenanthrene	45
Pyrene	42
Mercury (Dissolved)	1.4

Note:
µg/L – micrograms per liter

WATER QUALITY TRENDS OBSERVED DURING DREDGING

Real-time Turbidity Monitoring Results

There were no exceedances of the alert- or action-level turbidity standards due to dredging. Real-time turbidity data were collected 24 hours a day, 7 days a week over 23 months of construction operations that took place from 2012 through 2014. Two-hour running averages of the real-time turbidity results were computed and plotted as a cumulative frequency distribution to understand the range and frequency of turbidity values during construction. Figure 4 illustrates the cumulative frequency distributions for two example remediation areas (Remediation Area E in 2013 and Remediation Area D in 2014)[1]. In 2012, 90 percent of running average turbidity values were less than 10 NTUs; in 2013 and 2014, 85 percent of running average turbidity values were less than 10 NTUs. These results are consistent with the baseline monitoring program where turbidity values were less than 10 NTUs for 75 percent of the time and greater and show that construction activities did not adversely impact the turbidity within Onondaga Lake. In fact, the running average turbidity values without subtraction of the background values were rarely above the action and alert levels (less than 1 percent and 10 percent of the time, respectively; see Figure 4). When alert- or action-level exceedances occurred, field investigations were implemented and determined to be a result of other turbidity sources (e.g., tributary flows, nearby capping operations). There were no exceedances of the alert- or action-level turbidity standards due to dredging.

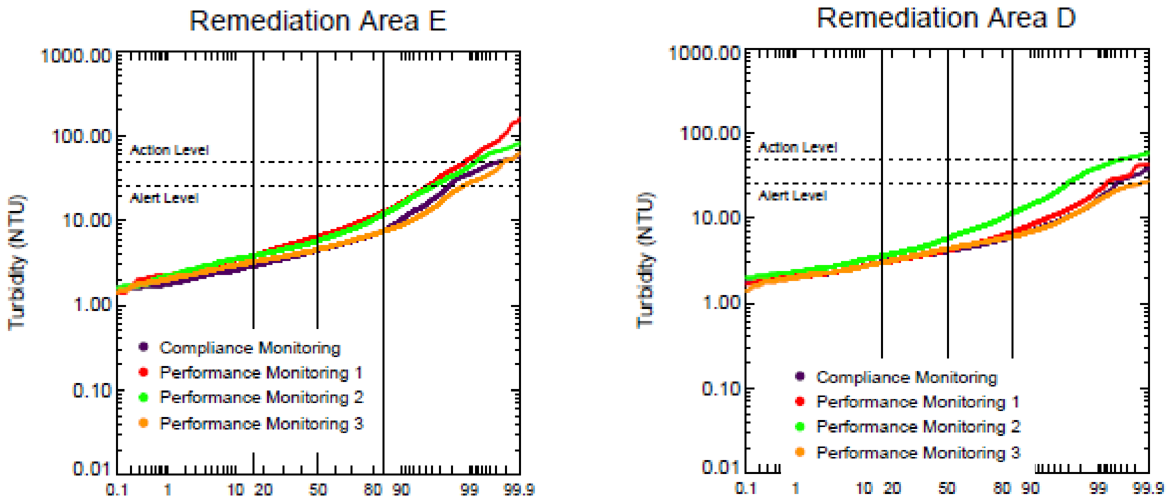

Figure 4. Cumulative Frequency Distributions of Turbidity Data Collected in Remediation Area E (2013) and Remediation Area D (2014)

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[1] The turbidity data plotted in Figure 4 are the running average values, not the value above background for each time step, which would be the basis of comparison for the alert- and action-level criteria; rather these graphics simply display the range and occurrence of different turbidity levels observed. The alert- and action-level criteria values are posted for reference of magnitude.

In addition to the magnitude and frequency of the turbidity levels, the duration of increased turbidity is important for the overall health of the Lake. Table 3 provides a summary of the average duration of alert-level turbidity criteria exceedances by cause and by year.

Table 3. Average Duration (hours:minutes) of Alert-level Turbidity Criteria Exceedance

	Cause of Exceedance			
Year	**Capping**	**Weather and Capping**	**Weather**	**Unknown**
2012	2:31	--	--	0:50
2013	3:11	3:05	5:26	2:10
2014	3:29	6:15	4:31	1:20

Over the 23 months of active operations in five remediation areas, there were 186 exceedances of the alert-level turbidity standard. Of those, 51 were identified to be a direct result of weather or other meteorological conditions; 106 were identified to be a result of nearby capping operations; 17 were identified to be a result of a combination of capping and weather or other meteorological conditions; and 12 were due to unidentified causes. Figure 5 shows a cumulative frequency distribution of the duration of all exceedances observed.

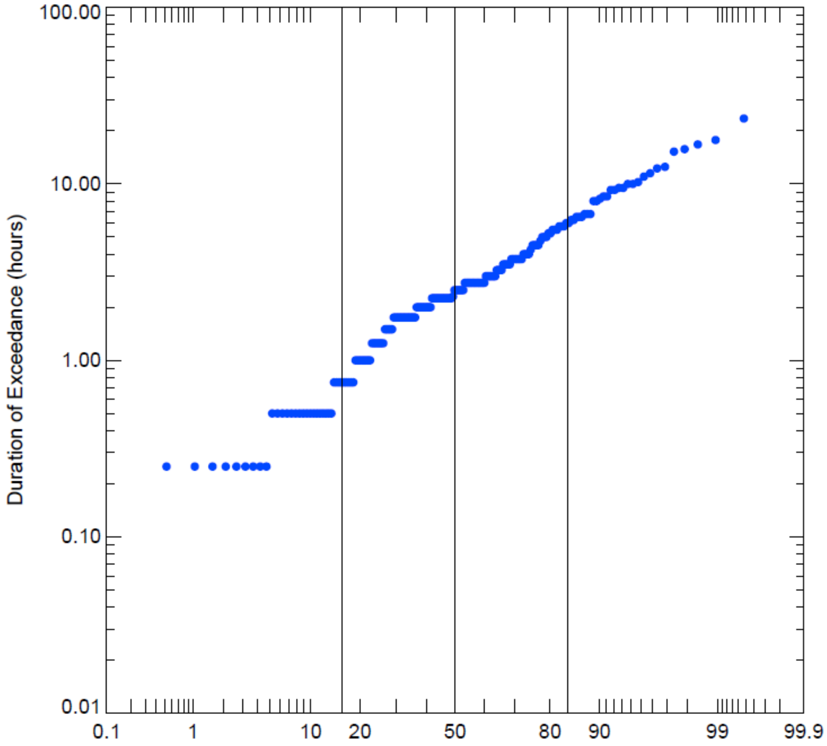

Figure 5. Cumulative Frequency Distribution of Exceedance Duration Observed 2012 through 2014

Similar to what was observed during the baseline monitoring program, turbidity levels collected during construction exhibited a strong relationship with meteorological conditions, such as wind direction and speed, adjacent tributary flow, and precipitation. Figure 6 shows the turbidity levels collected in Remediation Area A during the course of construction operations in 2014, plotted contemporaneously with the flow in Ninemile Creek. Looking closely at the middle of May, the turbidity levels increase at all monitoring stations at about the same time that flows in Ninemile Creek increase. The period of elevated turbidity also closely mirrors that of elevated flow. A similar pattern can be seen in early August, when a pulse of high flow in Ninemile Creek is mirrored by brief elevated turbidity at two of the monitoring stations within the operational array.

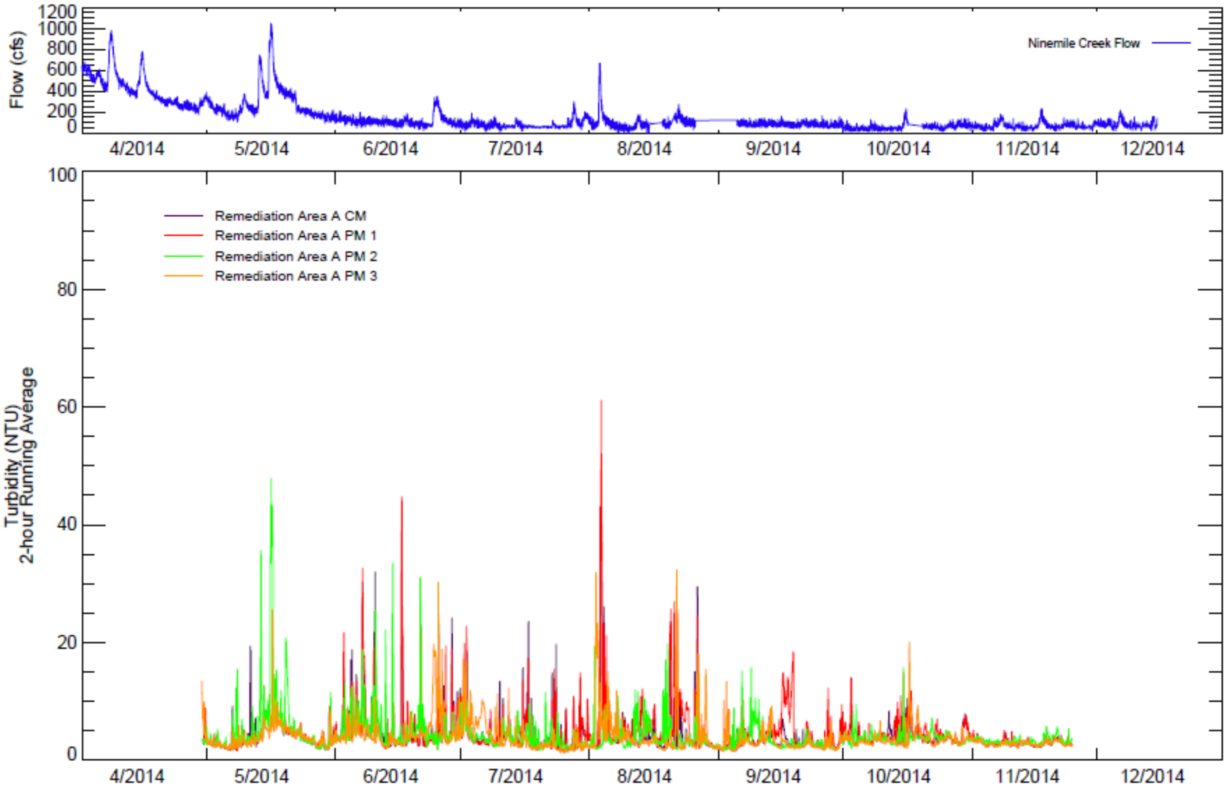

Figure 6. Example Time Series of Turbidity Plotted with Adjacent Tributary Flow

Trends Observed During Dredging Operations

The distribution of turbidity data observed from 2012 through 2014 matched what was expected in light of the data collected during the baseline monitoring program. As stated previously, slight variations in turbidity on a year-to-year basis can be expected, simply based on differing meteorological conditions (i.e., winds and/or precipitation totals). The data collected generally followed the same patterns as those seen in the baseline monitoring program, where 85 to

90 percent of the running average turbidity data were below 10 NTUs, with occasional elevated values in excess of 100 NTUs.

