Western Dredging Association

PROCEEDINGS

OF THE

DREDGING SUMMIT & EXPO 2021

June 15-17, 2021

Virtual via Live-stream Video

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WESTERN DREDGING ASSOCIATION

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FOREWORD

The Western Dredging Association (WEDA) sponsored ***Dredging Summit and Expo 2021,*** a virtual conference, from June 15 to 17, 2021. The conference originated virtually from WEDA's headquarters in Bonsall, CA. ***Dredging Summit and Expo 2021*** was organized by Mr. Thomas Cappellino, Executive Director of the Western Dredging Association (WEDA), the WEDA Technical Papers Committees, and the WEDA Events Committee. The Technical Papers Committee members were Dr. Shelly Anghera (Chair), Mr. Robert Ramsdell, Ms. Lori Brownell, Mr. Walter Dinicola, Mr. Paul Fuglevand, and Dr. Donald Hayes. Events Committee members were Mrs. Carol Shobrook (Chair), Mr. Mathew Binsfeld, and Mr. Jos Clement.

Proceedings of Dredging Summit and Expo 2021 includes 23 papers by authors from all areas of the dredging community. It also includes two papers that were the basis of webinars presented prior to the conference. Two papers were previously published in WEDA's Journal of Dredging. These papers were subjected to stringent peer-review prior to publication in the Journal and are reprinted here for the convenience of conference attendees. ***Proceedings of Dredging Summit and Expo 2021*** represents a significant body of technical information that will inform the dredging community for years and decades.

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NAUTICAL DEPTH DETERMINATION THROUGH DEFINITION OF FLUID MUD CHARACTERISTICS

K. Marijnissen[1], L. Hemerijckx[2]

ABSTRACT

Safe navigation in waterways and ports must be insured. By using the proposed concept of nautical depth determination to manage navigation channels this will significantly reduce the costs associated with maintenance dredging, while at the same time ensuring the security of the vessels.

In channels with fluid mud, it can be difficult to determine the nautical depth, which leads to the question: With the goal of safe navigation in mind, how can the presence of fluid mud be optimally measured for the determination of the nautical depth?

Fluid mud is denser and more viscous than water, however still navigable in certain conditions. Though it must be noted that fluid mud can exert additional forces on the vessel that result in a decrease in manoeuvrability and an increase in potential vessel damage.

Density is the dominant property of fluid mud on which the nautical depth is currently based; however, the shear stress exerted by the fluid mud on the vessel is also a significant factor of vessel manoeuvrability. Which means both density and yield stress need to be taken in conjunction to ascertain the optimal navigation depth for vessels, also known as nautical depth.

To obtain these fluid-mud characteristic properties, density and yield stress, a survey system consisting of a RheoTune together with the EBP (enhanced sub-bottom profiler) system can be used. The RheoTune is a probe which is used to measure density and yield stress of the fluid mud, based on the tuning fork principle. By using the RheoTune the critical density level can be determined; below this level, the material has reached a certain point of consolidation that cause reduced navigability for vessels. The seismic data, acquired by EBP system, is combined with the RheoTune data, which results in an interpolation of the critical level across the surveyed waterways.

An interesting case where the RheoTune and the EBP systems were used for monitoring fluid mud, is the Port of Rotterdam. At the Port of Rotterdam, water injection dredging is used for the maintenance of the nautical depth in and around the Port.

The monitoring campaign resulted in a demonstrable reduction in both dredging costs as well as CO_2 emissions (Kirichek et al., 2020). Besides water injection dredging, there are other methods of dredging, but the principals of the monitoring remain the same. It is therefore the conclusion, that the RheoTune and EBP system can be used as an important tool to look for the most effective solutions to sub bottom problems.

Keywords: Density, yield stress, water injection dredging, beneficial uses, slurry transport, dredged material disposal, contaminated sediment.

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INTRODUCTION

Most harbours and their access channels need to be dredged to the nautical depth to ensure safe vessel passage. The nautical depth is the distance between the water surface and the "nautical bottom" (the level where it is not possible, for the harbour to guarantee safe navigation for the vessel). The nautical depth can be determined more accurately with the use of the Rheotune, the costs associated with maintenance dredging for save navigation in channels can be significant reduced by the use of the methodology discussed in this paper.

Fluid mud is a layer composed of water and a high(er) concentration of fine-grained sediments in suspension. In channels with fluid mud it can be difficult to determine the nautical depth, compared to those with more consolidated bottom materials, thus leading to possible superfluous dredging.

The Above leads to the question: With the goal of safe navigation, how can the presence of fluid mud be optimally measured for the determination of the nautical depth?

Fluid mud consists of high concentration aqueous suspension of fine-grained sediment particles combined with microbial slims (Wurpts, 2005). Fluid mud is denser and more viscous than water; however, is still navigable in certain conditions. However, fluid mud also exerts additional forces on the vessel, which results in a decrease in controllability and manoeuvrability. These additional forces are related to the fluid mud's yield stress, which means both density and yield stress need to be taken into consideration to ascertain the optimal navigation depth for vessels. In this paper the composition of fluid mud is discussed more briefly together with further explanation of a non-Newtonian fluid, rheological properties of fluid mud, the importance of density and yield stress and the tuning fork principle to measure the rheological properties.

To obtain these fluid-mud characteristic properties, a survey system consisting of a RheoTune together with the EBP (enhanced sub-bottom profiler) system can be used. To demonstrate this, a case study from the Port of Rotterdam is discussed as an example of this measurement methodology, it can be used under other circumstances as well. In the Rotterdam example the fluid mud layer was monitored before and after water injection dredging (Kirichek et al., 2020).

BACKGROUND

Fluid Mud and Non-Newtonian fluids

Fluid mud is composed of water and has a high(er) concentration of fine-grained sediments in suspension, in which settling is hindered due to the presence of sediment grains and flocs. Fluid mud has not formed an interconnected matrix of bonds. Interconnected matrix of bonds that are strong enough to eliminate mobility, causing persistent suspensions that behave as a non-Newtonian fluid (McAnally et al., 2007).

The spatial contact in fluid mud between the single solid particles is filled with microbial slime. Microbial slime is layer natural occurring bacteria and extracellular material surrounding the bacteria cells. The microbial slime causes the particles in fluid mud to stay longer in suspension, because the microbial slime is lighter than water and therefore provides buoyancy.

The microbial slimes come from attached bacteria. Therefore, a fluid mud layer can only exist in an oxygen rich environment, so that the bacterial cultures have the ability to continue to produce this slime. This slime fills the gaps between solid particles, but also reduces the internal friction, forcing the particles to stay in suspension (Wurpts, 2005). The microbial slimes in fluid mud provides buoyancy and reduces the internal friction of fluid mud.

First was thought, fluid mud only occurred in a few locations around the world, but research shows that it is quite a common feature of water bodies with fine-grained sediment (McAnally et al., 2007). Fluid mud typically forms in near-bottom layers of lakes and estuaries. It can form naturally due to, for example, an influx of sediment or reworking of the bottom during a storm, but it can also form as a result of anthropogenic actions such as dredging in harbors. Initially eroded material is mixed through the water column in a homogenous suspension. When the energy level is decreased, the suspension starts to settle and will form a denser and static suspension: fluid mud.

The fluid mud can stay in place or can again be eroded by a high energy event, that starts the cycle again (Kirby and Parker, 1977). Fluid mud can cause a critical management problem; in some ports the fluid mud accumulates so fast that it exceeds the capacity of dredges to keep the channel clear.

The upper part of the fluid mud has a higher density than water as well as a possible higher sheer stress level, but other properties of fluid mud are comparable to water. Therefore, it can be difficult to map the fluid mud, but the characteristics of the fluid mud are important for the determination of the nautical bottom. One method in mapping fluid mud, is measuring the density, which will be discussed later.

Fluid mud can exhibit pseudo-plastic or viscoelastic flow properties. The rheology varies between different fluid muds and can be site specific which makes it difficult to analyse and/or generalize flow properties (McAnally et al., 2007).

During some circumstances an initial stress is required to start the flow in fluid mud, which is the yield stress. The fluid mud viscosity and yield stress also depend on the stress history of the fluid mud, both viscosity and yield stress will decrease with time when being constant under high stress or strain.

Fluid mud behaves as a non-Newtonian fluid, which means that it inhibits shear-thinning viscosity and hinders settling of the fluid. It could also show non-fluid yield strengths (Welp et al., 2016). Fluid muds are thixotropic, which means that the faster a body moves through the fluid, the less resistance the body will encounter from internal friction with the fluid. When the body moves slower through the fluid it encounters a larger internal friction with the fluid. This internal friction will be exerted upon the vessel by fluid mud, causing reduced manoeuvrability of the vessel.

A thixotropic substance will fluidize when shear stress is applied and will regain its firmness after the rest period, which is depending on the substance. Fluid mud density ranges from a bit denser than water to stiff dense lower layers, 1100 to 1350 g/l. The most common critical density used in harbours for fluid mud is 1200 g/l (Kirichek et al., 2018), (PIANC, 1997).

<u>Density and Yield Stress</u>

Density has been the dominant property in determining the nautical depth, because density is a property that can be measured by survey equipment (Welp et al., 2016). Other technologies incorporate other physical properties such as shear strength or yield stress. While density and viscosity / yield stress are related, the relationship can also be effected by other factors like, stress history, sand content, particle diameter, clay mineralogy, rate of deformation and water chemistry (PIANC 1997). A vessel sailing through fluid mud can be effected by it due to the viscosity and yield stress of the fluid mud. The viscosity of fluid mud is dependent of the shear-rate and therefore depends on the vessels size and speed. Yield stress is a less variable property and determines the breaking force of the fluid mud’s resistance against the ship.

Based on long lasting tests, Wurpts (2005) determined that a yield strength of 70 Pa was the upper limit for ships to safely navigate through fluid mud, for the fluid mud in Emden was determined that a value of 100 Pa was still acceptable, which based on the relation between strain and stress following the Herschel-Bukley curve. Wurpts (2005) also states that viscosity is subject to change under increasing shear rates and is therefore not a parameter that should be used for the nautical depth. Furthermore, density is only a static parameter and is not suitable to determine the resistance against a moving vessel. Important for the navigability is the resistance against the ship's movement, the resistance of fluid mud is mostly dependent on shear stress. Fluid mud shows variable viscosity and is therefore hard to determine with a static property such as density. Therefore Wurpts (2005) states that the yield stress of the fluid mud has to be determined, to know whether a fluid mud is navigable or not.

Tuning Fork Principle

One of the survey systems to survey fluid mud is the EBP system together with the RheoTune from Stema Systems. The RheoTune is a fluid mud profiling probe which measures density and yield stress based on the tuning fork principle. The eigenfrequency is found based on the medium surrounding the tuning fork. First, one of the legs starts vibrating at a specific frequency. As a result, the other leg starts vibrating with a natural frequency and amplitude, depending on the medium in which the probe is inserted. Because the medium also starts to vibrate, the eigenfrequency is dependent on the density of the medium. When the density of the fluid mud increases, the natural (resonant) frequency of the tuning fork decreases. The amplitude of the vibrations decreases with an increasing viscosity.

For the calibration of the RheoTune, measurements are done in different containers with pre-determined densities. Together with a large fluid mud database, the densities and yield stresses can be linked to measured amplitude and voltage from the containers. In addition to this general calibration, site specific calibration might be necessary sometimes. After the measurements with the RheoTune, the measured data will be processed and visualized in a graph for density and viscosity of fluid mud.

METHOD

RheoTune

To determine the nautical depth in waterways, the RheoTune together with the EBP system manufactured by Stema Systems can be used. The RheoTune is used to measure density and yield stress of fluid mud. In Figure 1b an example of RheoTune data can be viewed.

During the processing of the density and yield stress graphs, strange spikes or deviating data points are interpolated. Strange spikes can be caused by for example, fluctuations in the water column or if the Rheotune starts measuring under a tilt. Furthermore, density levels for 1050, 1150 and 1200 g/l, for this example, are marked in the graph. A density level shows for the measured data, at which depth (y-value) a certain value for density (x-value) is exceeded. The first level shows, as an example, the transition between water and fluid mud, the second level is the density level above which safe navigation is still possible and the third level is the level between fluid mud and hard bottom. The choices for the density levels are site specific and can depend on the type of fluid mud. Assumed is that above a density level op 1200 g/l fluid mud will be too dense to navigate through, therefore this is the critical limit, below this horizon the material has reached a certain point of consolidation that causes issues in navigability for vessels. For the yield stress levels for 0.3, 5.1 and 16.3 Pa are shown. The depth at which these levels occur differ per measurement. The values for density (x-value) at which these levels are taken is arbitrary and chosen for each location. The x-value to indicate the critical depth (navigation depth) changes per location based on the rheological properties (and thus composition) of the fluid mud at that location.