Exceedances of the alert-level criteria due to weather can be explained by the localized effect some tributaries have in the area immediately surrounding where they enter the Lake, effects that may be picked up by one PM station, but not another which may be acting as the background station at that given time. Exceedances of the alert-level criteria due to capping occurred in cases where capping operations (mechanical and/or hydraulic) were taking place in close proximity to monitoring stations. Due to progress within capping areas, and the large amount of equipment moving in and out of capping demarcation lines, managers were not always able to reposition the PM stations at their target distance prior to the continuation of operations. The tiered criteria system, and specifically monitoring at near-field stations, allowed for early detection of capping-related turbidity issues, and modification of relevant control structures or other BMPs to prevent an impact to the larger Lake-wide conditions. Exceedances of the alert-level criteria with unknown causes were typically short-lived, followed by a quick return to background conditions. The most likely explanation for these cases is passing debris or a temporary sonde malfunction, causing erroneous values to be recorded.

The duration of turbidity standard exceedances observed was generally short: 90 percent were less than 8 hours, and 50 percent were less than 2.5 hours. This lends support to the utility of the alert-level standard to act as a warning system, allowing managers to investigate turbidity causes in real time and modify any operations or BMPs as needed in order to avoid unnecessary shutdowns of construction activities.

As stated previously, there were no discernable negative impacts to water quality that could be directly tied to dredging operations. The monitoring plan design and implementation was such that anticipated issues were accounted for prior to construction, thus eliminating any threats to the Lake-wide water quality conditions during dredging construction activities.

Discrete Sampling Chemistry Results

A total of 97 surface water chemistry samples were collected during construction monitoring from 2012 through 2014. This total includes daily sampling during the verification period in the first 14 days of dredging, followed by weekly sampling for the remainder of dredging operations, as well as weekly sampling at the CM station for capping activities at the time of sampling for capping activities in 2012. All results of the discrete water column sampling were below the applicable NYS SWQ standards.

Trends Observed During Dredging Operations

Similar to what was observed during the baseline monitoring program, the results of discrete SWQ sampling performed during active construction were all below the applicable NYS SWQ standards. Table 4 provides a comparison of the mean, minimum, and maximum, as well as detection frequency for baseline monitoring and construction monitoring for three particular CPOIs (or their surrogates): dissolved mercury, benzene, and naphthalene.

Table 4. Summary of Discrete Surface Water Quality Sampling for Select Chemicals

		Benzene (µg/L)	**Naphthalene (µg/L)**	**Dissolved Mercury (µg/L)**
NYS SWQ Standard		760	110	1.4
Baseline Monitoring (2010-2011)	Minimum	0.12	0.032	0.00012
	Mean	0.97	3.15	0.00035
	Maximum	1*	5*	0.0013
	Det. Freq.	4%	4%	89%
Construction Monitoring (2012-2014)	Minimum	0.11	0.013	0.00012
	Mean	0.87	0.35	0.00087
	Maximum	5.9	13	0.0037
	Det. Freq.	25%	28%	67%

Notes:
* Value is report detection limit
Det. Freq. – detection frequency

In all cases above, the mean is approximately an order of magnitude less than the NYS SWQ standard for that chemical, indicating a high level of environmental protection. The increased detection frequency seen in benzene and naphthalene could potentially be a result of dredging, as may be expected when removing contaminated sediments. Comparing the data summaries above, it is clear that removal methods and BMPs have limited the spread of potential contaminants into the Lake system as a whole, and thereby maintained the status of the overall Lake water quality in relation to the NYS SWQ standards.

CONCLUSIONS

The Onondaga Lake construction monitoring program has enabled an environmentally protective dredging and capping project. Site-specific protective turbidity criteria were identified through the baseline monitoring program. The tiered water quality standard and real-time monitoring program ensured that water quality issues were detected and mitigated before they became an issue for the Lake-wide environment.

Real-time monitoring and tiered criteria used also helped maintain the efficiency of the construction project. Early investigation and mitigation of water quality issues at PM stations enabled the project to continue without unnecessary and costly work stoppages that might be required if water quality criteria were exceeded at the CM locations.

The results of the monitoring program after 3 years of dredging and capping show consistency with the results of the baseline monitoring program. Turbidity levels at the PM and CM stations remained largely within the range of ambient conditions seen due to natural forcing conditions. Surface water chemistry results remained below the applicable NYS Aquatic (Acute) SWQ standards. In summary, the water quality monitoring program, through design and implementation, helped preserve the Lake-wide water quality in relation to the conditions observed prior to the start of construction.

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PREDICTION OF MINOR LOSS COEFFICIENT AT SUCTION INLET OF CUTTER SUCTION DREDGE

Joshua M. Lewis[1] and Robert E. Randall[2]

ABSTRACT

One of the most efficient and versatile types of modern dredges is the cutter suction dredge. Specific regulations mandate the placement of screens over the suction mouth during dredging operations to prevent ordnance, wildlife, and other debris from entering the system; however, these screens change the operational capability of the dredge in the form of an additional minor loss. The objective of this paper is to describe experimental results showing the effects of different dredge operating parameters—namely, cutter head rotational speed (Ω); ladder arm swing speed (V_L); non-dimensional suction flow velocity ($\hat{V}$); screen opening area ratio (β); and screen opening shape—on a screen's calculated minor loss coefficient (or k-value).

The results showed that neither cutter head speed nor swing speed had a significant, direct correlation with the screen's minor loss in the range of selected parameters; however, they did have an indirect effect on k-value through an increased specific gravity (SG) of the slurry. The minor loss coefficient showed a direct correlation with β and was quantified for water tests and sand tests in the form of an empirical equation, which can be applied to both model and prototype cutter suction dredges. The k-values for different screen opening shapes showed the possibility of an upward or downward shift in the overall k-value curves, indicating the possibility of inherent efficiencies for differently-shaped openings. Qualitative observations included sediment spillage at high cutter head speeds and a sand-bulldozer effect at low cutter head speeds. The test results were used to develop a prediction equation for estimating the minor loss coefficient for the suction inlet fixed screen.

Keywords: slurry, screen shape and size, cutter head speed, swing speed, minor loss coefficient

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INTRODUCTION

Modern Dredges

Today, the world uses different types of hydraulic and mechanical dredges to transport materials like silt, sand, mud, gravel, clay, or reef material (Fusheng et al. 2010). Of these dredges, the most widely used is the cutter suction dredge due to its versatility, high production capacity, efficiency, and ability for uninterrupted operations (Fusheng, Li-juan, et al. 2010).

A hydraulic dredge system (like the cutter suction dredge) experiences head losses in the form of friction between the slurry and the pipe and minor losses from various pipeline components. Dredgers are often required to install a screen over the suction inlet of the hydraulic dredge system to keep animals, large rocks, debris, and even unexploded ordnance from traveling through the pipeline. These screens cause a minor head loss, which is quantified by the minor loss coefficient (k-value). Previous experiments have quantified this k-value as a function of specific gravity (SG) and suction inlet velocity (V_s) for a suction inlet screen on a laboratory cutter-suction dredge (Girani 2014). This experiment sought to quantify the changes in screen k-value across different cutting depths and flow rates when the following dredge operating parameters were changed: cutter head rotational speed (Ω); ladder arm swing speed (V_L); total screen opening area (β); and screen opening shape.

LITERATURE REVIEW

Research has shown that many factors affect both the specific gravity and production of a hydraulic dredge system. Additionally, past research has shown that operating parameters like swing speed and cutter head speed are correlated with turbidity, spillage, and production – possibly leading to changes in specific gravity. Hayes et al. (2000) state that, among others, the most important dredge operating parameters include cutter head speed, swing speed, sediment size, suction intake slurry velocity, dredging depth, cutting thickness, volume of cut, soil properties, and ambient environmental conditions.

Influence of Flow Rate

At relatively low flow rates and high cutter head speeds, the hydrodynamics of the overall flow (from still water through the rotating cutter head and into the suction entrance) is dominated by the influence of the rotating cutter head. Spillage occurs at high cutter head speeds and has been estimated at 5 to 40% of the total dredged material (Dekker et al. 2003). Spillage is defined as the percent of excavated material that does not enter the suction pipe (den Burger et al. 1999) and comprises both re-suspended sediment (sediment in the water column) and residual sediment

(sediment that falls back down to the sea floor). At high flow rates, the overall flow is dominated by the suction flow through the entrance and relatively less spillage occurs (Henriksen, et al. 2011). The amount of spillage is not insignificant when seeking a production-maximizing and cost-minimizing state of dredge operations (Henriksen 2009).

It has been shown that the minor loss coefficient (k-value) for fixed screens increases with both velocity and specific gravity of the slurry (Girani 2014). Girani (2014) introduced an equation predicting that a fixed screen's k-value is dependent upon the suction velocity of the system and the specific gravity of the slurry, eventually converging the screen's predicted k-value at high values for V_s and SG.

Influence of Cutter Head Speed

Little data are available correlating cutter head speed directly to sediment spillage or specific gravity of the slurry in the system. However, higher re-suspended sediment concentrations (indicators of spillage) have been positively correlated with cutter head speed (Henriksen, et al. 2011), indicating the possibility of less sediment going through the dredge system.

Den Burger et al. (1999) showed that there exists an optimum cutter head rotational velocity at which spillage can be minimized, resulting in maximum dredge production under his definition. Their tests confirmed that sharp decreases in dredge production on either side of the optimum value could be easily explained. When cutter head speed was less than optimum, the gravitational forces on the sediment particles outweighed their centrifugal and drag forces, reducing the amount of particles becoming entrained in the suction flow. Conversely, when the cutter head rpm was greater than the optimum, centrifugal forces caused particles to be thrown out of the cutter head and the suction flow's region of influence. While the research of den Burger et al. (1999) used coarse-grained sand and cemented gravel, this paper will qualitatively show that a similar phenomenon occurs with medium-grained sand.

Influence of Ladder Arm Swing Speed

Glover (2002) suggested that greater ladder arm swing speeds may result in a greater amount of spillage, implying a lower specific gravity (with constant fluid velocity) and a smaller k-value. Conversely, the dimensional numerical model developed by Hayes et al. (2000) shows a slight decrease in sediment loss (or spillage) with increasing swing speed, while their non-dimensional model shows a very slight increase; however, these models suffer from low coefficient of determination values in the range of 0.4 to 0.6.

Experiments conducted by Yagi et al. (1975) showed that the average mud content (i.e. a measure of solids concentration similar to SG) of slurry increased linearly with ladder arm swing speed for four different cutting thicknesses. Their data suggest that average specific gravity and k-value according to Girani (2014) should increase with ladder arm swing speed; however, a limitation of their data is that the dredged material was classified as silt/clay, which behaves differently than sand in most cases.

The Need for Evaluating Minor Losses

In 1975, the operation of dredges was governed primarily by “rules of thumb” that were developed by experienced dredgers (Basco 1975). Despite improved technology, even quite recently greater than 95% of the thousands of operable dredges in the world are operated manually, with significant performance fluctuations among seasoned operators (Tang et al. 2008). The rule-of-thumb mentality has likely not faded from the dredging community, despite evidence that computer automation increases production and decreases costs. The dynamic nature of dredging implies that full automation will not occur for a long time; however, in order to accelerate the process, more research is needed to quantify the unknown variables in dredging operations.

The mandate for dredge suction inlet screens introduces considerable uncertainty in the planning and estimating of dredging operations. In order to provide good contract bids and remain profitable, dredgers must be able to quantify the characteristics of the screens they are required to install, especially because it affects their production capacity. This research is needed so that dredgers can become knowledgeable about how the required screens behave under a variety of different operating conditions.

Objectives

The objectives of this research were to conduct independent experiments to quantify the relationship between k-value and Ω, V_L, β, and screen opening shape in the form of a k-value prediction equation that could be used for both model and prototype scale dredges.

EXPERIMENTAL TEST SETUP

Model Scaling

The model dredge at the Haynes Coastal Engineering Laboratory at Texas A&M University was designed as a 1:10 scale model relative to discharge pipe diameter (Glover 2002) and built according to the design parameters that were achievable in the laboratory. The parameters used for this experiment are outlined in Table 2, and were scaled according to the process outlined in Lewis (2014). The cutting thickness was intentionally maximized relative to cutter head diameter in order to achieve the greatest possible SG in the slurry to evaluate the full range of SGs typical of hydraulic dredging.

Table 2: Model/prototype scale relationships for the Haynes Laboratory model dredge.

Operating Parameter	Prototype	Haynes Lab Model Dredge	Model to Prototype Ratio
Cutter Head Rotational Speed	30 RPM	15 to 45 RPM	1:2 to 1:$^2/_3$
Cutter Head Diameter	60 in (152 cm)	16 in (40.6 cm)	~1:4
Cutting Thickness	30 in (76 cm)	10 in (25 cm)	1:3
Water Depth	40 ft (12.2 m)	8 ft (2.44 m)	1:5
Grain Size (d_{50})	0.00164 ft (0.5 mm)	0.00090 ft (0.275 mm)	~1:2
Grain Settling Velocity*	0.207 ft/s (63 mm/s)	0.108 ft/s (33 mm/s)	~1:2
Discharge Pipe Diameter	30 in (76 cm)	3 in (0.076 m)	1:10
Ladder Arm Swing Speed	12 in/s (30 cm/s)	1.0 to 3.0 in/s (2.5 to 7.6 cm/s)	1:12 to 1:4
Flow Rate	30,000 GPM (113,550 l/min)	250 to 400 GPM (946 to 1514 l/min)	1:5 to 1:4

MODEL DREDGE SETUP

The model dredge was set up as shown in Figure 1, with different regions marked for discussion. The reference datum was taken at the location of the suction inlet and the Y-axis pointed into the page. Region A was the suction zone of the hydraulic dredge system and was where all of this experiment’s data analysis took place. Region A started with otherwise quiescent water near the cutter head and ended at the entrance to the centrifugal pump. Region B contained a vertical section of pipe where a nuclear density gauge and electromagnetic flow meter were located. It was an optimum sensor location because vertical flow homogenizes sediment layers, providing accurate sensor measurements (Randall 2014b). Region C contained the end of the discharge line and the hopper barge (with overflow weir), which was used to collect the dredged material for each day’s experiments.

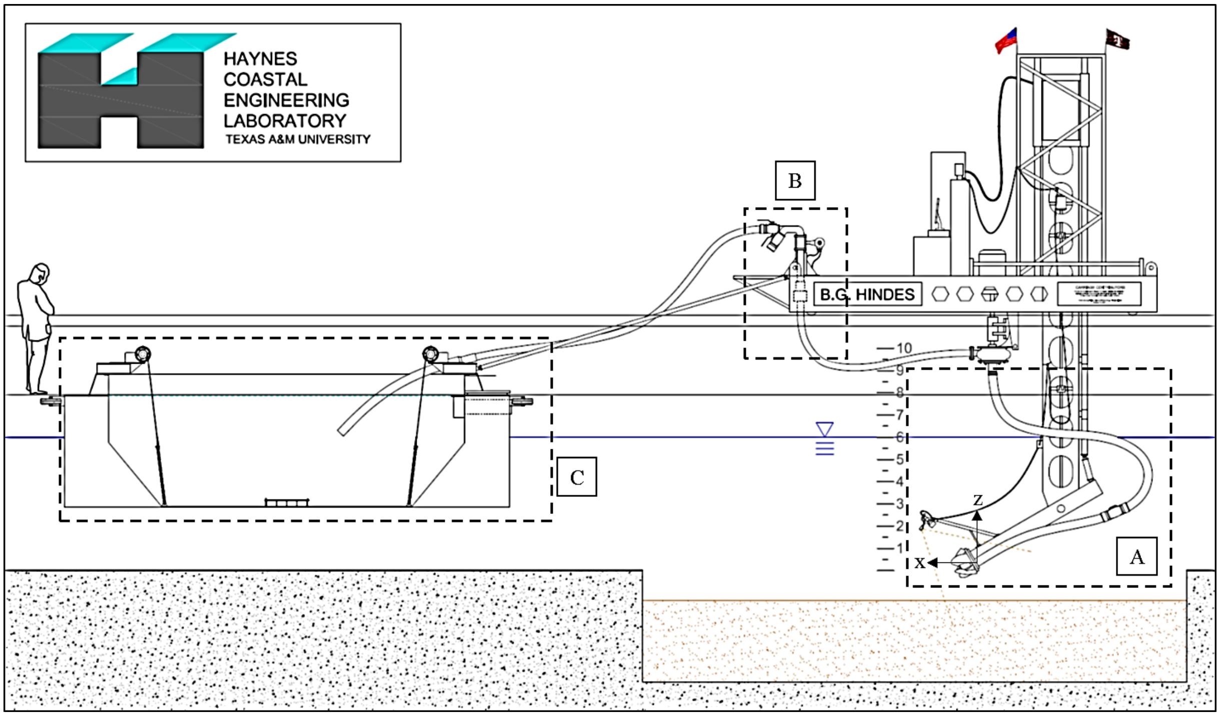

Figure 1: Overview of the model dredge at the Haynes Coastal Engineering Laboratory

SCREEN CONFIGURATIONS

Four screen configurations were used on the suction entrance for this experiment: Screen 0 (no screen installed), Screen 1, Screen 2, and Screen 3, which are shown in Figure 2. Screen 1 and 2 were designed with different β values to show its effect on k-value. Screen 3 was designed with the same β value as Screen 1 to show the effects of screen opening shape on k-value. Screen 0 was considered a 100% opening of the suction mouth with a total opening area of 14.0 in^2 (90.3 cm^2).

CALCULATION OF SCREEN OPENING AREA PERCENTAGE ($\boldsymbol{\beta}$)

In order to determine the opening percentage of each screen as constructed, high definition photographs were taken of each screen, imported into AutoCAD 2014, and scaled based on the measured width of the screen. Lines were then traced on the image around each opening, creating a digital copy of the screens; this process is outlined in Figure 2. The area within the openings was automatically calculated in AutoCAD 2014 and entered into Equation (1), yielding: $\beta_1 = 0.619$, $\beta_2 = 0.450$, and $\beta_3 = 0.617$.

$$\beta_n = \frac{[Opening\ Area\ of\ Screen\ "n"]}{[Opening\ Area\ of\ Suction\ Entrance]} \tag{1}$$

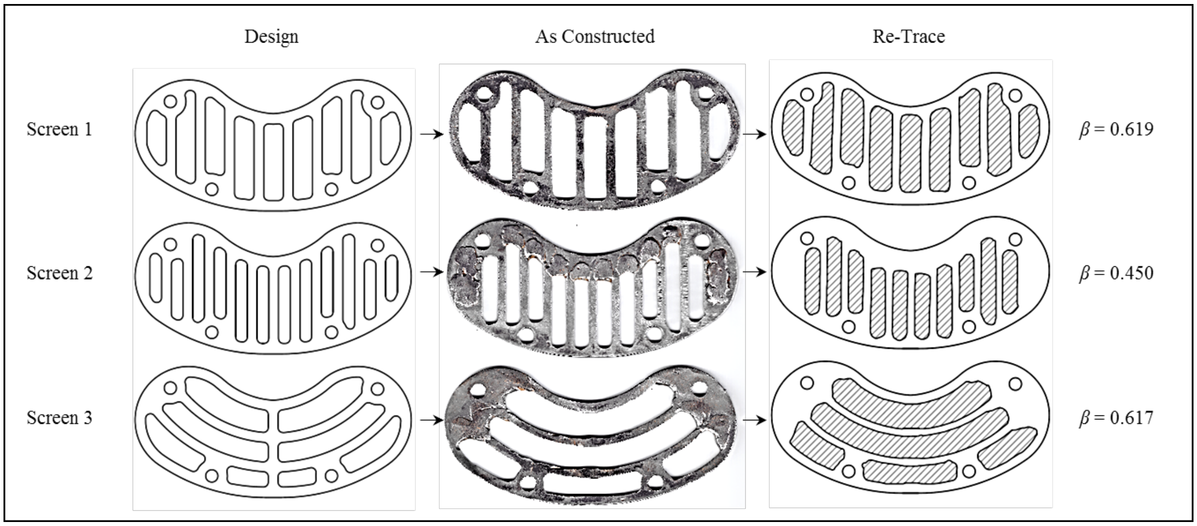

Figure 2: Screen configurations

TEST SETUP

Each test was run as shown in Figure 3, where ΔX = 9 in (23 cm) and ΔY = 79 in (200 cm).

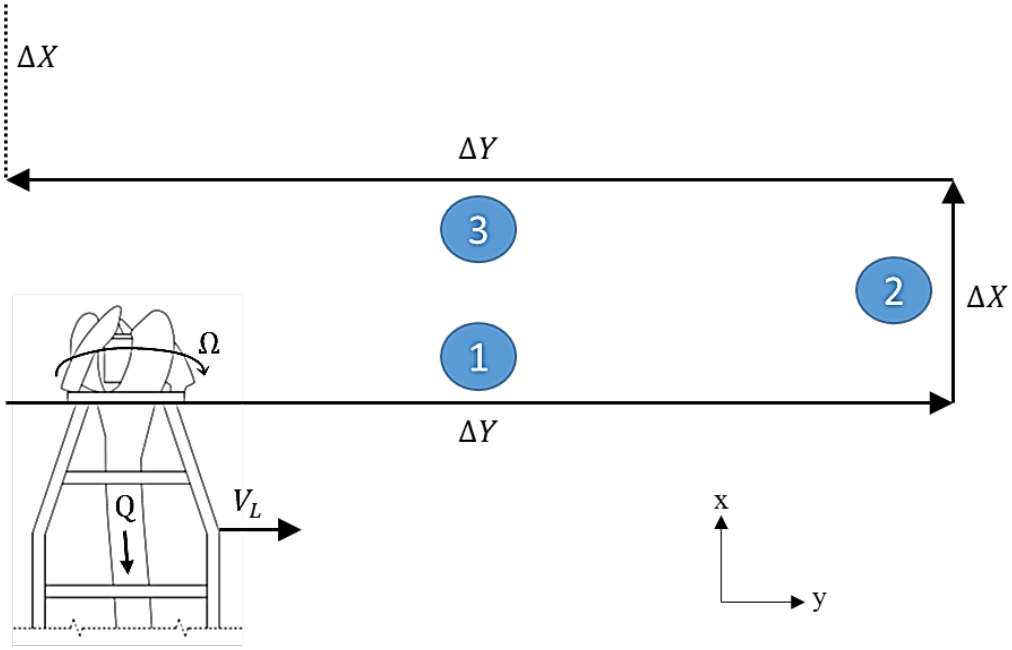

Figure 3: Scheme of cutting path for each test run

The cutting depth, defined by the vertical distance between the bottom-most edge of the cutter head blades and the undisturbed surface of the sand, was alternated between 0 inch (water only) and 10 inches (25.4 cm) in order to evaluate the effects of slurry. Past research with the Haynes Laboratory model dredge showed that a full cut of 12 inches (30.5 cm) produced the least turbidity near the cutter head (Henriksen 2009), suggesting a decrease in dredged material spillage with thickness of cut. The measurement of 10 inches (25.4 cm) was chosen to maximize the total amount of excavated material without completely burying the cutter head in the sand. Prior to each set of test runs, the Z-coordinate where the cutter head blades first touch the sand surface (corresponding to a cutting depth of 0 inches) was measured using the force sensors on the dredge carriage.