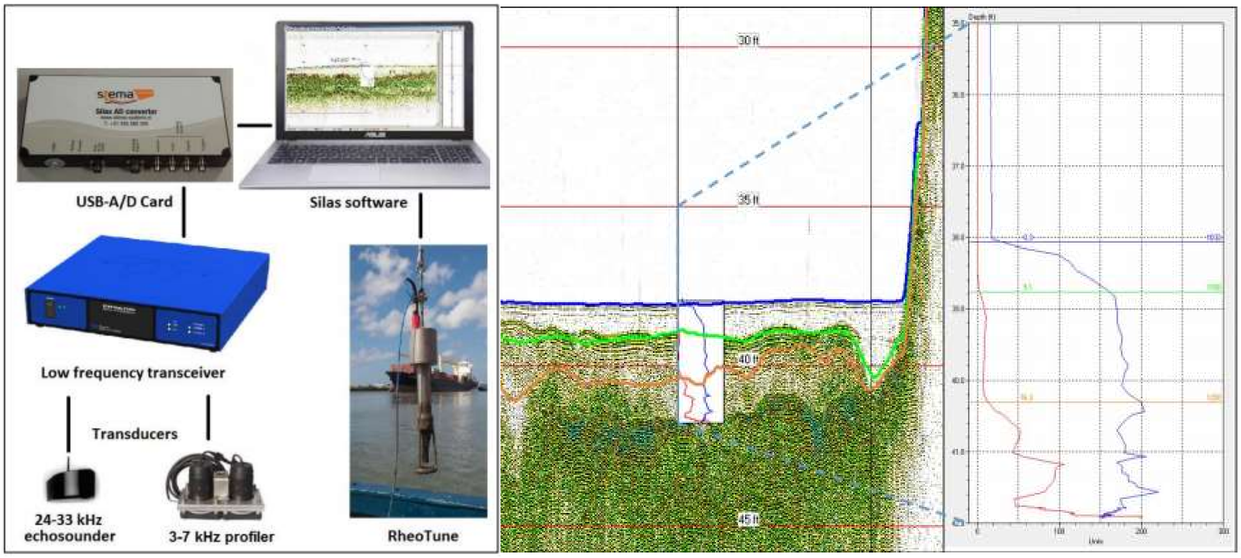

Figure 1: On the left (a) the proposed setup for the RheoTune together with the EBP system is shown. On the right (b) an example of the outcome from the RheoTune implemented in Silas Processing is shown. For the RheoTune measurement the density levels are stated at 1050, 1150 and 1200 g/l and the yield stress levels are 0.3, 5.1 and 16.3 Pa. The y-axis shows depth in feet and the x-axis shows both the density in g/l and yield stress in Pa. The density graph is displayed in blue and the yield stress graph in displayed in red. The same RheoTune measurement is displayed in the seismic line.

Silas

Silas Acquisition is used to acquire the seismic data, together with the EBP system. After the acquisition the seismic data can be imported and processed in Silas Processing. In Silas Processing the fluid mud bottom and silt bottom can be determined through layer detection, during layer detection is being searched in each trace for a certain power, that corresponds with the fluid mud layer. A seismic reflection comes from a change in density and/or velocity (both are described by the impedance).

This change in density and/or velocity, occurs for example at the water-mud interface. When the layer of the fluid mud is determined, the silt bottom is drawn, this is done below the fluid mud bottom and with a threshold value that is slightly larger than for the fluid mud bottom. When the layer tracing has been completed, the RheoTune data can be implemented into Silas Processing. Both the density and yield stress graphs can be implemented in the seismic line (Figure 1). With the use of a calibration file, based on the different RheoTune measurements, the chosen density levels can be traced laterally across the different seismic lines, which makes the combination between the RheoTune and EBP system so useful. For example, 1200 g/l is assumed to be the critical value, the value can be shown across the seismic line, showing the depth for safe navigation. The density levels can also be interpolated across the other seismic lines of the same area. In this way the nautical depth based on a density level can be achieved for the whole measured area.

Based on a validation study of Silas, caried out by Diaferia (2013) at Maasmond in the Netherlands, the resolving power for the density in Silas of 10 g/l within the range of 1160-1250 g/L. The accuracy for the bandwidth of depth or thickness of the individual density measurements is 30 cm. Which makes the determination of the nautical depth, defined by critical density values accurate and the RheoTune-EBP system combination an effective method to map the nautical depth.

Acquisition

For monitoring of the fluid mud in the Port of Rotterdam, the RheoTune is used together with the EBP system. The Calandkanaal in the Port of Rotterdam was the main region surveyed (Figure 2). Parallel lines were sailed with a speed of 2 knots with the Stema SILAS system. The distance between the lines was approximately 20 m, to obtain enough overlap with the multibeam on board. The Silas system consists of an EBP. The EBP combines the echotrac CV200 and USB-A/D converter. In turn, The CV200 is connected to a 38kHz transducer, installed below the keel of the vessel. The USB-A/D converts an analog signal to a high-resolution digital signal. With Silas Acquisition this signal is turned into an image of the sea bottom.

Perpendicular to the initial set of parallel lines, an additional set of crosslines has been sailed to form a raster of seismic lines. By executing RheoTune measurements at the cross points of the raster, the RheoTune data can later be plotted on both sets of lines to ensure a better calibration. During a one-day survey approximately 25 RheoTune measurements were taken in the Calandkanaal region.

When taking the RheoTune measurements, it is important to maintain a constant lowering speed to avoid sudden spikes in the data. When the RheoTune reaches the sea bottom the lowering speed must be ±0.2 m/s to ensure sufficient datapoints. The aid of a winch makes the use of the RheoTune easier.

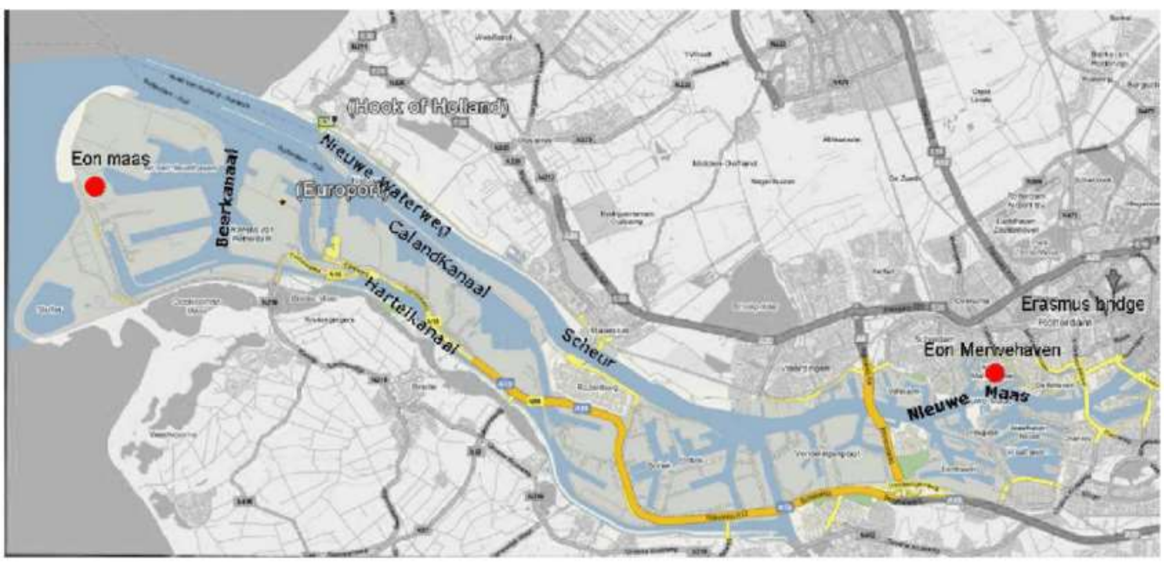

Figure 2: Location of the Port of Rotterdam and the Calandkanaal. Retrieved from De Wit et., 2007.

RESULTS

In Figure 3 two measurement points from the RheoTune can be seen. Both density and yield stress are shown, for the two measurement points. The density, levels of 1050, 1200 and 1300 g/l are marked with a respectively green, blue and red line. The critical level for vessels to navigate through is determined to be the 1200 g/l horizon. For the yield stress, levels of 0.50, 20 and 50 Pa are shown in respectively green, blue and red line. For both of the RheoTune measurements, the graphs show similar trends. The density values show a sudden increase after the transition from water to fluid mud. Followed by a stagnation at a value of around 1180-1200 g/l during the fluid mud, and a small peak near the bottom of the graph what indicates the transition from fluid mud to hard bottom. The increase in yield stress occurs at slightly larger depths

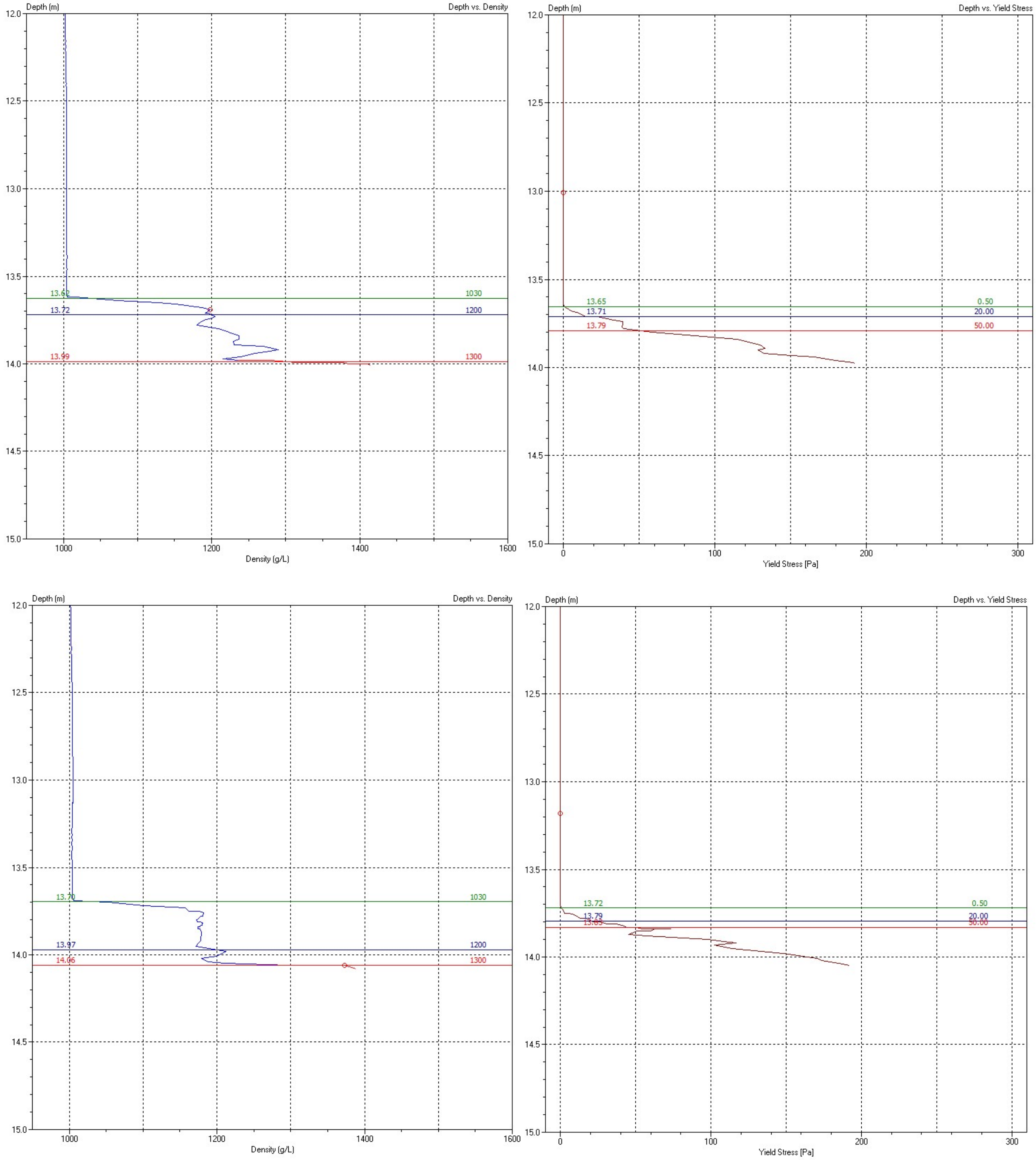

Figure 3: Two examples of RheoTune measurements points, bottom and top left show the density versus depth and bottom and top right show the yield stress versus depth. Indicated are the limits, 1050, 1200 and 1300 g/l for the density and for the yield stress are the values for 0.50, 20 and 50 Pa indicated, from the Port of Rotterdam shown in RheoEdit.

than the density increase. The yield stress shows steady increase with depth except for two minor phases of stagnation, the deepest of which correspond to the peaks in density values.

After the processing in RheoEdit the RheoTune measurements are implemented in the seismic line in Silas Processing. In Figure 4 an example of a seismic line can be viewed. The blue line shows the auto-traced fluid mud bottom across the seismic line, the brown line shows the auto-traced silt bottom. After the implementation of the RheoTune data, lines for the density levels 1200 g/l and 1300 g/l can be interpolated across the seismic line. The green line indicates the 1200 g/l density level, and the orange line indicates the 1300 g/l density level. The density levels for 1200 g/l and 1300 g/l are interpolated across the other seismic lines for this area. The bottom figure in Figure 3 shows an example, when no RheoTune measurements are present on the seismic line how the density levels of 1200 g/l and 1300 g/l are interpolated, with the use of a calibration file.

In Figure 4 is shown that the critical depth is, as expected, deeper than the fluid mud bottom and the green and orange line don’t always show the same trend as the blue line. At the right RheoTune measurement in Figure 4, the silt bottom drops, whereas the orange and green line both go up. This indicates that the depth of the critical density can vary unrelated to the traced bottom and silt bottom. Therefore, visualizing of the Rheotune measurements on the seismic lines, does yield important additional information.

Case Study: Port of Rotterdam

An example where the RheoTune together with the EBP systems were used to monitor fluid mud after water injection dredging (WID) at the Port of Rotterdam. Normally dredging is done by removing the sediments that are deposited by tides or currents, to keep the Port navigable.

At the Port of Rotterdam most of the deposits form muddy layers and were always dredged by a Trailer Suction Hopper: suction dredging. To reduce the maintenance costs and CO_2 emission for dredging, water injection dredging was introduced (Kirichek et al., 2020). With water injection dredging the top layer is injected with water and becomes more fluid, this creates a homogeneous fluid mud layer with a low yield stress and can therefore be easily transported. Close to the location where the WID took place a sediment trap was present, where the homogeneous fluid mud could be naturally transported to with the current.

After the first day of the WID, weekly monitoring campaigns were held. In Figure 5 the results from the RheoTune and Silas at Calandkanaal can be seen, for different weeks during the campaign. With Rheotune measurements and implementation in seismic line, the fluid mud layer should become visible as a more homogenous layer after WID. The red line in Figure 5 shows the critical density level of 1200 g/l. Within these sections the density is linked to the seismic data, based on the RheoTune measurements. At the section of day 7, the critical density line aligned with the change in amplitude in the seismic data (going from lighter to darker green). In the sections of day 21 this correlation is less visible, because the fluid mud became more homogenous. At the bottom section (day 42), the fluid mud layer is already quite homogeneous, especially compared to the earlier sections from day 7 and 21.

DISCUSSION

It is shown that the RheoTune can successfully measure density and yield stress in fluid mud layers. The measurements can then be implemented into seismic lines and the density level can be interpolated across that seismic and other seismic lines. In this way the nautical depth can be monitored across a large(er) area. However, yield stress is also an important factor for determining the safe navigation through fluid mud.

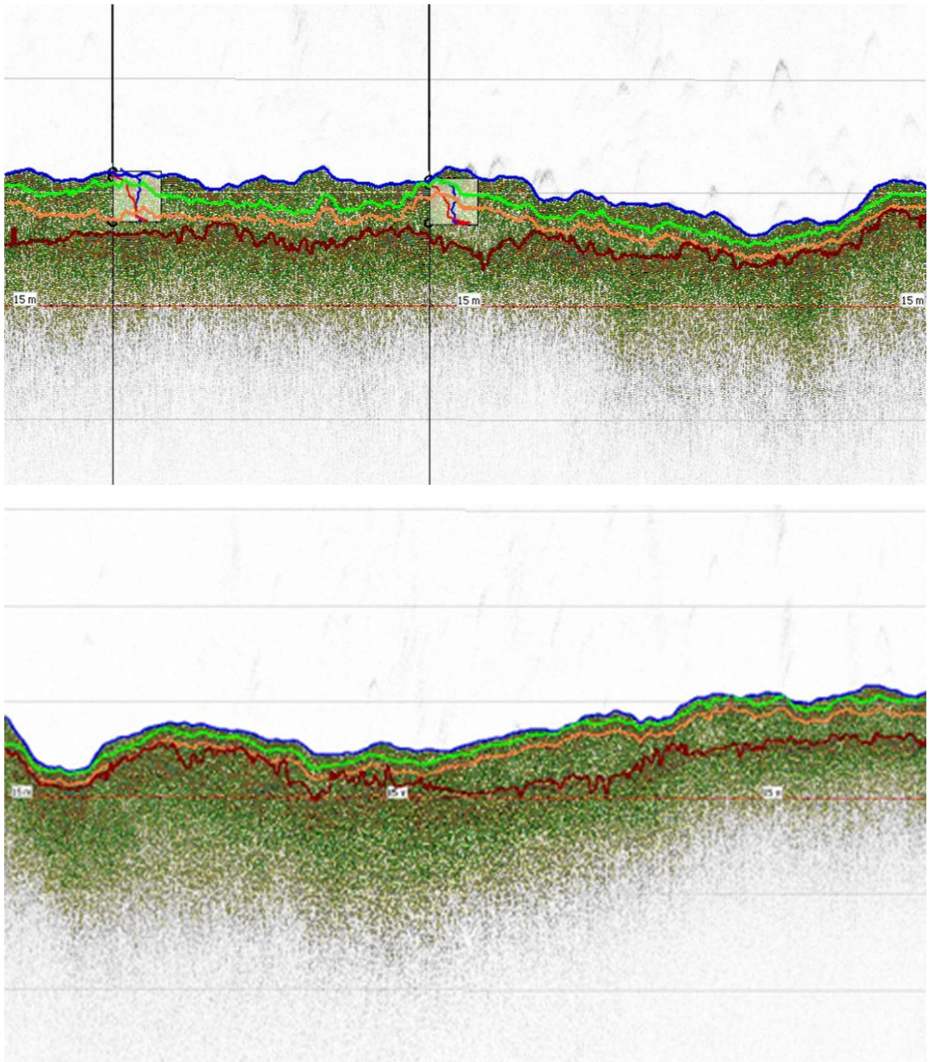

Figure 4: Top figure shows the implementation of RheoTune data into a seismic line in Silas Processing. Blue line is the fluid mud bottom, brown line is the silt bottom, the green line is density level of 1200 g/l and the orange line is the density level of 1300 g/l. The bottom figure shows that the density levels can be interpolated to other seismic lines of the same area.

The RheoTune can already measure the yield stress in the fluid mud, but at this point only the density can be interpolated into the seismic line. We think that yield stress should be considered, following the reasoning of Wurpt et al. (2005). We have shown the potential of the RheoTune system, but we think there is also more to gain from this system. We do already have the yield stress measurements; we aim to make it possible to interpolate not only the density levels across seismic lines but expend our software to also interpolate the yield stress across the seismic lines.

With the Port of Rotterdam an example was shown how the RheoTune and Silas can be used. The Calandkanaal was monitored after water injection dredging. With the RheoTune measurements the behaviour of the fluid mud and fluidized sediments were researched and monitored, this could be done as well for other dredging methods. Based on the RheoTune measurements and interpolation in Silas, it can be seen that after a few weeks the fluid mud becomes more homogenous and consolidated, which also

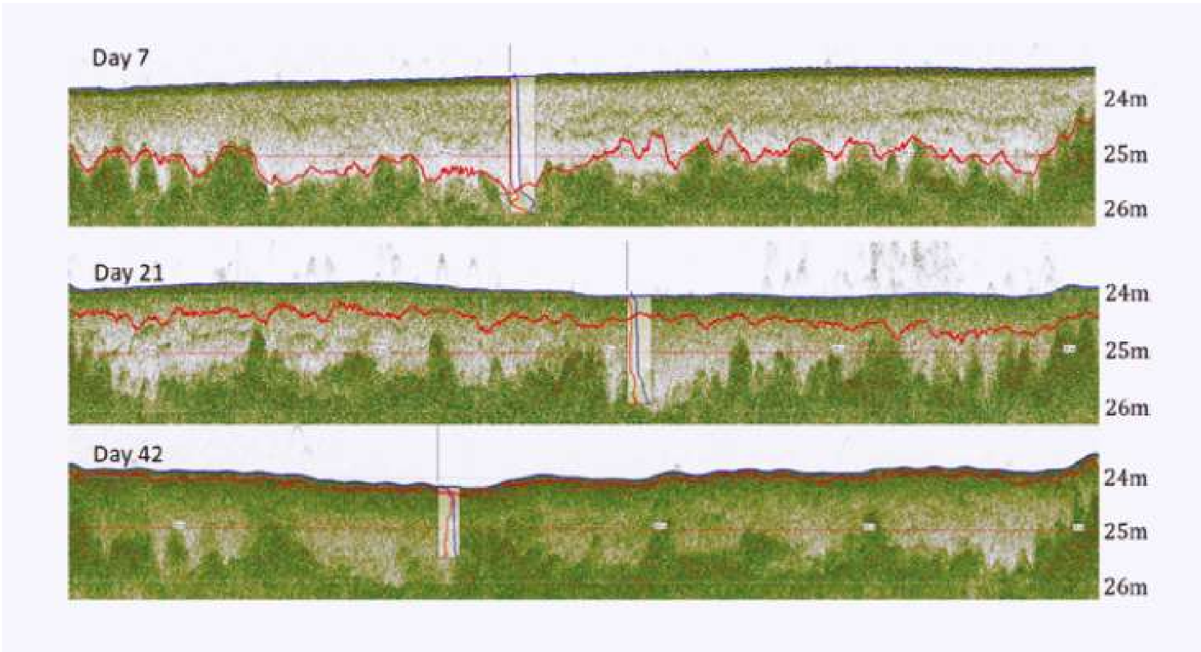

Figure 5: Seismic lines with RheoTune measurements from the WID campaign at the Calandkanaal. Red line shows the density level of 1200 g/l. In the RheoTune measurements the blue line indicates the density graph and the red line the yield stress. Retrieved from Kirichek et al. (2020).

means that the yield stress of the material will decrease. The homogenous fluid mud can more easily be transported by natural currents or forces to the sediment trap.

With this monitor campaign and visualization, the water injection dredging is proven to be an effective technique. Therefore, the RheoTune and EBP system can be used as an important tool to look for the most effective solutions to sub bottom problems. Eventually the WID method has reduced the dredging costs and CO_2 emission in the port of Rotterdam, thereby resulting in an effective dredging strategy for this case. (Kirichek et al., 2020).

CONCLUSIONS

How can the presence of fluid mud be optimally measured for the determination of the nautical depth, with the goal of safe navigation in waterways? With the use of the RheoTune and the tuning fork principle, the amplitude and frequency can be measured which are coupled to density and yield stress, based on the calibration and a database. The determined critical density level, above which safe navigation is insured, can then be interpolated across the seismic lines of the region and the nautical depth can be determined for the measured area.

The Port of Rotterdam is an example shown how the characteristics of fluid mud, density and yield stress are used to determine and monitor the fluid mud after water injection dredging. With this new technique and useful monitoring of the fluid mud with the RheoTune and Silas EBP, the dredging costs and CO_2 emissions were reduced.

Based on the validation of the use of the Rheotune in conjunction with the EBP system in Rotterdam, it can be assumed that this measuring techniques would be applicable to other situations where the goals would vary from: reduction in superfluous dredging cost, insurance of navigability in ports, harbours, water ways etc.

Besides the Port of Rotterdam, the EBP system together with the Rheotune can be helpful to monitor and visualize fluid mud or determine the nautical depth in other harbours or during dredging projects. It is therefore the conclusion of the author that the RheoTune and EBP system can be used as an important tool to look for the most effective solutions to sub bottom problems.

REFERENCES

De Boer, P.J., Werner, C.J., (2016). *Provide end users with the most accurate nautical depth measurements by using the combination of echo sounders and density measurement equipment*. HYDRO 2016.

De Wit, P. C. B., Bolier, G., Paalvast, P., Van der Velde, G., & De Vries, M. B. (2007). *Contribution to the development of ecological goals and indicators for the aquatic environment in ports. Challenges in the port of Rotterdam area.* New Delta. Ports and nature, striking a new balance. Report Theme, 2.

Diaferia, G. (2013). *Validation study of Silas: study area Maasmond*. Deltares.

Kirby, R., and Parker, W. (1974). *Seabed density measurements related to echo sounder records*. Dock and Harbour Authority, 641.

Kirichek, A., Chassagne, C., Winterwerp, H., & Vellinga, T. (2018). *How navigable are fluid mud layers.* Terra et Aqua, 151, 6-18.

Kirichek, A., & Rutgers, R. (2019). *Water injection dredging and fluid mud trapping pilot in the port of Rotterdam.* Proceedings for CEDA Dredging Days, Rotterdam, the Netherlands.

Kirichek, A., & Rutgers, R. (2020). *Monitoring of settling and consolidation of mud after water injection dredging in the Calandkanaal.* Terra et Aqua, (160).

McAnally, W. H., Friedrichs, C., Hamilton, D., Hayter, E., Shrestha, P., Rodriguez, H., & ASCE Task Committee on Management of Fluid Mud. (2007). *Management of fluid mud in estuaries, bays, and lakes. I: Present state of understanding on character and behavior.* Journal of Hydraulic Engineering, 133(1), 9-22.

PIANC, P. (1997). *Approach Channels A Guide for Design.* Report of Working Group II-30., 95, 14-28.

Wurpts, R., & Torn, P. (2005). *15 years' experience with fluid mud: Definition of the nautical bottom with rheological parameters.* Terra et Aqua, 99, 22-32.

Welp, T., Webb, D., Martin, K., Reid, S., Bullock, H., Sullivan, M., Colombo, C., Oakman, A. (2016). *Corps implementation of nautical depth in channels with fluid mud*. WODCON XXI Proceedings.

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DATA AVAILABILITY

Some data, models, or code generated or used during the study are available from the authors.

SALT MINING DREDGE – ELECTRIC 1100 HP LADDER PUMP WITH 94" DUAL WHEEL EXCAVATOR

Duncan A. McTaggart[1], Sape A. Miedema[2], Paul Quinn[3]

ABSTRACT

A dredge was designed and built for a customer who needed to mine halite mineral to feed Ethylene Chloride stock into downstream petrochemical processes such as plastic production. A production guarantee for excavation and pumping at depths up to 9 meters was required. The goals for this dredge were to produce 550 metric tons per hour of un-blasted halite ore, with a minimum excavation recovery rate of 85%, in an environment where temperatures range from 40 to 130 degrees F (5-54C). The dredge was required to be built and tested in the United States, then disassembled, shipped, re-assembled and commissioned at the mine site.

The specifications asked for process characteristics that were subsequently confirmed via a study of halite and saturated brine. The customer, though, had a particular pump in mind and would not deviate from that, bringing additional constraints not mentioned in the original specs. The specifications for the excavation system were not detailed with regard to power or volumetric displacement, but Ellicott had experience with this application and could work from tonnage requirements. While the sizing of the proposed unit was marginal, again the customer had a particular excavator in mind and would not deviate from that selection.

Detailed analysis to rationalize the power requirements from the given compressive strength of the material was undertaken. This analysis included building a detailed understanding of the applied fracture and crack propagation characteristics as well as the need to transfer and pump the resulting particles. It was determined that our sizing would be adequate to meet production requirements under favorable conditions and the customer confirmed that this was acceptable.

The dredge was manufactured, assembled, and tested in Baltimore and then shipped to the customer's mine site for final assembly and commissioning. Construction practices under such hostile environmental conditions were remarkably challenging and could be the topic of a separate case study.

In the end, the pumping system performed better than anticipated. The material, while providing serious challenges with extremely high slurry SGs and extremely low line speeds, was also more forgiving than anticipated. The excavation system turned out to be a particular challenge for multiple reasons, some related to design, some related to procurement, and some related to operational approaches. The balance between the cutter and pump turned out to be good.

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The biggest challenge encountered was excessive vibration. The pump was driven by a line shaft from a motor mounted at the aft end of the ladder, causing concern in the design stage. This turned out to be a minor issue at worst. The more significant challenges came from sustained cavitation of the pump, from complexities of the hydraulic system, and from the hammering action of the excavator. Additionally, sustained wind speeds created vibrations in sun shades originally thought to be significantly overbuilt.

The dredge was successfully built, shipped, rebuilt and commissioned at site. Despite the unknowns and challenges faced along the way, the dredge performed as required and was accepted by the customer.