TEST PLAN

First, test dredge runs were conducted by varying cutter head speed across three values: 15 rpm, 30 rpm, and 45 rpm, with V_L held constant at 1.5 in/s (3.81 m/s). That series of tests was conducted with water only and with slurry, using a cutting thickness of 10 inches (25.4 cm). Then test runs were conducted varying swing speed across three values: 1.0 in/s (2.54 cm/s), 1.5 in/s (3.81 cm/s), and 2.0 in/s (5.08 cm/s) while cutter head speed was held constant at 30 rpm. In the same manner as the last section, test runs were conducted at two cutting depths. The entire procedure was conducted for four screen configurations—Screen 0, Screen 1, Screen 2, and Screen 3—as shown in Figure 4.

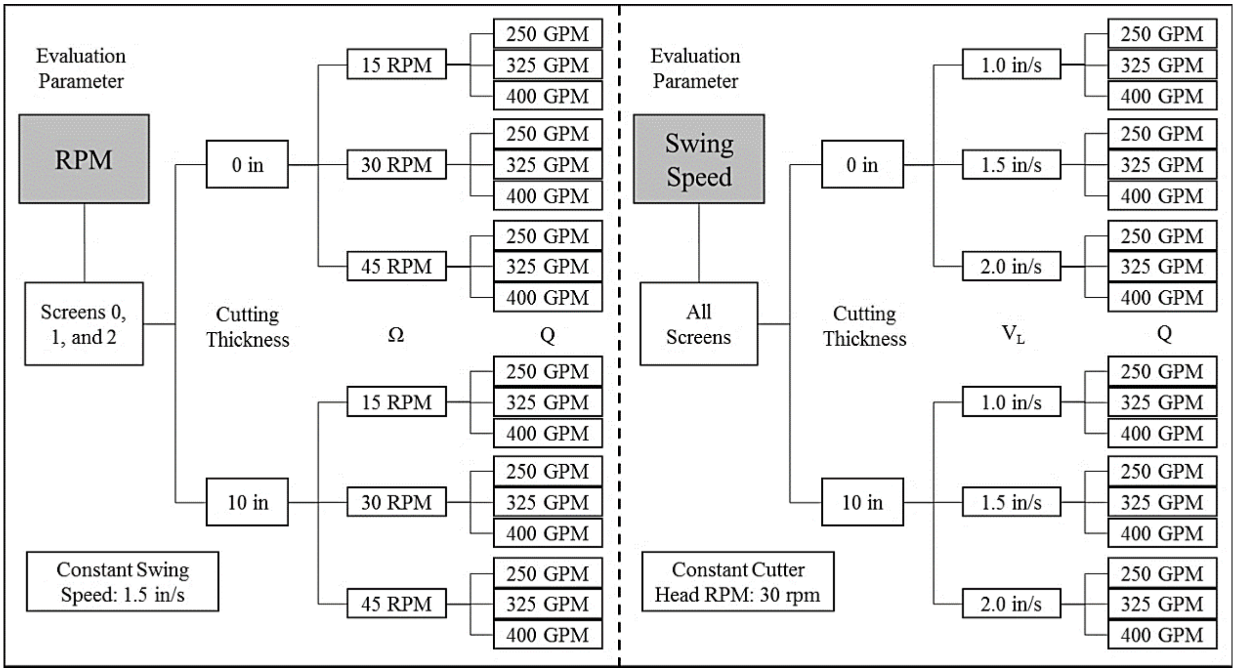

Figure 4: Test plan summary

SENSORS

The sensors used for this experiment were the Ohmart GEN2000 Density Gauge, Krohne IFC 090 Electromagnetic Flowmeter, Rosemount 1511AP (Range Code 5) Smart Pressure Transmitter, and ToughSonic Distance Sensor Model TS30S1-1V. All sensors were factory-calibrated; however, the density gauge measured SG around 1.05 when only water (SG=1.00, theoretically) was present. In order to calibrate the SG readings, nine water-only test runs were conducted during each series of tests and their SG data were averaged. Since the fluid going through the system was known to be pure water (SG=1.00), the difference between the average SG reading and 1.00 was used as a calibration constant and subtracted from all SG values for each of the day's test runs. The average adjustment was -0.055.

DATA PROCESSING

For each test, the pump power was continuously adjusted to keep the flow rate as constant as possible in the system; however, the SG and suction velocity were inherently unsteady with respect to time and direction of cutting (overcutting or undercutting). These phenomena are common in dredging operations (S. Miedema 2001) and were experienced by past researchers at the Haynes Laboratory (Girani 2014). In order to provide more precise data, the full time series for each test's raw data was truncated to only include the steadiest sections of data, as shown in Figure 5. The data were then averaged to provide single values representative of each test run, which were then used for further analysis. In many test runs, the suction pressure was greater than the discharge pressure due to the high location of the dredge pump and the short discharge line.

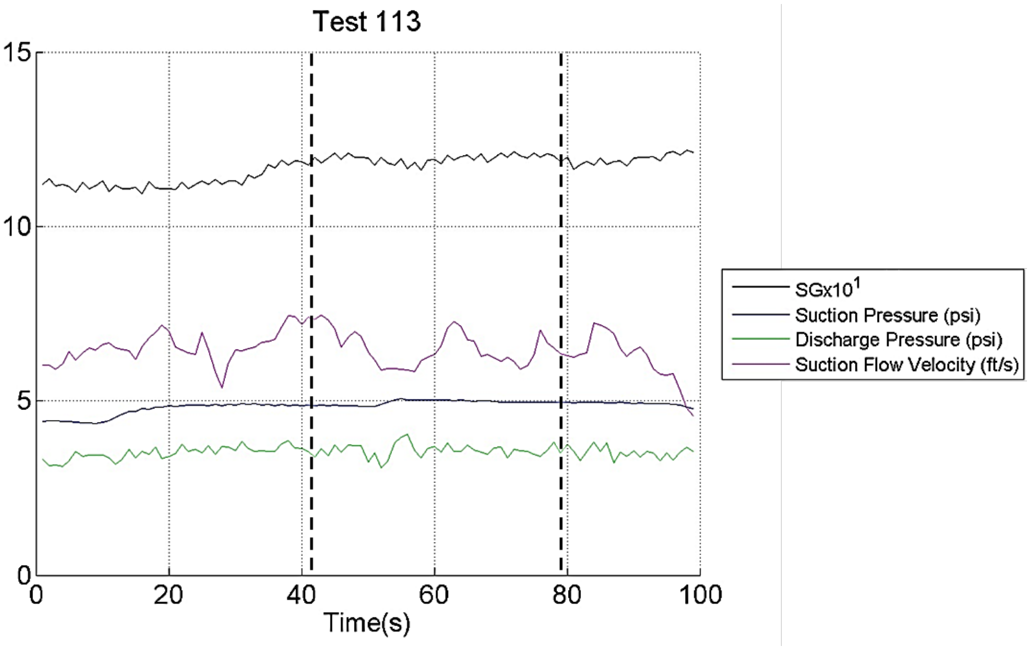

Figure 5: Example of data selection range

RESULTS

The Pseudo Bulldozer Effect

Miedema (2012) described a bulldozer effect that occurred in the cutting of water-saturated sand at high cutting angles. A different phenomenon—similar to Miedema's—was observed in this research during some of the test cases at the lowest cutter head speed (15 rpm) and is shown in Figure 6. In this case, the cutter head rpm did not produce enough rotational force to overcome the sand's gravitational and frictional forces acting on the blades, causing it to stop rotating while the ladder arm continued to move.

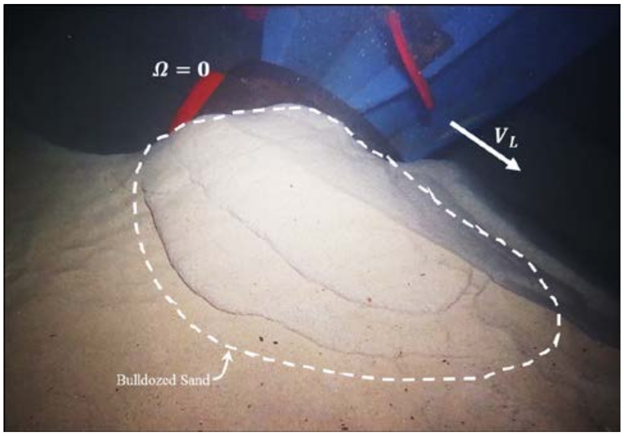

Figure 6: Pseudo bulldozer effect at slowest tested cutter head speed

Spillage

The amount of spillage was found to be positively correlated with the cutter head speed, which was consistent with the observations of den Burger, et al. (1999). The sediment suspended by the cutter head at 15 rpm was nearly all entrained in the suction flow velocity field, resulting in very little spillage. The cutter head at 30 rpm produced a moderate amount of re-suspended and residual sediment. At 45 rpm, significant spillage around the cutter head was observed, as shown in Figure 7. This trend across cutter head speeds was consistent with the positive relationship predicted by the numerical models of Hayes, et al. (2000). Greater spillage and re-suspended sediment was observed at smaller cutting thicknesses (i.e. when the cutter head was first being lowered into the sand) than at deeper cuts, concurrent with the observations of Henriksen, et al. (2011).

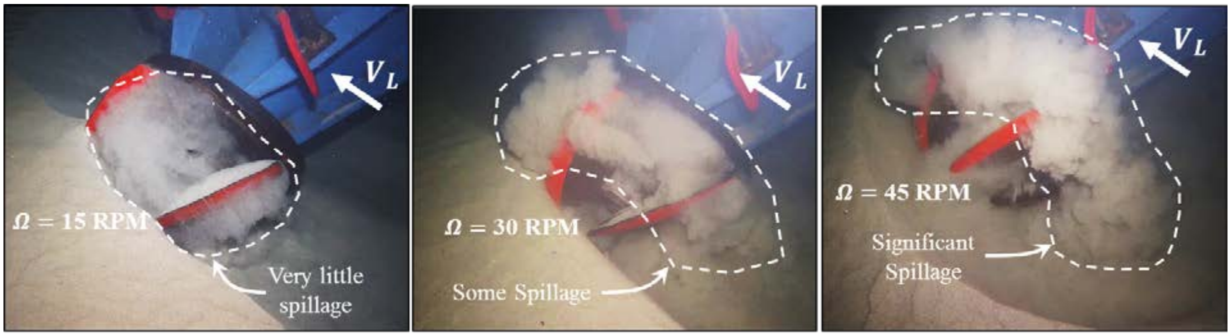

Figure 7: Spillage at different cutter head speeds

The Influence of Flow Rate on Specific Gravity and Production

Conventional dredging science says that production increases with flow rate (Randall 2014a) and that an optimum, production-maximizing flow rate exists (Ogorodnikov et al. 1987). In this research the maximum SG achieved in a test run (on average) decreased with flow rate, balancing out the production effects of the increased flow rate, resulting in an almost constant average production across all tests.

Screen Clogging

In this experiment, screen clogging is defined as excessive sediment build-up on the upstream face of the fixed sediment screen that produces an artificially high-calculated k-value for the tested screen. In this experiment, screen clogging occurred with a screen opening area ratio of 0.45 (Screen 2 only). While in the research of Girani (2014), clogging occurred at a ratio of 0.50. Upon analysis of the calculated k-values it was determined that only two consecutive test dredge runs in sand could be completed before screen clogging occurred in Screen 2.