Keywords: Halite, Bucket Wheel, Brine, Equipment Sizing, Rock Cutting

INTRODUCTION

A customer contacted Ellicott in 2011 with interest in a dredge to mine from an ancient and very pure halite deposit. After extraction, they process the extracted halite into ethylene chloride feedstock for petrochemical and plastics manufacturing. The customer issued a formal RFQ in 2013. Detailed technical clarifications and commercial negotiations took place over the next 2 years, resulting in an award in April of 2015.

The dredge was required by contract to produce 550 metric tons per hour of un-blasted ore with a minimum excavation recovery (scavenge) rate of 85%. The dredge was to be powered electrically from shore, and to employ a ladder pump, a bucket wheel excavator capable of mining up to 9 meters below the water line, and a spud carriage.

A set of pumping system requirements were outlined that required 11,000 gpm (2500 m^3/hr) of slurry flow with densities ranging from 1.29 to 1.45. Expectations to use an existing pipeline and booster train were clear. A pump was identified but the description and a rubber lining requirement made it clearly invalid. This was clarified before award as an invalid specification.

Environmental demands on the machine were extreme. Ambient temperatures ranged from 40 to 130 degrees F (5-54 C). Wind speeds up to 100 mph (161 km/hr) were to be considered. The ponds are composed of saturated brine which is aggressively corrosive.

The contract required the dredger to be built and tested in the United States. It was then to be disassembled, shipped, re-assembled, and commissioned at the mine site. A large number of engineering submittals were also required.

INDUSTRY / MARKET SIGNIFICANCE

Dredges designed and built exclusively for mining Halite (solid Sodium Chloride in mineral form) are quite rare, making this a once-in-a 10 or 20 year dredge. They work in an uncommon environment for a dredge and face unusual excavating and pumping conditions. In this case, the dredge buyer also had several performance goals and other requirements that had to be met.

In order to successfully comply with the strict requirements of the owner, several significant and unique factors had to be dealt with:

- Production rate guarantees were required despite there being limited industry-specific data on:

    - Excavation characteristics of Halite, including determining the forces required to fracture the material and the resulting size of the dislodged chunks.
    - Pumping system characteristics. This required determining the behavior of a slurry composed of solid halite crystals in super-saturated brine. Another factor that was considered is the loss of halite solids in the pumping system, as smaller particles dissolve into solution during transport.

- Designing the bucket wheel to excavate solid, un-blasted halite ore. This required determining the shape, size, power and drive unit of the bucket wheel so that it could effectively dig. The existing dredge on site required that the halite be blasted prior to excavation, and the new dredge was expected to eliminate the need for blasting.
- Designing the bucket wheel and its internal hopper configuration to increase the recovery rate of the excavated material. The owner established a goal that at least 85% of the material excavated be drawn into the pumping system.

- To maximize the recovery rate, the bucket wheel "cuts up" (rotates with the teeth pointing upwards). This puts extremely heavy and unusual loads on the bow gantry and forward part of the hull. These forces had to be considered during dredge design.

- The owner pre-selected a dredge pump which limited our freedom to optimize pumping system design. Additionally, due to the plant capacity, there was a maximum flow rate established of 1,700m3/hour. This became a limitation on reaching the Tons per Hour goal by simply increasing the flow rate.

- Having the electrically powered dredge operate reliably in temperatures up to 130 degrees F (54 C).

- The control system was required to communicate with the existing plant monitoring infrastructure and booster pump.

- Providing a superior coating system that would protect the dredge against corrosion from permanently working in a brine pond. The design of certain components was also modified to make them less prone to corrosion.

- Building the dredge and selecting components to meet hundreds of customer specifications which were based on Petrochemical Industry standards.

- The dredge was built in modules to facilitate inland shipment to the mine site which was over 100 kilometers from the nearest seaport. 28 trucks were required for inland transportation of this 605 ton dredge.

- As this was a turnkey project, Ellicott first assembled the dredge at its Baltimore facility, tested it, disassembled it, shipped it to the Saudi mine site, and was responsible for the complete re-assembly and launching.

EQUIPMENT SIZING

To ensure that Ellicott would meet the production requirements, a thorough sizing check was required for each of the production subsystems. The pump and excavator would not only need to meet the production target, but exceed it significantly for sustained periods. This would make up for time lost in tough areas near the bottom of the pond and the end points of the swing.

Pump Sizing

Pre-award calculations showed pump capacity for our selected model at Cv=0.25 (25% volumetric concentration, or "solids by volume") to be 1250 mton/hr – presumably adequate margin for success. Ellicott encountered a major challenge with approval of the dredge pump, however. While we were satisfied with the original set of pumping parameters, after award the customer made it clear that the dredge pump was already selected to match the existing booster pumps. This was a problem because the 12" x 14" (305 mm x 356 mm) gravel pump they wanted to use was undersized for the flow rate requirement.

To further complicate the matter, the gravel pump manufacturer had discontinued their 14" x 16" (356 mm x 406 mm) model in this series. Ellicott was prepared to use the 16" x 18" (406 mm x 457 mm) version, but the customer had concerns with flooding their plant. So given a minimum production requirement and a significant reduction in flow capacity, we were facing a significantly increased commercial risk.

Excavator Sizing

At the customer's request from past experience, Ellicott planned to use an existing bucket wheel design. This wheel was designed to be physically small to maximize cutting force, but this brought concerns about whether sufficient material could be acquired by the wheel as it traversed the cut. If this volumetric capacity was not greater than the pump capacity then it would limit overall performance. There also needed to be sufficient margin to allow some variation in the volume of material in the hopper at any given time. Too much material could create suction line clogs and shut down production altogether.

Finally, even with adequate pumping capacity and volumetric displacement capacity, the excavator also needed sufficient power to avoid being the limiting factor on production. The existing design was rated at 600 shp (450 kW) and it was considered impractical to redesign the structure for higher loading. We decided that the structure could handle no more than 5% over the design target but we needed to understand the capacity limit imposed by having 630 shp (450 kW) available to the excavator.

To quantify this power limit, we studied the strength and fracture characteristics of halite. We determined that Dr. Miedema's book *The Delft Sand, Clay & Rock Cutting Model* was an excellent resource, but we struggled to quantify the power calculations so we undertook a direct consultation. We provided the wheel design, material identification, and material strength specifications from the contract to Dr. Miedema.

PUMPING ANALYSIS

Design

Ellicott studied the process characteristics in advance of accepting the order. This was an important and interesting exercise that took us out of the norms of pumping calculations. The key factor that makes pumping halite unique is that the chemical basis, sodium chloride (salt), is water soluble. This fact makes calculation of solids content difficult, requiring a detailed understanding of definition of slurry concentration.

For example, an important equation for calculating the density of a typical sand slurry from its volumetric concentration:

$$SG_{slurry} = 1 + 1.65C_v \tag{1}$$

is dependent upon assumptions that the carrier fluid is water, the solids are silica, and that solubility is zero. With the subject dredge, while the carrier fluid remains water, the solubility of salt complicates that. So if we substitute the density of salt, 2.16, for the density of sand, 2.65, the following equation is misleading:

$$SG_{slurry} = 1 + 1.16C_v \tag{2}$$

as it would overestimate the solids content that is useful for the customer. If they had time for evaporation, this approach would eventually yield a good prediction of solids. In reality, any material that is not in gravel sized particles when it reaches the plant is returned to the ponds as brine. For our purposes, whatever returns to the pond cannot be considered solids, so we must consider it to be part of the carrier fluid.

So a better model for calculation is to treat the carrier fluid as a super-saturated brine and “solids” as the salt neither dissolved in solution nor suspended by the slurry. This requires using the more general form of the above equation.

$$SG_{slurry} = SG_{carrier} + C_v\,(SG_{solids} - SG_{carrier}) \tag{3}$$

It is tempting to assign an estimated brine SG as 1.20, the accepted density of a saturated brine solution. A thorough study reveals further complexity, however. A moving pipeline of slurry keeps small particles in suspension, not technically in solution. Experimentally, densities taken from the brine ponds yield values in the 1.22 to 1.23 range, but passing a slurry through four or five impellers and miles of pipeline pulverizes many of the particles and increases the solids that remain suspended. The plant separation wheel lets the smaller particles go back to pond, so a functional density for brine in this scenario is closer to 1.32 when fully considering these losses.

All of the above had significant influence over our ability to deliver tonnage of halite from the dredge to the plant, a key contractual obligation. Using this understanding, the original slurry density range from the specifications of 1.29 to 1.45 was thus found to be unrealistically low. A 1.29 SG salt slurry provided zero production. A 1.45 SG salt slurry only yields C_v=0.167, a 33% reduction from our pre-award capacity.

To achieve C_v=0.25 as intended, an *average* slurry SG of 1.52 would need to be maintained. For reference, this is a value higher than our typical threshold for *peak* density. To be able to absorb the extra material from a fully loaded excavator hopper, the pump would need to handle higher peak densities, likely 1.6 to 1.65. This concerned us as a major risk. It later turned out that slurry densities of 1.7 consistently clogged the discharge line, so the concern was valid: the solution space was very tightly constrained.

Contract

It turned out that 11,000 gpm (2500 m^3/hr) was too much flow for the customer’s plant to accept. Given our theoretical findings that the density range was unrealistically low, this limit further confirmed our production guarantee to be a serious risk.

It also turned out that the 12” x 14” gravel pump was properly sized for the system – the specifications were more flexible than the infrastructure. We were given a revised set of process requirements with flow rates in the 7000-8000 gpm (1600-1800 m^3/hr) range. To perform at these lower flow rates, not only would we need to maintain slurry densities of 1.5 to 1.6 as described above, but we would have to accept a lower peak production. At 7500 gpm (1700 m^3/hr), C_v=0.25 yields a pump capacity of only 850 mton/hr.

There were also other concerns with this pump selection for our dredge. NPSHr was dangerously low at the higher flow rates when the pump was near the surface. The power requirements with such a dense slurry were a concern. Dropping below critical velocities and clogging the pipeline was a particular worry since no empirically confirmed model for settling was readily available.

The end assessment was that the production results were still achievable, but the margin for error was very low. The minimum line speed concerns were discussed directly with the customer and they insisted this was not a problem. Ultimately Ellicott reconciled the customer's reported experience with a sliding flow regime (thanks to the WEDA pumping lectures of Dr. Miedema).

EXCAVATION ANALYSIS

Design

Power Consumption

The production estimation is carried out based on the book *The Delft Sand, Clay & Rock Cutting Model* of Miedema (2019). The book gives models for different types of soil to predict cutting forces, cutting power and specific energy. Specific energy is defined as the energy required to excavate 1 m^3 of soil, although this definition can be used for any material. So, the dimension of specific energy is kJ/m^3. It should be clear however that specific energy is not a pressure. For sand and clay kPa is used, but for rock like materials MPa is often used. The specific energy depends on the geometry and dimensions of the cutting tool and on the soil mechanical properties of the soil considered. The specific energy can be used for production estimation by dividing the installed cutter power by the specific energy. The result is the production in m^3/sec. Of course, the specific energy and the installed power should have similar dimensions, kPa and kW or MPa and MW.

In the case of pure ancient halite considered here, the rock model is assumed to be the closest to the halite behavior. The halite has UCS values of about 10 MPa for the first 8 meters and about 16 MPa for the next 2 meters. The tensile strength of the halite is unknown, but a ratio UCS to tensile strength of a factor above 8 is not uncommon. The internal and external friction angles are also unknown, so a default value of 20° for the internal friction angle φ is assumed, while for the external friction angle δ the rule $\delta=2/3\cdot\varphi$ is applied. These values are probably too high and will result in slightly underestimating the production.

Blade angles of 50° to 60° relative to the vertical are not uncommon in the dredging industry for cutter head and dredging wheels. In the examples 60° is chosen, not to overestimate the production. The installed power on the dredging wheel is 630 hp or 475 kW (0.475 MW).

Two failure mechanisms are possible. The Flow Type, which is shear failure. In the case of rock this is cataclastic shear and not plastic shear. The second possibility is the Tear Type which is failure based on tensile failure, resulting in big pieces of halite moving into the suction mouth.

Figure 1 shows the specific energy to UCS value ratio for the Flow Type as a function of the blade angle and the internal friction angle. Figure 2 shows the specific energy to tensile strength ratio in case of the Tear Type failure. Both specific energies should be determined, while the smaller of the two should be chosen. If this is the Flow Type then there is shear failure, if this is the Tear Type then there is tensile failure. First the production will be estimated assuming shear failure. ***Figure 1*** shows an E_{sp}/UCS ratio of about 0.7 giving a specific energy of 7 MPa for the 10 MPa halite and about 11 MPa for the 16 MPa halite. This results in productions of 0.475/7=0.068 m^3/sec (244 m^3/hr) for the 10 MPa halite and 0.475/11=0.043 m^3/sec (155 m^3/hr) for the 16 MPa halite. Choosing a 50° blade angle and a 5° internal friction angle results

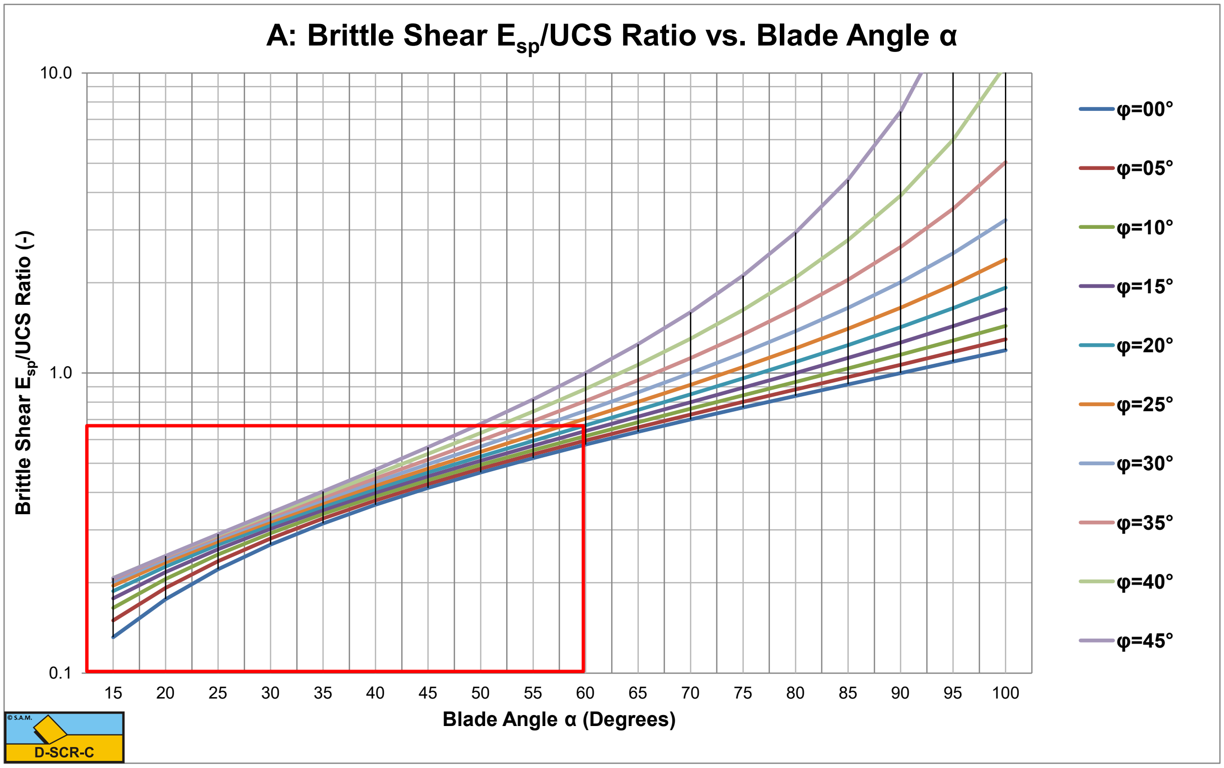

Figure 1. Specific energy to UCS value ratio.

in an Esp/UCS ratio of about 0.475, giving a specific energy of 4.75 MPa for the 10 MPa halite and 7.6 MPa for the 16 MPa halite. The resulting productions are now 0.1 m^3/sec (360 m^3/hr) and 0.063 m^3/sec (230 m^3/hr). These numbers give a lower limit to the production.

Next, in Figure 2 the specific energy to tensile strength ratio for the Tear Type as a function of the blade angle and the internal friction angle is shown. If a UCS to tensile strength ratio of 8 is assumed, and an Esp/σ_T of 4 is found from Figure 2, a specific energy of 5 MPa is found for the 10MPa halite and 8 MPa for the 16 MPa halite. This results in productions of 0.095 m^3/sec (342 m^3/hr) for the 10 MPa halite and 0.06 m^3/sec (214 m^3/hr) for the 16 MPa halite. Choosing a 50° blade angle and a 5° internal friction angle results in an Esp/ σ_T ratio of less than 2, giving productions of 0.19 m^3/sec (684 m^3/hr) for the 10 MPa halite and 0.12 m^3/sec (428 m^3/hr) for the 16 MPa halite.

For the cases considered the Tear Type gives the smallest specific energies and the highest productions. So, the expectation is tensile failure with big pieces of halite entering the suction mouth. For more accurate estimations, the internal friction angle and the tensile strength of the halite should be determined.

If we look in more detail at the failure mechanisms, Figure 3 and Figure 4 can be constructed. These figures show which failure mechanism we have. In reality there are not two, but 3 possible failure mechanisms. First of all, the Flow Type, based on shear failure, giving 100% shear failure. Secondly the Tear Type, based on tensile failure, giving 100% shear failure. The third mechanism is named the Chip Type, based on first some shear failure, followed by a tensile crack. The latter is the mechanism that most often occurs in dredging. The figures show that the larger the internal friction angle, the more probable the occurrence of the Chip Type, given UCS/BTS values from 5 to 10 for blade angles of 45 to 60 degrees. When the Chip Type occurs, the cutting forces and specific energy are close to the values found for the Tear Type.

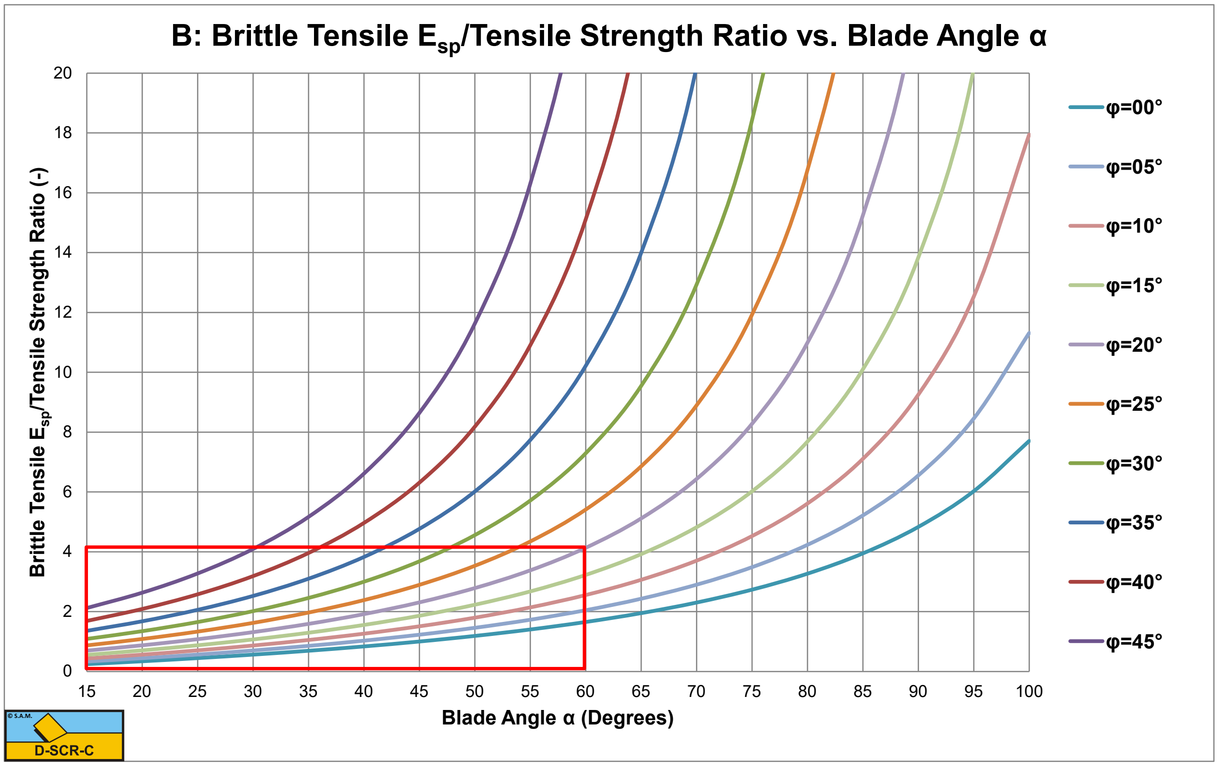

Figure 2. Specific energy to tensile strength ratio.

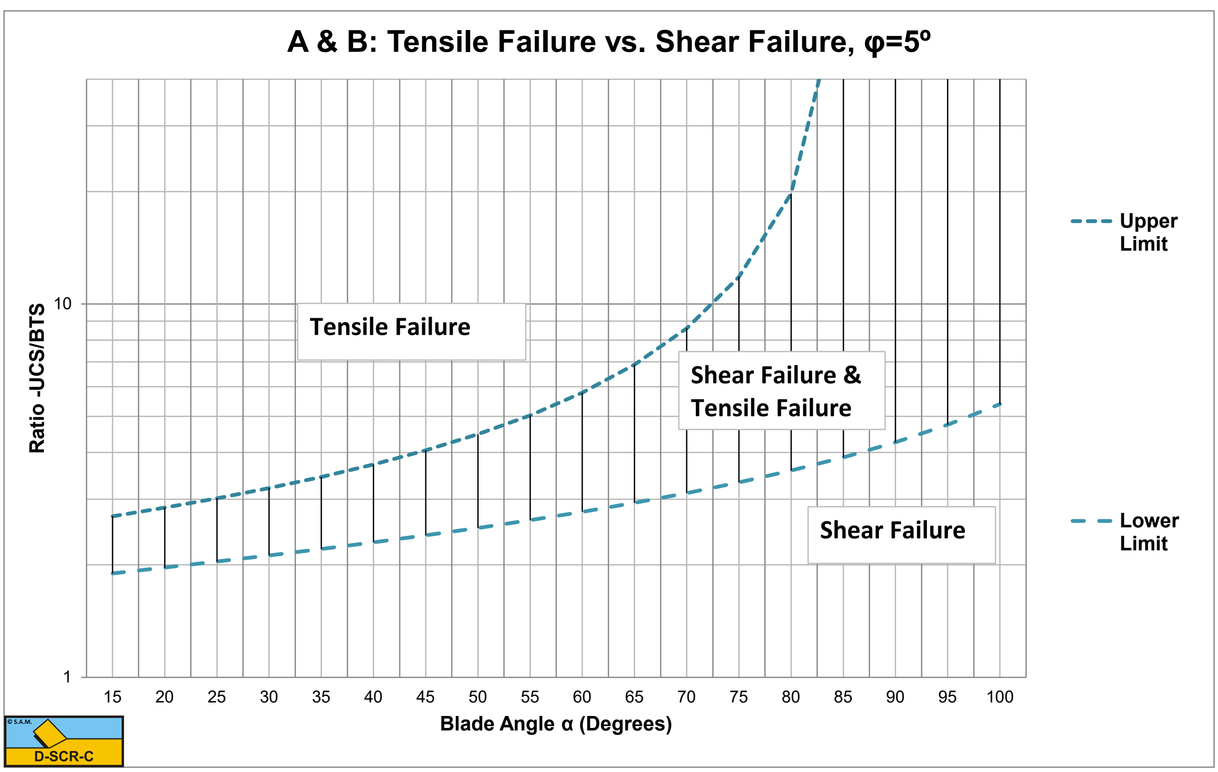

Figure 3.The possible cutting mechanisms for an internal friction angle of 5°.

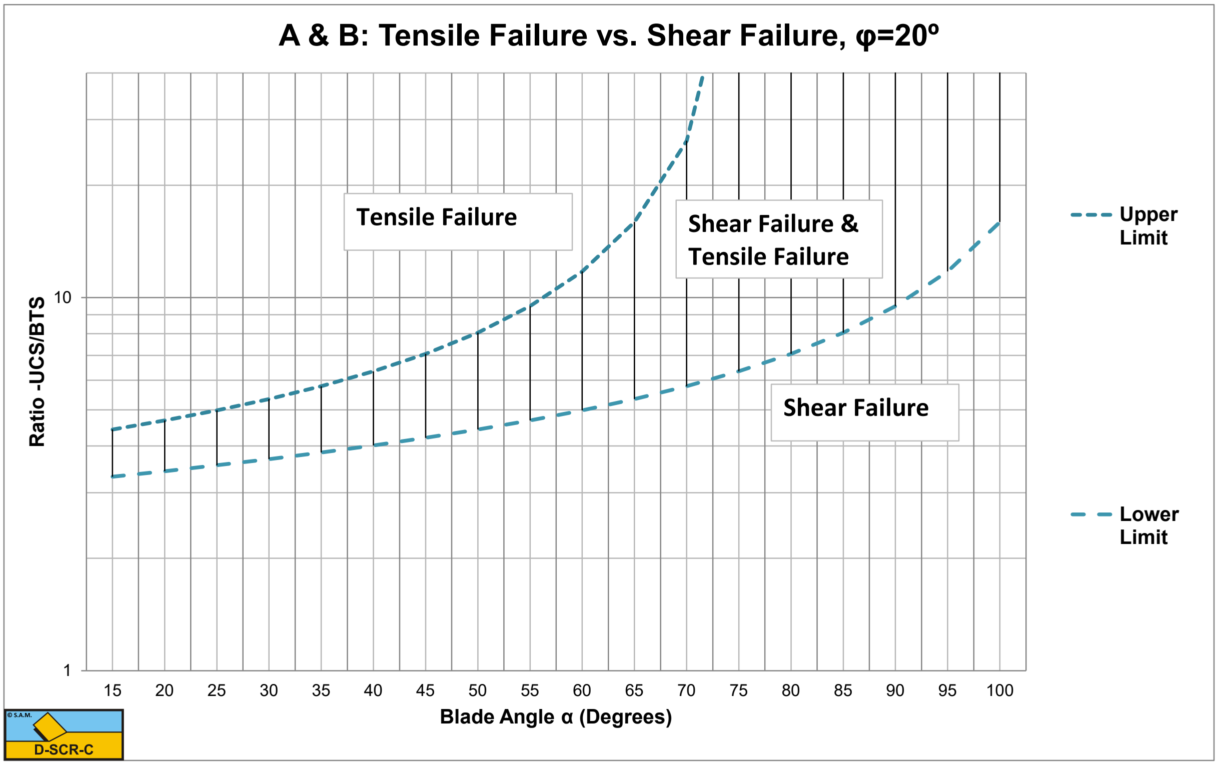

Figure 4. The possible cutting mechanisms for an internal friction angle of 20°.

Volumetric Limits

The volumetric capacity of the bucket wheel excavator was also a critical factor that required validation. The geometry of the wheel's cutting surfaces limits the cross section of material that the wheel can address in a single pass. The swing rate is also a limiting factor on volumetric capacity. The product of these values quantifies the maximum volumes that could be cut at full penetration and full speed. It is important to note that this is a solid material and "bulldozing" as if it were sand would likely lead to catastrophic failure in the ladder and/or trunnion structures.

Figure 5 shows cross sectional areas that were developed from the cutter geometry and anticipate a staggered cut strategy. Overlapping scallops or crescents characterize these cuts and we were able to use this approach to develop an average cross section across the full array of ladder angles necessary to ensure coverage up to full depth. We did not include overburden cuts in our assessment.