THE INFLUENCE OF OPERATING PARAMETERS ON SPECIFIC GRAVITY

In general, the maximum specific gravity readings increased between cutter speeds of 15 to 30 rpm and decreased at cutter speeds greater than 30 rpm. At the highest cutter head speed of 45 rpm, the spillage and rate of excavation (due to swing speed) likely limited the maximum specific gravity possible during each test. If the swing speed were increased during the tests at 45 rpm shown in Figure 8, it is expected that the specific gravity would have also increased.

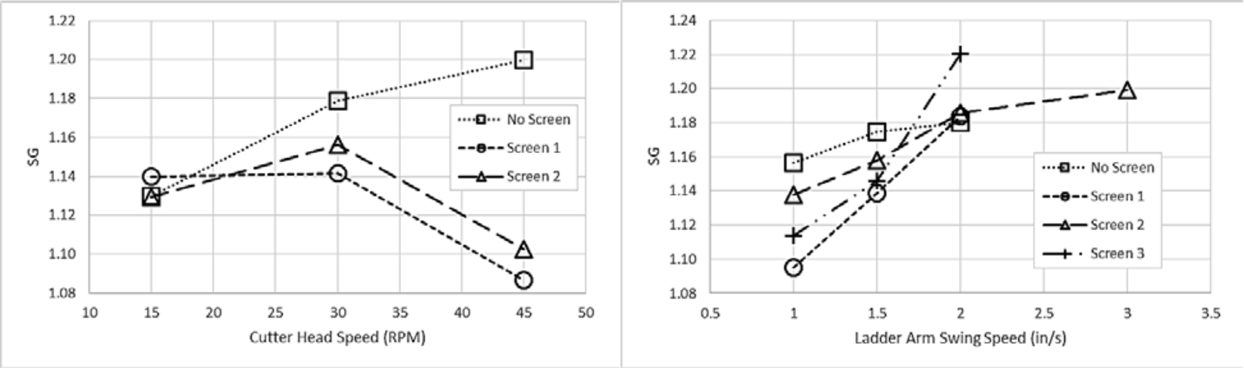

Figure 8: Maximum specific gravity achieved during testing at different cutter head speeds (left) and swing speeds (right)

A positive trend between maximum specific gravity and swing speed was consistent across every screen, with the overall maximum SG of 1.22 occurring with Screen 3 at 2 in/s (5.08 cm/s). This reading was greater than the one observed with Screen 2 at 3 in/s (7.62 cm/s) due to the increased β value of Screen 3 versus Screen 2.

DATA ANALYSIS

The conservation of energy (Modified Bernoulli) equation was applied between Points 1 and 2 in Figure 9 for two screen conditions: Screen 0 and Screen "n", yielding Equation (2).

$$\frac{P_{1n}}{\gamma} = \frac{P_{Sn}}{\gamma} + \frac{{V_{2n}}^2}{2g} + z_2 + h_{Ln} \tag{2}$$

where, the values P_{1n} and V_{2n} are defined as "the pressure at Point 1 with Screen 'n' in place" and "the slurry velocity at Point 2 with Screen 'n' in place," respectively. Evaluating the difference in Equation (2) when applied at the Screen 0 and Screen "n" conditions, substituting the specific gravity of the slurry, and rearranging terms yielded Equation (3):

$$\Delta h_{Ln} = \frac{(P_{Sn} - P_{S0})}{SG \cdot \gamma_w} - \frac{(P_{1n} - P_{10})}{SG \cdot \gamma_w} + \frac{({V_{2n}}^2 - {V_{20}}^2)}{2g} \qquad \textbf{(3)}$$

where Δh_{Ln} was the head loss caused by Screen "n." Using Δh_{Ln} in the general equation for a minor loss coefficient resulted in Equation (4).

$$k_n = \Delta h_{Ln} \frac{2g}{{V_S}^2} \qquad \textbf{(4)}$$

where k_n was the minor loss coefficient of Screen "n".

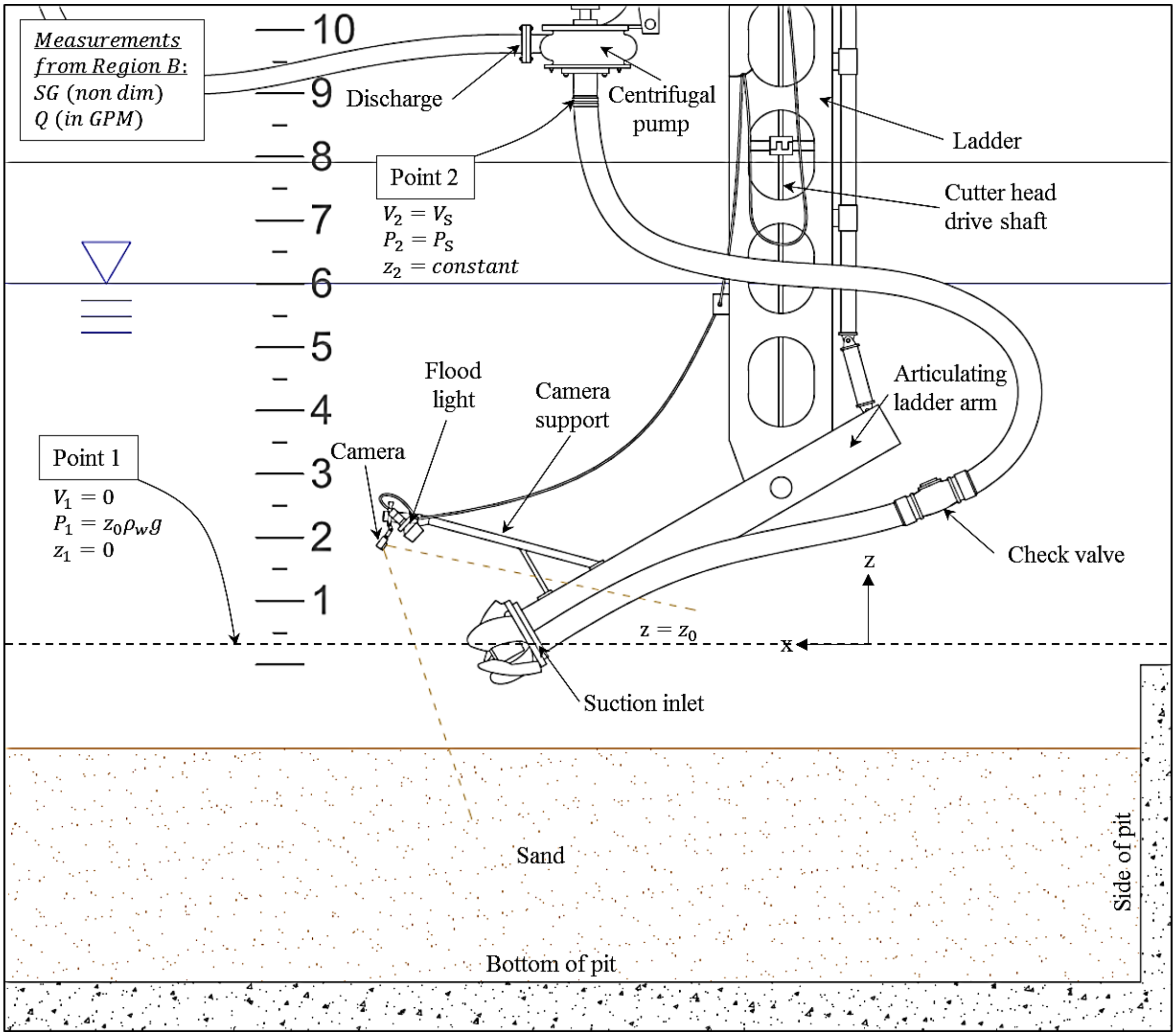

Figure 9: Suction side evaluation using the modified Bernoulli equation

RESULTS OF WATER TESTS

Cutter Head Speed and k-Value

No definitive trends between k-value and cutter head speed were consistently identified. The spread of calculated k-values (i.e. the difference between the least and greatest k-value) across the different cutter head speeds was very small compared to the overall range of values measured. At each flow rate (indicated by the different marker sizes in the figures), the total spread in k-values across each of the cutter speeds was very small—roughly 0.2 to 0.3—so for this reason, a quantitative relationship between k-value and cutter head rpm during water tests was not attempted.

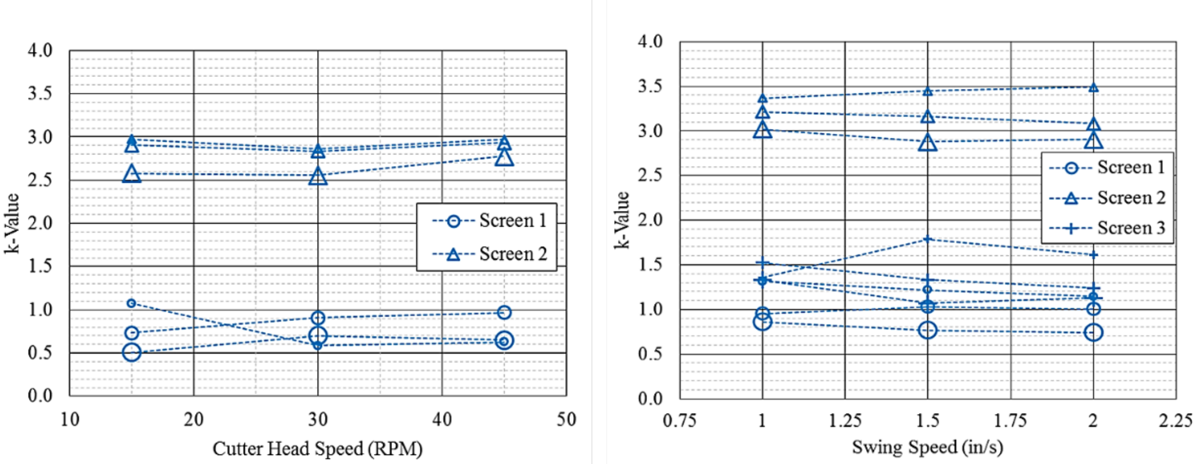

Figure 10: Water tests - the influence of cutter head speed (left) and swing speed (right) on k-value of fixed screens; marker sizes indicate nominal flow rates of 250, 325, and 400 GPM

Swing Speed and k-Value

Figure 10 shows very little correlation between k-value and swing speed. Although specific gravity has already been shown to increase with swing speed (during sand tests); when there was no sand present, swing speed on its own had no significant effect on k-value. This phenomenon is explained by the scales of the velocity fields involved. The swing speeds themselves correspond to relatively low velocities of 0.083 to 0.166 ft/s (0.025 to 0.076 m/s), while the flow rate produced flow velocities of 5.68 to 10.43 ft/s (1.73 to 3.18 m/s). This difference of two orders of magnitude ensured that the suction velocity overwhelmed any contributions from the swing speed.

Flow Rate and k-Value

The water-only test case data in Figure 11 show that k-value decreased linearly with flow rate during both cutter head tests and swing speed tests. This trend is inconsistent with the positive correlation between flow rate and k-value during water tests found by Girani (2014). The differences between the two sets of research were screen type and opening area. However, the results of this research demonstrated internal consistency, showing the negative correlation between k-value and flow rate (during water-only tests) across the three different screens tested. The linear decrease in k-value had a relatively constant slope and was similar across all screens, making the spread of k-values across all flow rates ranging from 0.4 to 0.7 as shown in Figure 11.