The resultant average cross section was taken at about 12 ft^2 (0.93 m^2) per pass. At swing speeds of 50 ft/min (15 m/min) this results in 600 ft^3/min (17 m^3/min) of volumetric material removal capacity. This equates to about 2000 mton/hr. Compared to 850 mton/hr capacity on the pump, this was an encouraging result, allowing freedom for shallower cuts, slower swing rates, or more variation in how full the hopper could be without creating suction clogs.

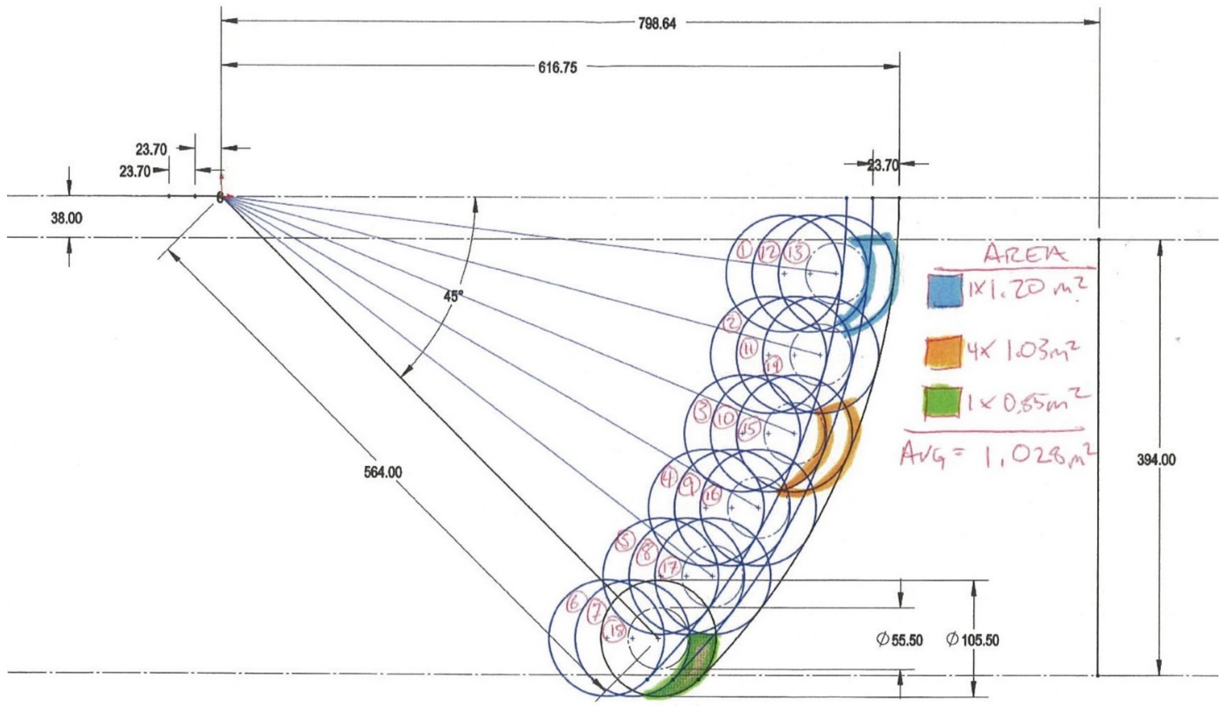

Figure 5. Analytical geometry underpinnings of volumetric capacity assessment

Modularity

The Ellicott bucket wheel excavator design is modular, allowing the cutting characteristics to be adjusted without changing the structure or the power train. This was an important factor in our acceptance of the performance guarantee as we knew it was possible to make improvements if necessary. For example, if findings in the field were that the wheel had inadequate power or volumetric capacity, new rim designs could be developed empirically and swapped out with existing rims.

Contract

Blasting

The contract called for the machine to perform to full capacity with "un-blasted" salt. The existing dredge required blasting with dynamite before cutting, so this was an important point to our customer as removal of the blasting step would lower cost.

Performance Guarantee

In addition to the many pumping concerns, the bucket excavator design added its own risks. Not only must it have sufficient volumetric and power capacities, but the hopper must be kept from overfilling to prevent plugging the suction line. So even a wheel with sufficient capacity would require careful tuning of wheel rotation and swing rate to sufficiently balance the pump and excavator throughput.

RESULTS

Production Guarantee

Ellicott was successful in meeting our production guarantee. In exchange for allowing post-award changes to the requirements, we were able to obtain forgiveness on the methods of measurement. This revised interpretation of our agreement essentially limited the sources of error to the capabilities of the pumping and excavation systems. Operator delays, scavenging losses, line losses, and other sources of productivity loss were eliminated from the measurement.

It should be noted that the customer had stated production requirements in excess of their actual plant capacity. Of course they did not expect to *pay* extra for that extra production, so a negotiated outcome was inevitable. The complexity of the subject matter and the nature of estimation made the negotiation difficult, but in the end the dredge was successful at meeting the customer's production needs.

Pumping

The pumping system performed better than anticipated. Slurry densities in excess of 1.6 turned out to be sustainable. Much of this benefit was due to a high risk tolerance for clogging the discharge pipe, allowing operators to push the productivity aggressively. When the line clogged, fresh water could be used to dissolve the clog. The customer's operation group was able to sustain lower line speeds than expected which provided a key improvement from expectations.

The consistency of excavation, likely due to the combination of: consistently hard material, the buffering effect of the excavator hopper, and the low line speeds in the discharge pipe, all contributed to a very stable slurry SG. That stability in turn allowed the process to run much closer to the natural limits of the slurry SG. That natural limit empirically proved to be about 1.7, a value we could exceed only slightly and for short periods of time without clogging.

Cavitation from higher flushing flow rates at shallow submersion and from suction pipe clogging were issues periodically, but did not hamper productivity once operational procedures were developed and maintained. While a suction relief valve was installed, clogs upstream of that valve occurred a few times during commissioning and training. These clogs caused sustained cavitation and were very difficult to resolve, but ultimately were not a persistent problem. They were symptomatic of excited operators running a new, more powerful excavator on *blasted* material and over-filling the hopper.

Cutting

The cutter performed as expected, but the material at the bottom of the pond was likely harder than stated in the specifications. Ultimately, the customer was so pleased with the machine's performance in blasted material that the performance in un-blasted material was not a driving factor in acceptance. Their productivity increase more than paid for the blasting.

While theory predicted that cutter power was the theoretical limit on production, we never reached that point in practice. The cutter, driven by a hydraulic motor, was never observed to stall in normal operation. Motor stall conditions were observed only when the excavator's *hub* was engaged in the material, and when major physical obstructions were present.

The pumping system capacity and volumetric excavation capacity also did not limit production, but in practice the constraint was volumetric. The customer chose to manage throughput by tuning the depth of penetration of the excavator into the material. Their rationale was not fully clear but was likely complex and based on numerous reasons such as plant requirements/limits, risk of clogging suction/discharge pipe, and comfort with the equipment response.

When the depth of penetration was high and the material was un-blasted, there were reasons for operator caution. The most interesting was when hard material resisted fracture and the bow of the dredge was drawn down in response. When the material broke free and the now excess buoyancy equalized, the movement challenged the secure footing of onboard personnel. There was also a persistent hammering vibration under such conditions that was outside of previous operator experience.

Vibration

The key lesson learned was related to the intensity and persistence of vibration. The cutting of un-blasted, high strength halite caused heavy vibration which increased with production volumes. Almost all fasteners subjected to these sustained conditions started to loosen. Regardless of motivation to intervene and retighten nuts and bolts, mechanically fastened joints became loose and the accompanying sounds were unsettling if not predictive of pending failures. Reduced penetration into the material was used as an effective means of reducing the magnitude of vibration. Eventually the customer decided to continue blasting the halite in advance of dredging.

Another major source of vibration was pump cavitation. While a pump can vibrate for many reasons, true cavitation in the NPSH3 range is distinct and of significant concern. The dredge design prevented all but minor cavitation events unless clogging was present near the suction mouth. Under clogged suction scenarios the cavitation was serious. The operators were less risk averse than we expected and preferred, and ran the cavitating pump for several minutes while attempting to free clogs by various methods other than manual cleaning. In the most extreme example, the expansion joint on the discharge elbow ruptured from excessive displacement.

There was also an interesting vibration problem in our hydraulic room as well, where 6 electric motors drove a variety of pumps. Ultimately solved by exchanging couplings, there were persistent low frequency rhythms of vibration that would crescendo and decay mysteriously, creating noise issues and shaking the whole dredge.

Finally, there was a surprising vibration set up in the sun shade from sustained winds. The corrugated roof panels, where not fastened in a proper lapping pattern, where subject to an extremely loud flapping which eventually caused failures of the metal roof panels in way of the hold-down fasteners. Also, the structure itself shifted persistently on its footings, eventually loosening joints to a dangerous extent.

CONCLUSIONS

There were several areas where we gained important direct experience with this application. The contract issues were instructional about this application, this customer, and the region to which we delivered the dredge. The detailed system sizing investigations followed by direct, hands-on feedback from commissioning and testing yielded numerous lessons. We also encountered driving issues that we did not anticipate, providing valuable experience which will bolster future product and further aid this customer in their halite mining activities.

REFERENCES

Miedema, S. A. (2014). *The Delft Sand, Clay & Rock Cutting Model*. Amsterdam: IOS Press.

CITATION

McTaggart, D., Miedema, S.A., and Quinn, P. “Salt Mining Dredge – Electric 1100 hp Ladder Pump with 94” Dual Wheel Excavator,” Proceedings of the Western Dredging Association Dredging Summit & Expo ‘21, Dredging: The Impact of Climate Change, June 15-17, 2021.

DATA AVAILABILITY

Some data, models, or code generated or used during the study are available from the authors.

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Utilization of Passive and Active Mechanical Dewatering Technologies to Process Navigational Dredged Material on a Small Footprint

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ABSTRACT

The Office of Maritime Resources (OMR) of the New Jersey Department of Transportation (NJDOT) is responsible for maintaining 200 nautical miles of shallow draft navigation channels statewide. The Shark River Channel and Spur and Shark River Bay, Monmouth County, New Jersey provide access for recreational and commercial marine traffic including commercial fishing. As is true along much of New Jersey's coastline, the bay's densely developed geography has made it very difficult to find a suitable location to manage dredged material. Maintenance dredging of the channels was last authorized by the U.S. Army Corps of Engineers (USACE) in 1985 and considered again in the late 1990s through the 2000s. However, the lack of an operationally sized dewatering space stalled the project for many years while local officials debated solutions. The landfall of Superstorm Sandy in the fall of 2012 caused sand, mud, and silt shoaling that severely impacted navigation and jeopardized the local economy, significantly increasing the pressure to find a solution. In January 2018, the project team completed the hydraulic dredging of 68,417 cubic yards (CY) of sediment from approximately 1.6 miles of the Shark River Channel and Spur. The project depth was 6.0 feet below mean low water, plus 1.0 foot of allowable overdredging. The dredging and dewatering operations occurred in three phases and included both passive (geobags) and active (hydrocyclones and belt filter presses) mechanical dewatering techniques. All sediment was or will be beneficially used for beach replenishment, daily landfill cover, or in a future shoreline stabilization project. This paper will review strategies used for dewatering, specific challenges addressed, costs, and how this project could be replicated for other projects in densely developed areas where traditional management methods are not viable.

Keywords: Dredging, dredged material management, mechanical dewatering, passive dewatering, beneficial use.

INTRODUCTION

The Shark River Bay is an 800-acre saltwater embayment on the Atlantic Coast of New Jersey in Monmouth County. It is almost completely surrounded by residential development and small scale commercial and recreational marine enterprises. The Shark River Channel and the Shark River Channel Spur are shallow draft navigation channels located in Belmar Borough and Neptune City, Neptune and Wall Townships. The channels provide access to the Atlantic Ocean via the Shark River Inlet. The U.S. Army Corps of Engineers (USACE) is responsible for the maintenance of

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the Shark River Inlet channel, whereas the New Jersey Department of Transportation's (NJDOT) Office of Maritime Resources (OMR) is responsible for the maintenance of the two State channels.

The Shark River Channel runs 6,400 linear feet from the Belmar Marina to Shark River Hills. The Shark River Spur channel provides an additional 2,300 linear feet along the Shark River Hills community (Figure 1). The design width of both channels is 100 feet with 3:1 side slopes. The permitted dredging template for this project was 6.0 feet below Mean Low Water (MLW) plus 1.0 foot of allowable over-depth. Surveys performed in December 2014 indicated that there were approximately 75,000 cubic yards (CY) of material in the Shark River Channel and 26,000 CY of material in the Spur Channel for a total of a little over 101,000 CY. It is of note that this compares to a total volume of 77,000 CY that was in the same channels just prior to Superstorm Sandy in the fall of 2012. Consequently, the Shark River channels project was considered a high priority in New Jersey's Superstorm Sandy recovery program.

Most dredging in the Atlantic shore region of New Jersey is performed via hydraulic cutterhead pipeline dredge and dewatered in confined disposal facilities (CDFs). Historically, a CDF in Wall Township had been used for maintenance dredging of these channels; however, the site was no longer available. In the 1990s, the Borough of Belmar had successfully performed maintenance dredging of their marina with mechanical equipment and dewatered the material in a gravel parking lot on their site. The small volume (less than 10,000 CY) of dredging required a very small footprint to dewater - less than an acre. However, the restoration of the State channels would require the dewatering and placement of over 100,000 CY of material. While the Federal inlet channel is mostly sand and can be placed in a nearshore berm for beach replenishment, the State channels are typically mixed sand and silt which are not suitable for beach placement. Several alternatives for dredged material management had been explored over the years, including ocean

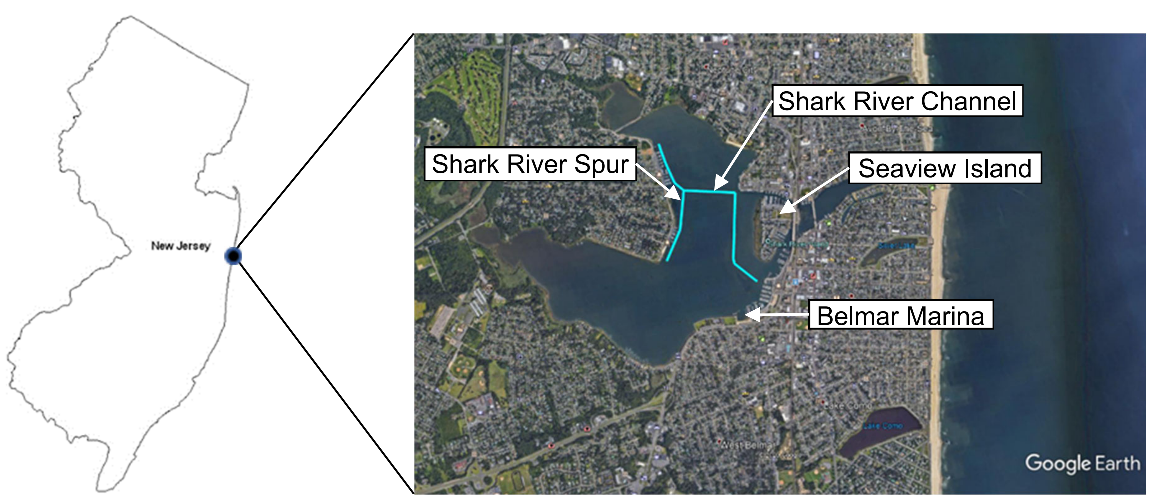

Figure 1. Site location of dredging project, Shark River Bay, Monmouth County, New Jersey.

disposal and upland placement following processing with Portland cement, but these were either prohibitively expensive, logistically impossible, or environmentally unacceptable. Consequently, maintenance dredging of the channels had not been performed since 1985 and navigation was becoming difficult, if not dangerous. The additional shoaling from Superstorm Sandy only made matters worse.

As the need to find solutions became critical, the NJDOT OMR took a hard look at alternative dredged material management options. No changes had occurred in the availability of the CDF, nor was ocean disposal any more practicable. The State of New Jersey has encouraged the use of dredged material in a variety of habitat restoration projects (Douglas *et al*., 2019); however, there were no potential projects in the area that would require the necessary volume. This left some type of upland processing and off-site placement as the only viable option. In general practice, there are three main categories of dewatering technology available: mechanical (both active and passive), chemical, and biological (Howard, 2019). Chemical and biological technologies are typically used in combination with other techniques or objectives or are used in the maintenance of disposal areas. Mechanical dewatering, using a combination of active and passive techniques, has been used successfully in both mechanical and hydraulic dredging operations of both clean and contaminated sediments (Averett and Estes, 2011). Given the time and equipment available, it was decided that either active or passive dewatering technologies had the potential to provide acceptable results at a reasonable cost.

The next challenge was finding a suitable site in the highly developed Shark River area. After evaluating several publicly owned sites with access to the waterfront, only two locations were deemed viable: a 1.3-acre gravel parking lot located in the Belmar Marina (905 NJ-35, Borough of Belmar, New Jersey) and a 2.5-acre public park located at Seaview Island (417 Seaview Circle, Township of Neptune, New Jersey). Further complicating matters, the dredging season in New Jersey is notoriously short due to permit restrictions and the long recreational boating season. All work would need to be conducted in the fall of any given year. While the placement of processed dredged material can often be problematic, Monmouth County was able and willing to accept the dewatered dredged material for landfill cover at their nearby waste recovery facility.

Due to the constraints of the project, it was decided that rather than specify a treatment train, OMR would evaluate proposals from contractors in a two-step process. A team of technical experts would evaluate the proposals and select the least cost option from among the acceptable proposals. Three proposals were received. All were considered technically acceptable. The contract was awarded to Mobile Dredging and Video Pipe of Chester, Pennsylvania on October 26, 2015.

METHODOLOGY

Sediment Characterization

A total of 14 vibracore samples were taken across the project footprint to characterize the sediments. These cores were combined into five composite samples for analysis. Semi-volatiles, pesticides, polychlorinated biphenyls (PCBs), metals, grain size, and total organic carbon were analyzed according to New Jersey Department of Environmental Protection (NJDEP) requirements using U.S. Environmental Protection Agency (USEPA) standard methods. The results of these analyses are presented in Table 1.

Table 1. Summary characterization of sediment dredged from Shark River channels.

Constituent	Composite A	Composite B	Composite C	Composite D	Composite E
% Sand	62.8	24.9	35.6	4.2	11.5
% Silt	23.7	60.8	48.5	76.4	68.6
% Clay	13.5	14.3	15.9	19.4	19.9
TOC (mg/kg)	12752	27511	23867	38509	35087
Benzo(a)pyrene (µg/kg)	370	<180	<180	<180	<180

The dredged material was a mixture of sand, silt, and clay, typical of maintenance dredged material in the area. The bulk sediment chemistry for four of the five composites were all below New Jersey Residential cleanup standards, meaning that it was considered suitable by the permitting agencies for most beneficial uses. Only a slight exceedance of the polycyclic aromatic hydrocarbon (PAH) benzo(a)pyrene was detected in one composite sample (New Jersey Residential criteria is 200 micrograms per kilogram [µg/kg]). This compound and level is typical for areas in the New Jersey coast with substantial recreational boat traffic. Given that the beneficial use identified was landfill daily cover, this was not considered a problem.

Treatment Bench Testing

To determine the proper geotextile to be used in the passive system, as well as to parameterize the mechanical dewatering equipment, a bench scale "bag" test was conducted on a sample of dredged material from the site. Results were used to set the polymer type and dosage and indicated that the treatment system would be able to achieve permit requirements (Table 2), although there was some concern about suspended solids. However, due to the small site, there was inadequate space for a final polishing tank large enough to be useful. It was decided that a turbidity curtain would be installed at the discharge point to capture any remaining solids.

Permit Conditions

Two of the primary constraints on the project from the beginning were the permit and site conditions imposed. In New Jersey, both State (NJDEP) and Federal (USACE) permits are

Table 2. Results of initial bench bag filter test.

Contaminant of Concern	Ambient Background	Bag Effluent
Total Suspended Solids mg/L	60	195
Hg (total/dissolved) mg/L	<0.00022/<0.001	<0.00022/<0.001
Cu (total/dissolved) mg/L	0.14/0.13	0.12/0.079
As (total/dissolved) mg/L	<0.015/<0.01	0.035/0.035
Total PCB (aroclors) µg/L	<0.5	<0.5
Total DDT µg/L	<0.1	<0.1
Chlordane µg/L	<2.0	<2.0

required for every dredging project. Both the State and Federal permits prohibited dredging from January 1 to June 30 of any given year to protect winter flounder and anadromous fish. In addition, the effluent was required to be monitored regularly for total and dissolved metals, pesticides, and PCB congeners in order to comply with a Total Maximum Daily Load agreement. A turbidity curtain was required to be installed at the discharge point to the bay to retain any solids that might be discharged during operations. Should effluent concentrations for any constituent exceed ambient background concentrations, adaptive management procedures up to and including cessation of operations were required. Although not a permit condition, the local community discouraged dredging operations between Memorial Day and Labor Day due to heavy recreational boat traffic. Channel closures to facilitate efficient dredging operations would not be allowed and move-on-demand procedures were required.

Dredging

The dredge plant used for the project was a Barracuda 12-inch by 10-inch cutter-suction dredge (12-inch intake pipe diameter, 10-inch discharge pipe diameter) with a draft of 32 inches (Figure 2). The rear spuds were 29 feet tall and the bow spud was 31 feet. The dredge was equipped with Dredge Pack®, two global positioning system (GPS) antennas, and an inclinometer. To verify stage, two tideboards were used; one mounted to a fixed structure near the dewatering sites and the other mounted on the dredge. Periodically, the shore crew read the tide board and communicated the reading via radio to the dredge to double-check the accuracy of the tide board located on the dredge.

Between 4,000 and 7,000 feet of 10-inch high-density polyethylene (HDPE) floating pipeline was used to convey the dredged material to the dewatering sites. In areas where the floating pipeline intersected a navigable channel, the pipeline was submerged and secured to the bottom of the

Figure 2. Barracuda 12-inch cutterhead pipeline dredge working in Shark River Bay.

channel using cement blocks and anchors. The floating portions of the pipeline were signed, marked, and lit according to U.S. Coast Guard (USCG) regulations.

Processing

Due to site availability, site size, and schedule constraints caused by environmental windows, the project was eventually broken into three phases. Both Phases I and II were planned to take place on the Belmar Marina parking lot site. The contracts for the project were not finalized until late October of year one, leaving insufficient time to mobilize, install, and test the originally proposed mechanical dewatering equipment. Geotextile bags, on the other hand, could be installed relatively quickly, allowing for several weeks of dredging in year one (Phase I) before the permit window closed on December 31. Once the bags were filled, the material would continue to dewater through the winter months and could be removed in the spring prior to the start of the next dredging season on June 30. During the second season (Phase II), it was believed there would be sufficient time to prepare the site, install and test the mechanical dewatering equipment, as well as complete the dredging. However, due to a government shutdown of transportation projects statewide, the mechanical dewatering did not begin until September 7, preventing the project from being completed before the start of the environmental window. The Belmar Marina parking lot was not available for a third season; but a second site, on nearby Seaview Island, was available. For a variety of reasons including schedule, cost, and proximity to residents, it was decided to use geosynthetic bags to dewater the remaining material in the channels during Phase III.

Passive Dewatering System

A system comprised of TenCate GT500 geosynthetic bags (TenCate Geosynthetics Americas, Pendergrass, Georgia) were utilized for passive dewatering in Phases I and III. An effluent containment area was created by installing a geotextile fabric surrounded by hay bales. A plastic liner was then placed over the geotextile fabric and the hay bales. Rebar stakes were driven through the hay bales to anchor the system in place.

Both sites were graded to ensure positive drainage to one corner of the containment area. A sump hole was constructed at this low point to allow for the placement of a pump which was used to discharge water back to the bay. As required by the permit, the discharge point was surrounded with turbidity curtain to retain any solids that might be lost during operation.

For Phase I, seven 40-foot by 100-foot geotubes were arranged in a single layer within the containment area and connected by a manifold. A pump and a polymer tank were installed in the northwest corner of the site. (Figure 3). The polymer used was SNF Polymer 331 (SNF Holding Company, Riceboro, Georgia). A dosage rate up to a maximum of four pounds per dry ton was used depending on the drainage efficiency or appearance of the discharge.

For Phase III, 18 geosynthetic tubes of various sizes were arranged in three layers with 10 tubes in the first layer, seven tubes in the second layer and one tube in the third layer. The tubes were sized to maximize the available footprint; ranging in width from 60 to 80 feet and in length from 72 to 256 feet. A polymer tank and pump were installed in the southeast corner of the site. A 10-inch non-nuclear density meter was installed on the system's intake pipeline to monitor the solids

Figure 3. Site layout and photograph of Phase I passive dewatering system

content of the dredge slurry and allow for adjustments in polymer dosage (Figure 4). Polymer (SNF Polymer #3310) dosage rate was adjusted as in Phase I up to a maximum of 4.0 pounds per dry ton. Polymer dosage was doubled and allowed to age for 45 minutes prior to addition at the end of October in order to improve the performance of the system. The discharge point for Phase III was under the Route 35 bridge. As in Phase I, the discharge point was surrounded by a turbidity curtain to retain any solids that might be lost during operation.

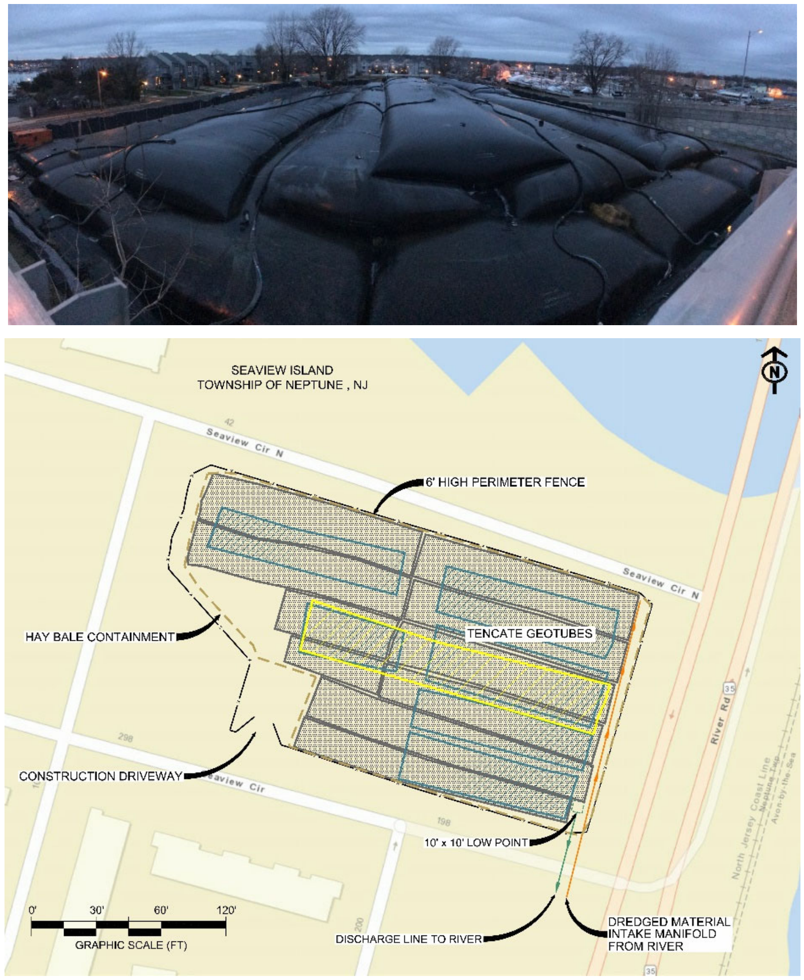

Figure 4. Site layout and photograph of Phase III passive dewatering system

Once the geosynthetic tubes were filled and dredging operations ceased, the tubes were left to dewater in place. The sump was observed daily until discharge ceased approximately eight weeks later. The length of this time period was impacted by weather conditions such as freezing temperatures, and significant snow and rainfall. Material condition was observed through portals on the top of each tube. Once the material was considered suitably dewatered, the tubes were cut open and the material loaded into trucks for transport to the Monmouth County Reclamation Center (MCRC) landfill.