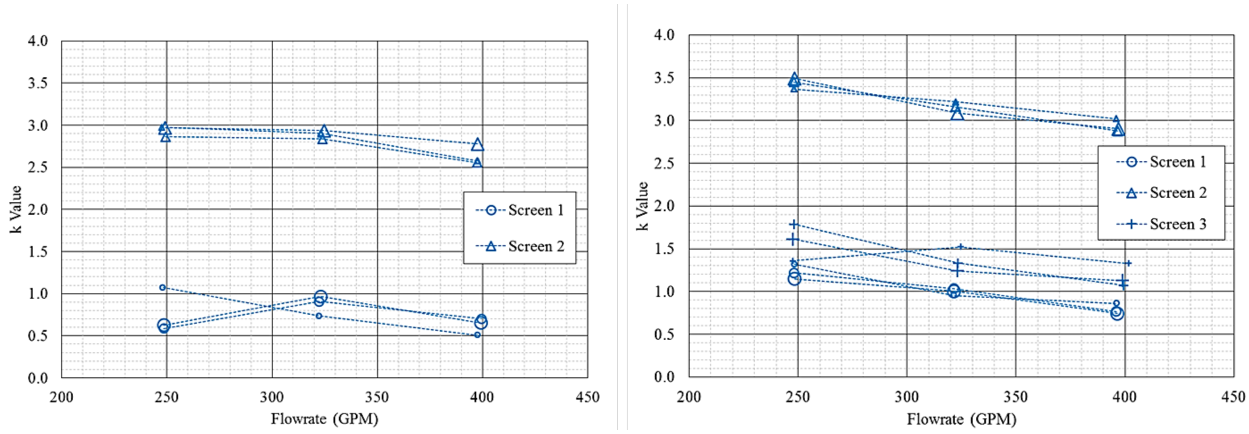

Figure 11: Water tests – the influence of flow rate on k-value of fixed screens during cutter head tests (left) and swing speed tests (right); marker sizes indicate nominal tested values for cutter head speed and swing speed

Screen Opening Area and k-Value

The primary objective of testing Screen 1 and Screen 2 was to quantify the effect of screen opening area ratio on k-value and establish a k-value prediction equation that can be used to predict the k-values of new screen designs or configurations at both the model and prototype scale. During water tests, the k-value of Screens 1 and 2 showed an inverse relationship with flow rate, which had a fairly constant slope. Additionally, all the k-values for Screen 2 were greater than those of Screen 1, indicating an inverse relationship with β. Figure 12 plots k-values for all water tests (varying both cutter head speed and swing speed) at the β value of the installed screen and has a curve fitted through the median value of each data cluster. The curve was fitted manually by an iterative process and is defined by Equation (5),

$$k(\beta) = 24.5(1-\beta)^{3.5} \tag{5}$$

However, Equation (5) still does not account for the influence of flow rate on k-value. In order to quantitatively account for that, the data shown in Figure 12 were evaluated for the spread across the three tested flow rates. The critical velocity (V_c) in the suction pipe (i.e., the velocity at which sedimentation occurs) was found to be 6.17 ft/s (1.88 m/s) using Wilson's et al. (2006) nomograph method, but can be approximated by Equation (6).

$$V_C\ [{}^{m}/_{s}] = \frac{8.8\left[\frac{\mu_S(SG_s - SG_f)}{0.66}\right]^{0.55} D^{0.7}{d_{50}}^{1.75}}{{d_{50}}^{2} + 0.11D^{0.7}} \tag{6}$$

where μ_S is 0.44, SG_s is the specific gravity of the solid material (2.65 for sand, in this case), SG_f is the specific gravity of the carrier fluid (1.0 for fresh water), D is the inside pipe diameter (in meters), and d_{50} is the median grain diameter (in mm) (Matousek 1997).

After determining the critical velocity, each nominal flow rate was converted to a dimensional velocity, then divided by the critical velocity (V_c) in the suction pipe. The new non-dimensional velocity is defined by Equation (7),

$$\hat{V} = \frac{V}{V_c} \tag{7}$$

where the three nominal flow rates of 250 GPM (946 l/min), 325 GPM (1230 l/min), and 400 GPM (1514 l/min) correspond to non-dimensional velocities of 1.04, 1.35, and 1.66, respectively. To account for velocity-induced spread of data points at each screen configuration, a scaled correction term was added to Equation (5). The average of the two spread values in Figure 12, which was 0.88, was scaled according to suction velocity and β value using Equation (8).

$$Scaling\ Term = \overset{\substack{\text{Average k-value spread}\\ \text{induced by flow velocity}}}{0.88}\left(\frac{\overset{\text{Median value for }\hat{V}}{1.35} - \hat{V}}{\underset{\substack{\hat{V}\text{ spread across}\\ \text{tested flow rates}}}{0.62}}\right)\underset{\text{Scale/shape term}}{\left(\frac{0.66}{\beta}\right)^{1/3}} \tag{8}$$

Combining Equations (5) and (8) and simplifying resulted in Equation (9).

$$k(\beta, \hat{V}) = 24.5(1-\beta)^{3.5} - (1.42\hat{V} - 1.916)\left(\frac{0.66}{\beta}\right)^{1/3} \tag{9}$$

Since Equation (9) uses only non-dimensional arguments, it may be applied to both model and prototype scale cutter suction dredging configurations; however, it is limited to water-only dredging flows. When used as a prediction tool, the k-value should be used as a baseline, as it is expected to increase with any increase in specific gravity. Additionally, the non-dimensional velocity must be calculated using the critical flow velocity in the pipeline. It can also be used to provide a good estimate of k-value of screens with different opening shapes than those of Screen 1 and Screen 2.

Figure 13 shows Equation (9) plotted at the three tested nominal suction velocities and data points from this experiment. Additionally, three points (at the nominal flow rates) from the $k(SG,\hat{V})$ equation proposed by Girani (2014) are plotted for comparison using a specific gravity of 1.0 and opening area ratio of 0.50. At β values greater than 0.62, Equation (9) has the possibility of predicting negative k-values, which would be meaningless. Additionally, according to fluid mechanics, the k-value for a sharp-edged opening is 0.5. For these reasons, the prediction curves manually converge to a horizontal line at a k-value of 0.5 in order to provide an inherent factor of safety and realism in the prediction of fixed screen k-values.

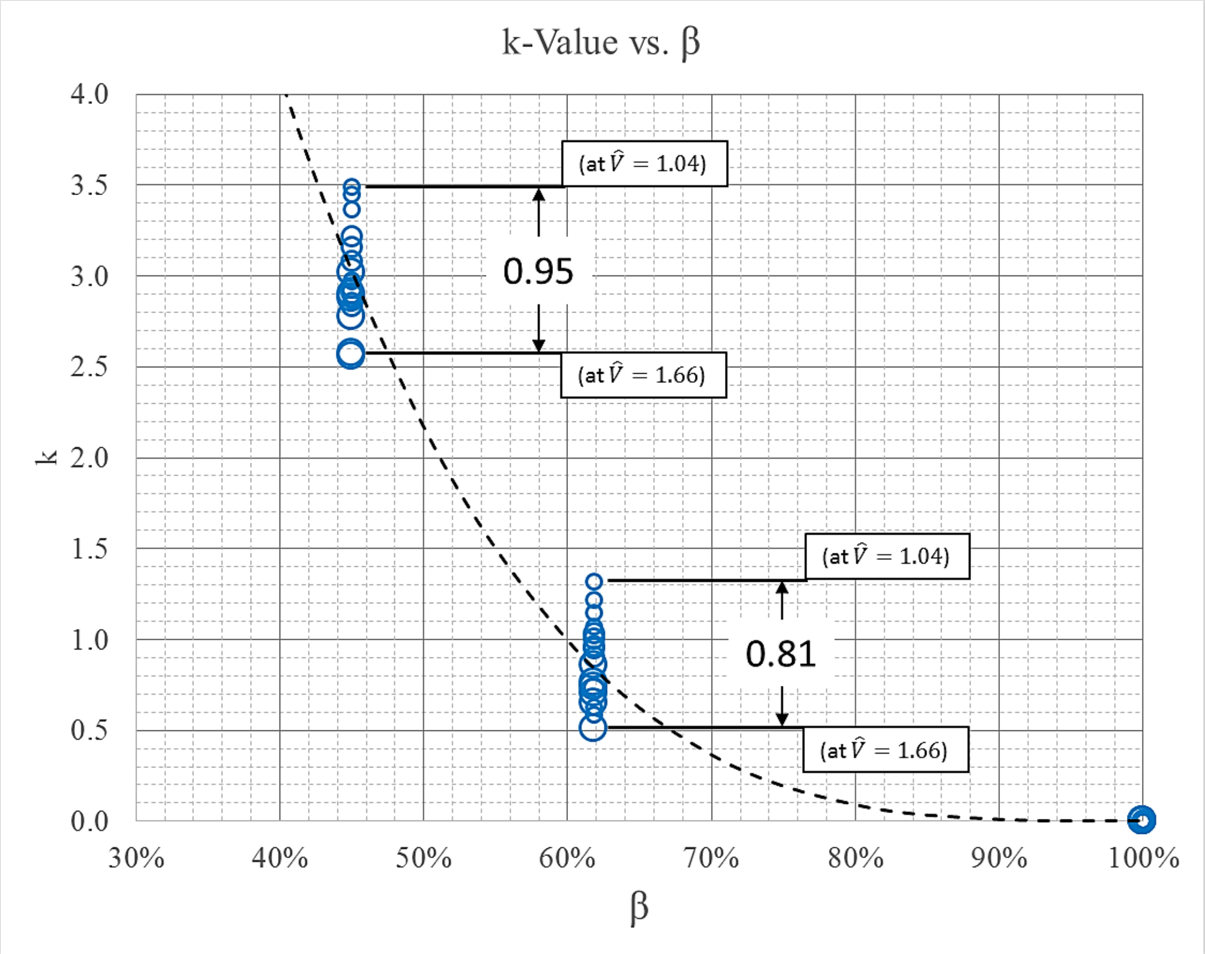

Figure 12: Effect of screen opening area percentage on a fixed screen minor loss coefficient for water tests

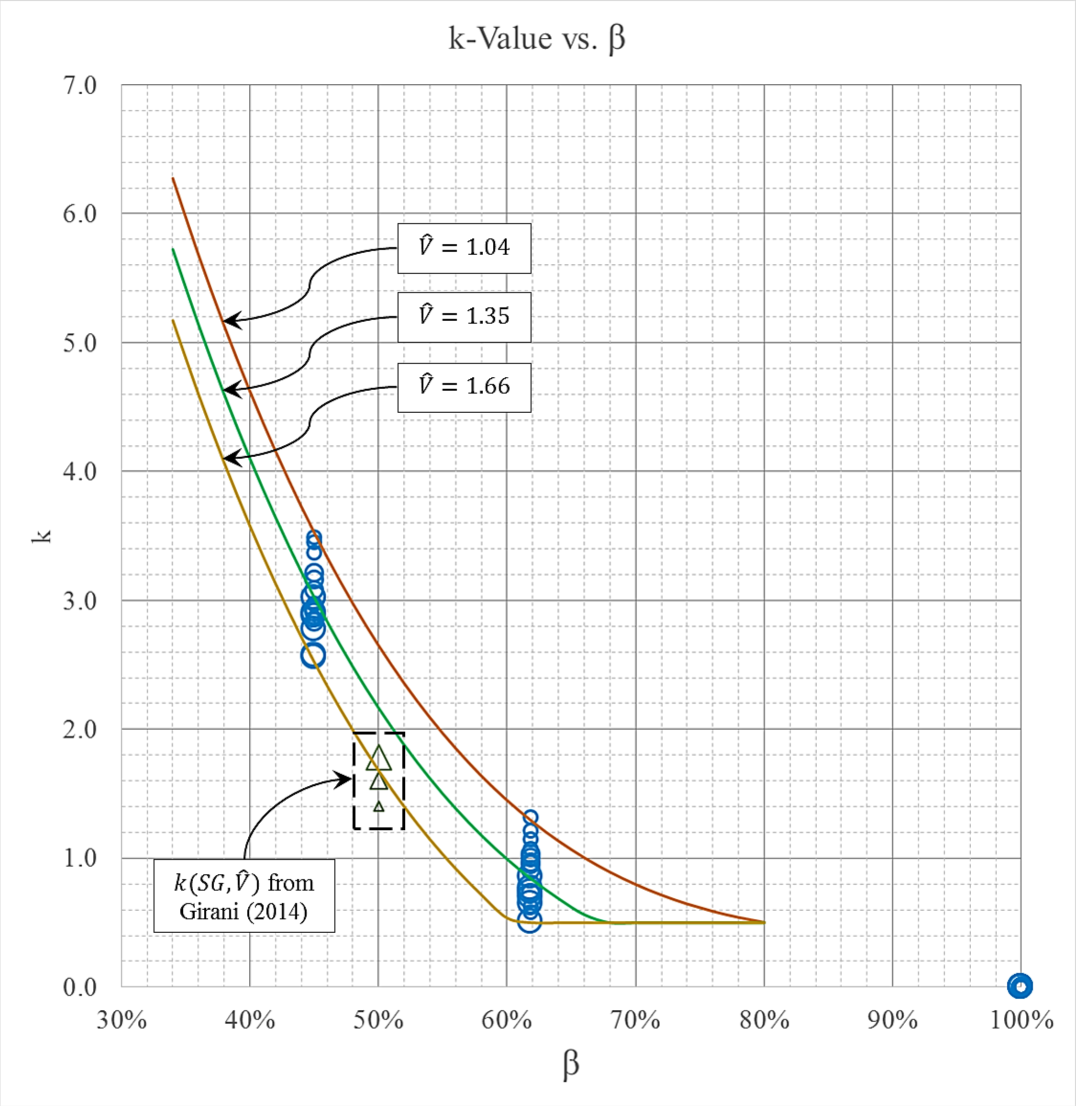

Figure 13: Minor loss coefficient (k) prediction equation plotted with experimental data

The Girani (2014) data shown in Figure 13 coincide closely with the prediction equation. The difference in data is explained by the fact that his equation predicted an increase in k-value with suction velocity, while Equation (9) predicts the opposite. The median point of the Girani (2014) data was approximately 0.6 below that of the Equation (9) prediction, indicating the possibility that the Girani (2014) screen may have had an inherent reduction in k-value due to its construction.

RESULTS OF SAND TESTS

Cutter Head Speed and k-Value

Figure 14 shows no relationship between k-value and cutter head speed; however, it does show a large range of calculated k-values, including significant outliers. The large spread was caused by artificially-inflated k-values from screen clogging. As can be seen in Figure 2, Screen 2 had relatively large, flat areas and a small opening area ratio, which allowed sand to build up on its front face. While it was not visually observed in this experiment, Girani (2014) captured the phenomenon on video and avoided it by temporarily reversing the flow direction in the suction pipe between test runs.

The first iteration of data analysis showed that three test runs produced very significant outliers (i.e. k-values around 7 to 8), indicating the screen was clogged; so, those tests were repeated and are circled with a blue-dotted line in Figure 14. The two data points circled in green in Figure 14 were the first two consecutive sand tests on the afternoon of Day 4 and did not show any signs of screen clogging. In general, for Screen 2, the data show that only two consecutive test runs in sand could be accomplished before clogging occurred. The remaining four tests, circled in red in Figure 14, experienced clogging.

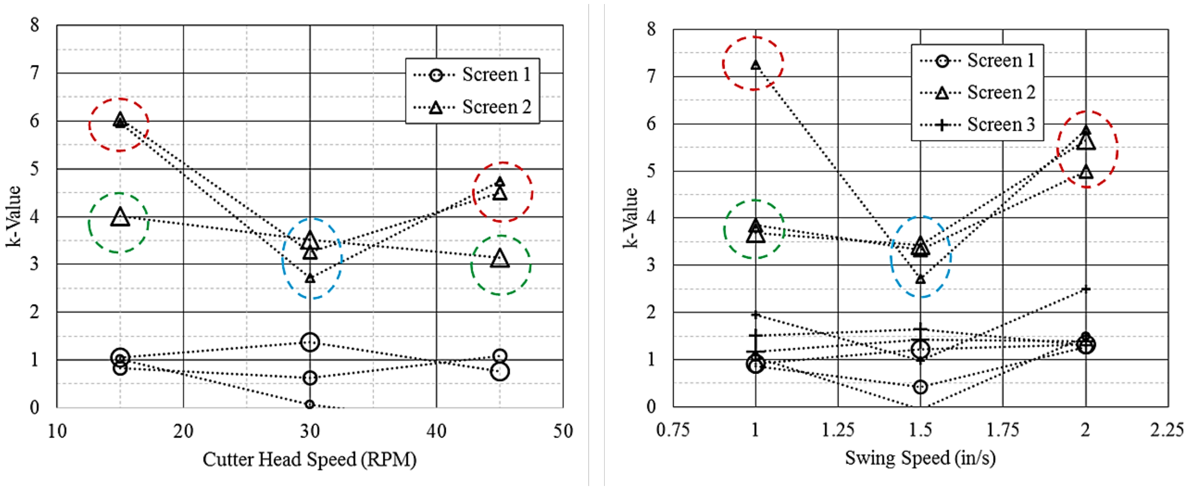

Figure 14: Sand tests - the influence of cutter head speed (left) and swing speed (right) on the k-value of fixed screens; marker sizes indicate nominal flow rates of 250, 325, and 400 GPM

Swing Speed and k-Value

Figure 14 shows that k-value had neither a significant increase nor decrease with swing speed. The Screen 2 data during swing speed tests have outliers due to screen clogging (circled in a red-dotted line) similar to those found during cutter head tests. The first two sand tests on Day 5 of testing are indicated by the points circled in a green-dotted line in Figure 14 (right) and are unaffected by clogging. The four outliers circled in a red-dotted line were completed after the first two good tests. Lastly, the three data points circled in blue represent the same tests, which were re-run on Day 6.

Similar to cutter head tests, the swing speed tests showed that only two consecutive test runs could be completed without screen clogging. The clogging only occurred with Screen 2, and it was impossible to identify any relationship between swing speed and k-value for any screen configuration.

Flow Rate and k-Value

The sand tests did not show the same trend as the water tests of decreased k-value with increased flow rate; Screen 1 had an average increase in k-value with flow rate, while Screen 2 had an average decrease. A more consistent and interesting phenomenon was the convergence of the k-values at higher flow rates shown in Figure 15. The spread of k-values across different cutter head speeds decreased with flow rate, effectively converging the k-values to about 1.0 and 3.5 for Screen 1 and Screen 2, respectively. This phenomenon is consistent with the flow field observations of Steinbusch et al. (1999), where suction flow-dominated velocity field at high flow rates, essentially eclipsing the influence of the cutter head.

All the greatest specific gravity measurements occurred at the lowest flow rate and the greatest swing speed, which explains the average increase in k-value at low flow rates. The clogging effects that occurred in Screen 2 are indicated by k-values greater than 4.0 in Figure 15.

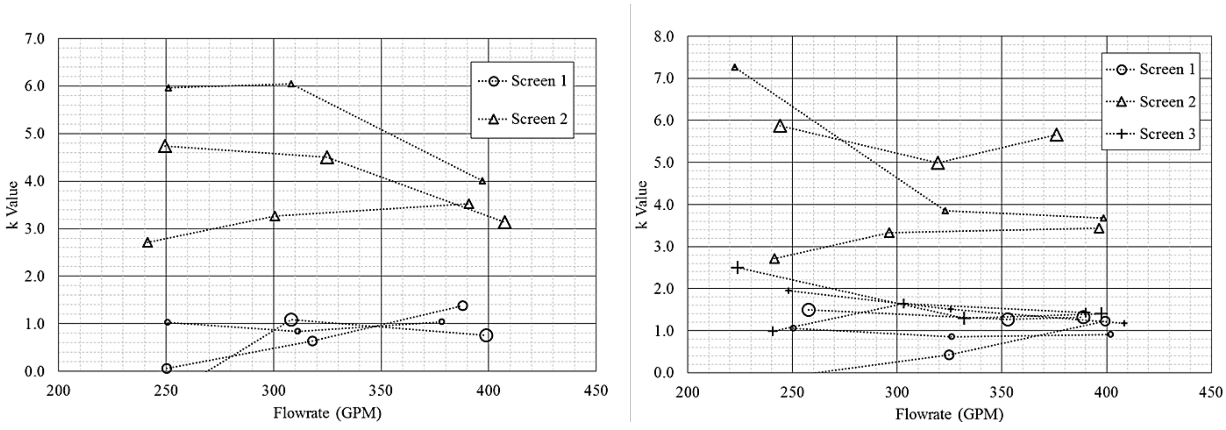

Figure 15: Sand tests – the influence of flow rate on k-value of fixed screens during cutter head tests (left) and swing speed tests (right); marker sizes indicate nominal tested values for cutter head speed and swing speed

Screen Opening Shape and k-Value

In order to test the effect of screen opening shape on k-value, Screens 1 and 3 were constructed with the same β value, but with differently-shaped openings. Screen 1 openings were vertically-oriented rectangles, and Screen 3 openings were curved contours following the shape of the suction mouth. The data show that the average k-values of Screen 1 and Screen 3 were significantly different (1.04 and 1.40, respectively) despite their β values being practically equal. This phenomenon was attributed to the addition of the flat, welded surfaces on Screen 3 (shown in Figure 2), which were necessary to match its β-value to Screen 1.

Screen Opening Area Ratio and k-Value

A prediction equation quantifying the relationship between k-value and β when slurry is present is a valuable tool for dredging operations. Since the experimental data in this research could not provide a quantifiable relationship between k and V_L or k and Ω, only SG, V, and β were left as variables affecting k.

Upon removal of the outliers that were caused by screen clogging, the relationship between k and β for sand tests was identified in the same way as the water tests. Figure 16 shows the high-value outliers previously identified and, additionally, some low-value outliers whose values do not make sense considering the concentration of most of the data points. The plotted curve (fitted through the remaining data) is defined by Equation (10).

$$k(\beta) = 29(1-\beta)^{3.5} \tag{10}$$

The presence of outliers and the large spread of calculated k-values for sand tests precluded the identification of a consistent relationship between k and $\hat{V}$. However, after the removal of outliers, the k-value, if anything, showed a slight increase with flow rate, which is consistent with the equation proposed by Girani (2014).

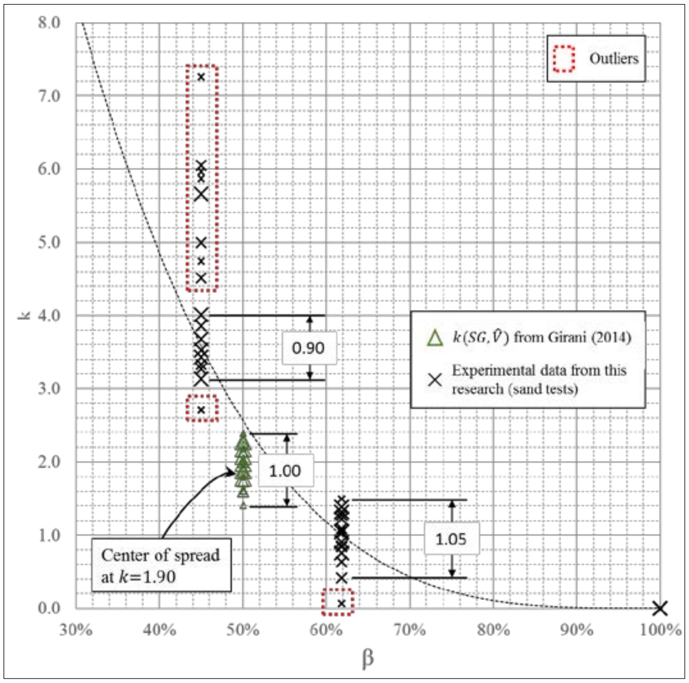

Figure 16: Effect of screen opening area percentage (β) on the minor loss coefficient (k-value) for sand tests. Identification of outliers and evaluation of spread

Instead of attempting to propose a new equation from inconclusive data, Equation (11) from Girani (2014) was used to account for the spread of data about the fitted curve.

$$k(V_S, SG) = \frac{2g}{{V_S}^2}\left(-0.694 - 0.442 \cdot V_S + 1.302 \cdot SG + 0.0468 \cdot {V_S}^2 + 0.187 \cdot V_S \cdot SG\right) \qquad \textbf{(11)}$$

where V_S is the suction velocity measured in feet per second. Since, the opening shape of the screen in Girani (2014) was different than that of Screen 1 and Screen 2, only the overall spread of the Girani (2014) data (which was almost identical to the magnitude of the data spread in this research) was used in the k-value prediction equation proposed here.

To evaluate the spread of the Girani (2014) data, the median value of 1.90 was subtracted from Equation (11), providing the scaling term shown as Equation (12).

$$Spread\ Scaling\ Term = \frac{2g}{{V_S}^2}\begin{pmatrix} -0.694 - 0.442 \cdot V_S + 1.302 \cdot SG \\ +0.0468 \cdot {V_S}^2 + 0.187 \cdot V_S \cdot SG \end{pmatrix} - 1.90 \qquad \textbf{(12)}$$

Combining Equations (10) and (12) resulted in the full, dimensional k-value prediction equation shown as Equation (13).

$$k(\beta, V_S, SG) = 29(1-\beta)^{3.5} + \frac{2g}{{V_S}^2}\begin{pmatrix} -0.694 - 0.442 \cdot V_S + 1.302 \cdot SG \\ +0.0468 \cdot {V_S}^2 + 0.187 \cdot V_S \cdot SG \end{pmatrix} - 1.90 \qquad \textbf{(13)}$$

where V_S is in feet per second. Equation (13) cannot be easily non-dimensionalized with respect to suction velocity because of its existing empirical relationship to dimensional values; therefore, in its current form it can only be used with the Haynes Laboratory model dredge parameters.

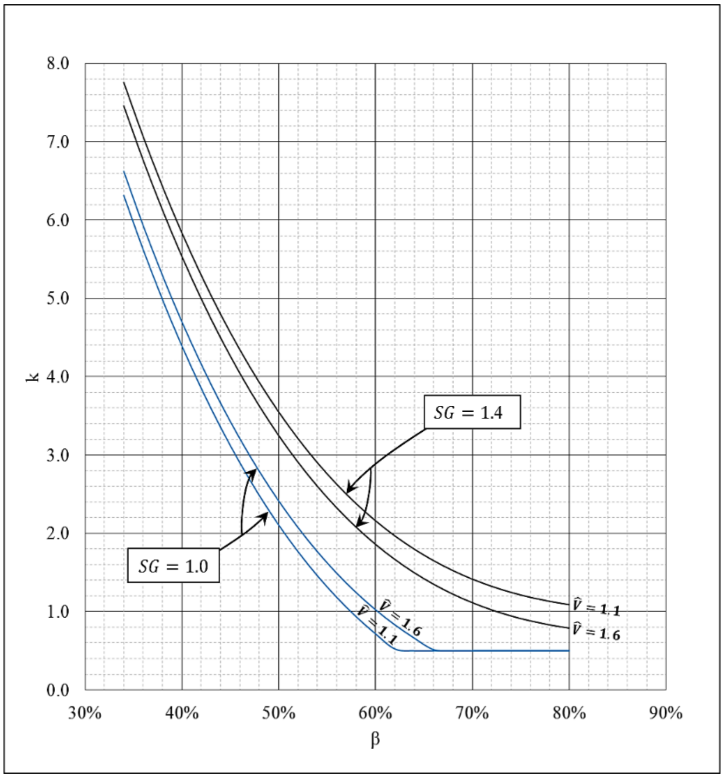

Figure 17: k-Value prediction curves with slurry present

However, the resultant plot in Figure 17 uses Equation (13) and is displayed with non-dimensional velocity, making it applicable to both model and prototype cutter suction dredge configurations. The curves are extrapolated to predict the fixed screen minor loss coefficient using specific gravities up to 1.4 and non-dimensional velocities up to 1.6; they can also be interpolated.

Figure 17 can be used for predicting the minor loss coefficient of a fixed screen installed on a prototype dredge using the screen opening sizes and operating parameters typically found in cutter suction dredging operations. The variance in k due to screen opening shape was not addressed in Equation (13) or Figure 17 because the data were not sufficient to support a relationship between various shapes and inherent k-value offsets. Although this experiment produced a maximum specific gravity of 1.22, Figure 17 can be extrapolated to predict minor loss coefficients at specific gravities of up to 1.4, non-dimensional velocities of up to 2.5, and opening area ratios from 0.34 to 0.80. Similar to Figure 13, the predicted k-values in Figure 17 reach a minimum of 0.5 near the greater β values in order to provide an inherent factor of safety in prediction, consistency with known minor losses through a sharp-edged entrance, and prevention of negative k-value predictions.

CONCLUSIONS AND RECOMMENDATIONS

These experiments showed that the minor loss coefficient was not significantly correlated with cutter head speed or swing speed at the ranges tested. This research also showed that cutter head speed and ladder arm swing speed had an indirect effect on the minor loss coefficient: they changed the specific gravity of the slurry, which then changed the k-value.

The slowest cutter head speed of 15 rpm proved to be unfeasible for large scale testing due to the bulldozer effect. The amount of spillage observed in the model dredge increased with the cutter head rpm. At constant flow rate, the amount of spillage is expected to increase at cutter head speeds greater than 45 rpm. However, when both cutter head speed and swing speed were increased, the specific gravity and production increased accordingly. If the upper limit of tested flow rates is increased, it is expected that the spillage phenomenon at high cutter head speeds would be minimized. The selected range of test swing speeds was very low; however, higher swing speeds are possible. Greater cutter head speeds and swing speeds should be tested to determine if a quantifiable relationship exists outside the range of speeds tested in this research.

The three screens tested showed a promising correlation between k and β; however, the k-value prediction equation admittedly suffers from a limited number of β-values. Future research should focus on testing more screens using screen opening area ratios from 0.45 to 0.62. Conducting similar tests on those screens would effectively fill the gaps in the experimental data.

The phenomenon of screen clogging was observed in Screen 2, which had an opening area ratio of 0.45, and in previous research with a screen opening area ratio of 0.50 (Girani, 2014). Screen clogging during multiple, consecutive test runs is expected to occur in the Haynes Laboratory model dredge at β values of 0.50 or less. The effect of this clogging was an amplified centrifugal pump suction pressure, which led to a very high calculated minor loss coefficient. Clogging was not observed in Screen 1 or Screen 3, which had β values of 0.619 and 0.617, respectively. In order to protect the validity of data, it is recommended that future researchers using screens with β values less than 0.50 be very careful to avoid screen clogging by following the un-clogging technique used by Girani (2014).

In contrast to the research of Girani (2014), the fixed screen k-values during water tests in this experiment were found to decrease linearly with suction velocity. However, at the greatest nominal flow rates, the effects of cutter head speed and swing speed were minimized, resulting in a convergence of calculated k-values, which was consistent with the Girani (2014) equation. The specific gravity during any test with a screen in place reached a maximum at the cutter head speed of 30 rpm. Additionally, the maximum specific gravity achievable at greater cutter head speeds may have been limited by slow swing speeds. The maximum specific gravity increased linearly and consistently with swing speed. These concepts can be applied to both model and prototype scale cutter suction dredges, such that the maximum specific gravity achievable in the system is at least a function of flow rate, screen configuration, cutter head speed, and swing speed.

The data show that relative to screens with rectangular openings, those with curved or expanded metal openings (Girani 2014) represent shifts in the minor loss coefficient (k-value) prediction curves of +0.3 and -0.6, respectively. Since these shifts were only observed for a limited amount of data, further testing of screens with different opening shapes should be performed at the full range of opening area ratios. This will result in more confident k-value prediction curves, from which the k-value shift across different opening shapes would be more accurately quantified.

Kharin et al. (1992) state that the computer-aided automation of a cutter suction dredge (i.e. the elimination of human influence) stabilizes the operation of a system—and even increases production. A more recent study using prototype scale dredging experiments showed that the slurry concentration, production, and suction and discharge pressures were steadier when operated by an automated computer system than when operated by an experienced dredger (Tang et al. 2008). The automation of the main centrifugal pump at the Haynes Laboratory would lead to overall data quality improvement by stabilizing inherent flow rate fluctuations. Dredge automation to stabilize slurry flow rate and specific gravity is recommended for both model and prototype cutter suction dredges.

An empirical relationship was found between the opening area ratio (β) and minor loss coefficient and was quantified in the form of a k-value prediction equation. The equation quantifying the effects of suction velocity and specific gravity on the minor loss coefficient from Girani (2014) was merged with the results of this experiment to re-define the minor loss coefficient as a function of opening area ratio, dimensional suction velocity (in ft/s), and specific gravity, as shown in Equation (51). Using non-dimensional parameters, the plot of the minor loss coefficient prediction equation was modified to predict a fixed screen's minor loss coefficient for any model or prototype cutter suction dredge using common operating parameters.

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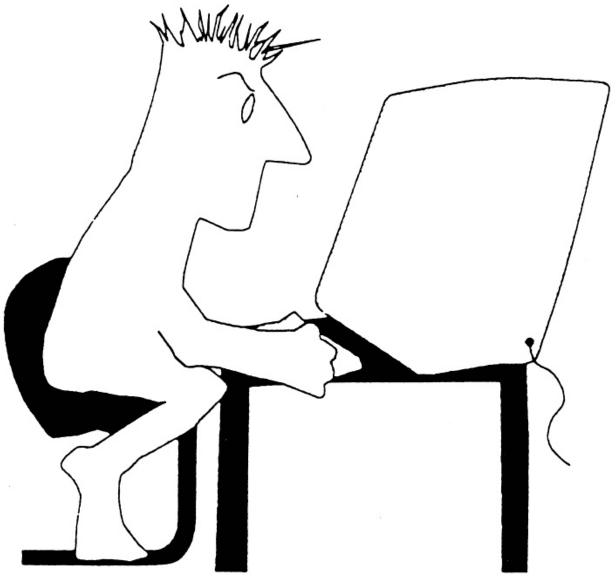

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