Active Dewatering System

Following the removal of the dewatered sediment from Phase I, the entire parking lot was cleared and paved to ensure a stable and level surface for the equipment and to facilitate storage and transportation of the processed sediment. An active mechanical dewatering system comprised of hydrocyclones and belt filter presses was used during Phase II of the project (Figure 5). The dredged material slurry entered two hydrocyclone tanks (Tri-flow #1 and Tri-flow #2), which

Figure 5. Photograph and equipment layout for active dewatering system used in Phase II.

separated the debris and coarse material (sand) from the slurry using shaker screens. Sand and debris were removed to a stockpile area. The effluent from the tanks, now consisting of water and fine material (silt and clay), was pumped from the Tri-flow tanks into a thickener tank. As the thickener tank filled, the fine material settled to the bottom of the tank. The overlying clean water was then pumped back to the Bay at the discharge point, using the same pipe as was used in Phase I. As with the passive system, the discharge point was surrounded with a turbidity curtain to contain any solids that might be lost during operation.

The fine material that collected at the bottom of the thickener tank was pumped into the mixing tank where polymer (SNF polymer #3310) was added. This tank kept the articles in suspension before being pumped to the belt presses. The belt presses processed the fine material into the form of dry layer cake (Figure 6). The polymer mix ratio was adjusted as needed to ensure that the desired filter cake was achieved up to a maximum of two pounds per dry ton. Throughout the first few weeks of Phase II dredging operations, belt presses were added and replaced as needed. The

Figure 6. Filter cake from belt filter presses used in Phase II.

project started with five belt presses, but as many as eight large belt presses were used to provide redundancy and maintain production.

The filtrate from the belt presses was then pumped to a clarifier tank where additional time was allowed for solids not processed by the system to settle out prior to discharge. As fine material accumulated in the clarifier, the sediment was recovered and pumped back to the mixing tank to be processed by the belt presses.

The low point of the dewatering site was located behind the belt presses. If at any time the collection pans under the belt presses overflowed, the water pooled in the low point where it was pumped into the thickener tank via a small sump pump. Material from the hydrocyclones and belt filter presses was allowed to accumulate on the paved apron and periodically removed using a bucket loader. The material was segregated by type in the stockpile area prior to loading and transport to the landfill. Transport operations were essentially concurrent with processing for the duration of Phase II.

Sampling and Testing

During all three Phases, water samples were taken periodically to evaluate system performance and to comply with permit conditions. During each event, samples were taken from the effluent stream and at the discharge point to the Bay, inside the turbidity curtain. An ambient sample was taken from the crew boat, in the general location of the dredge plant, but outside of the work area to avoid the plume of resuspended dredged material from the operation. Samples were analyzed by a New Jersey certified laboratory for total suspended solids, total and dissolved metals, pesticides, and PCB congeners (due to the short processing period, congener sampling was not performed during Phase I). Unfortunately, these results often took considerable time to obtain, making the data difficult to use for adaptive management purposes. Consequently, adjustments to the system were made based on visual observation of the effluent plume at the point of discharge.

Beneficial Use

Most of the dredged material, once dewatered, was placed into triaxle trucks for transport to the MCRC, located about 9.0 miles away in Tinton Falls, New Jersey, where it was utilized as daily landfill cover. The scales located at MCRC were used to track the tonnage of dredged material being delivered. A small amount of sandy material from Phase II was used to replenish the nearby public beach at Memorial Park in Neptune City.

RESULTS

Phase I Dredging and Dewatering

A total of 4,011 CY of sediment was removed from the channels during Phase I over 15 dredging days and placed into geotextile bags. Once filled, the geosynthetic bags were left to dewater for 171 days. Starting on June 7, the bags were cut open, and the material was excavated. A total of 4,830 tons of material was transported to MCRC in 182 trucks over seven days (Table 3).

Phase II Dredging and Dewatering

A total of 43,798 CY of material was removed from the channels during Phase II over 69 dredging days and dewatered using the active mechanical dewatering plant. A total of 46,888 tons of material was transported to MCRC in 1,816 trucks over the course of 78 days (Table 3). Concurrent with this operation, an additional 25 truckloads, carrying approximately 658 tons of sand were taken to the Memorial Park public beach in Neptune City and graded into place for replenishment. The recovered debris was trucked to MCRC and disposed of as solid waste.

Phase III Dredging and Dewatering

A total of 20,608 CY of sediment was removed from the channels during Phase III over 49 dredging days and placed into geotextile bags. Once filled, the bags were left to dewater for 260 days. Starting on June 18, the bags were cut open, and the material was excavated. A total of 12,048 tons of material was transported to MCRC in 472 trucks over 18 days (Table 3).

Approximately 11,000 CY of dredged material was stockpiled on the eastern half of the dewatering site for Neptune Township's future use. The stockpile was graded to 5.0 to 6.0 feet high with a gradual slope and 3:1 side slopes. A total of 142 loads of topsoil was applied to the entire site and a Tall Fescue Grass Seed Blend was applied to prevent erosion while awaiting beneficial use in a future shoreline restoration project.

Table 3. Project Detail Summary

	Phase I	Phase II	Phase III
Mobilization Start Date	11/30/2015	6/16/2016	7/28/2017
Dredging Start Date	12/18/2015	9/7/2016	9/21/2017
Transport End Date	6/7/2016	1/4/2017	7/13/2018
Phase End Date	6/15/2016	2/2/2017	11/2/2018
Sediment Volume (cy)	4,011	43,798	20,608
Dredging Days	15	69	49
Process Days	171	69	260
Transport Days	7	78	18

Chemical Monitoring

Due to historical water quality problems in the shallow system of Shark River Bay, the NJDEP had established a Total Maximum Daily Load program for the entire bay. This meant that the project could not be a significant contributor of several parameters of concern. Monitoring was conducted by taking samples of the effluent, at the point of discharge inside the turbidity curtain, and of the ambient bay water. While total suspended solids ranged widely from 15 to 713 milligrams per liter (mg/L) (Figure 7), and Total PCB congeners ranged from 24.5 to 74,200 picograms per liter (pg/L) in the effluent (Figure 8), overall the concentrations of both parameters at the point of discharge were very similar to or lower than background. Concentrations of other parameters of interest, such as copper (Cu), arsenic (As), mercury (Hg), Dichlorodiphenyltrichloroethane (DDT), and chlordane, were typically at or below detection.

DISCUSSION

Dredging

A total of 68,417 CY of sediment was dredged from the channels using a hydraulic cutterhead pipeline dredge with minimal over-dredging for a period of 222 calendar days (133 dredging days) over three dredging seasons, averaging 514 CY per dredging day. This is typical of maintenance dredging projects in coastal New Jersey, indicating that the treatment systems were not an impediment to efficient dredging operations. A total of 52,492 CY of sediment was removed from the Shark River channel and 15,925 CY was removed from the Shark River Spur channel. Both channels achieved the design depth of at least 6.0 feet and the design width of 100 feet.

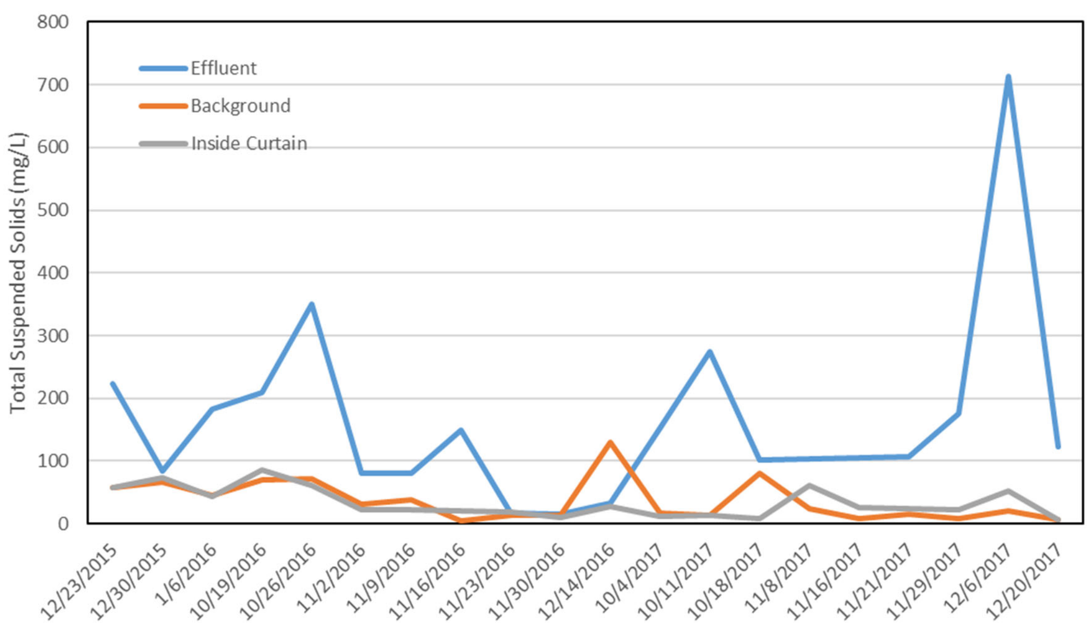

Figure 7. Summary of Total Suspended Solids in discharge from dewatering system as compared to site background and inside the discharge curtain.

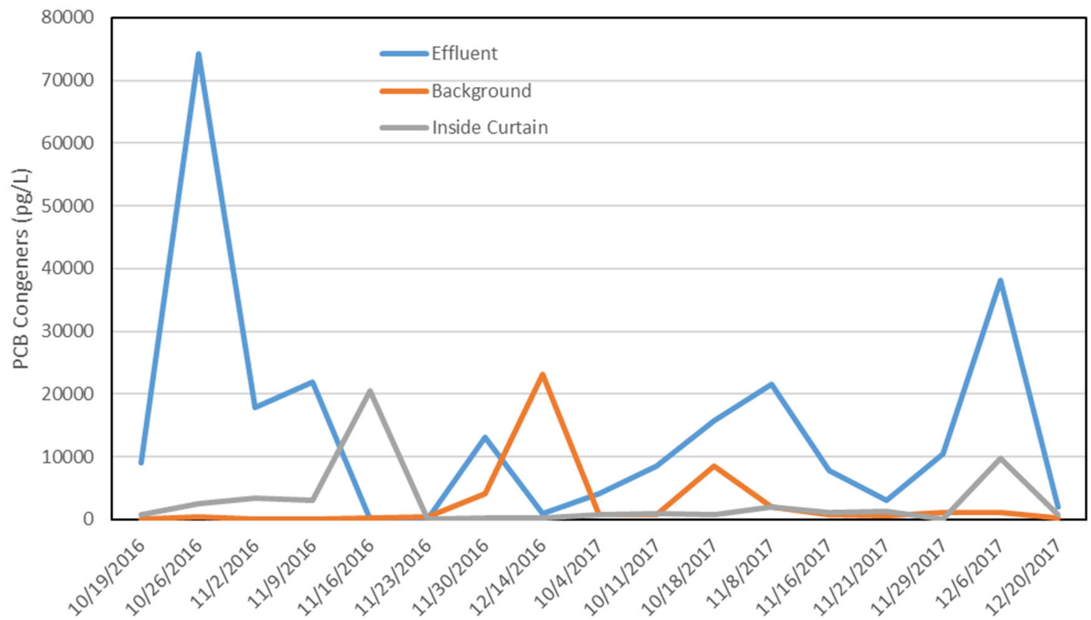

Figure 8. Summary of Total PCB Congeners in discharge from dewatering system as compared to project background and at the point of discharge during Phase II and III.

Processing

A total of 24,618 CY of material was dewatered and transported for beneficial use using TenCate geotextile bags over a period of 456 days (two phases). The time for processing material in this manner is divided into three phases: the loading of the geosynthetic bags, the dewatering period, and the unloading of the bags followed by transport. A total of 43,798 CY of material was dewatered using active mechanical dewatering equipment and transported for beneficial use over a period of 105 days. Transport of dewatered material was essentially concurrent with processing.

The typical rate of dredging for small hydraulic cutterhead dredges in coastal New Jersey, assuming an efficiency of 50 percent, is about 500 CY per day. During this project, dredging ranged from 267 CY per day to 421 CY per day when using geosynthetic tubes for processing, and 635 CY per day when using the belt filter presses for processing. The time required for passive dewatering did not impact the dredge plant in this case but could cause a problem if there was insufficient space for more or larger bags to accommodate a longer dredging period or faster dredge rate, or if the space was only available for a limited time.

Beneficial Use

A total of 63,767 tons of dewatered dredged material was taken to the Monmouth County Reclamation Center for use as daily cover and a total of 658 tons of sand was taken to the beach at Memorial Park in Neptune City. In addition, approximately 11,000 CY of dewatered dredged material was left on Seaview Island for future use by Neptune Township.

Discharge Quality

One of the challenges associated with using mechanical dewatering during a navigational dredging project is being able to synchronize the dredging and processing. On a small footprint, not only must the processing system be sized to the site rather than the maximum production rate of the dredge, there is no room for surge storage to allow for adjustments in the treatment train. Thickening of the sediment to facilitate flocculation and retention of solids is highly dependent on pH, temperature, percentage solids in the dredge slurry, organic matter (TOC), and grain size (Howard, 2019), all of which are notoriously variable in navigational dredging. This required the operator to continuously monitor the discharge quality and make adjustments on the fly, and these adjustments took time to take effect. Changes to the process treatment train included increasing the size of process tanks, reprocessing some portion of the effluent, changes in polymer dosage, or diverting material through a longer or shorter portion of the train. Consequently, the discharge was not consistently free of solids. It should be noted that additional sediment sampling in advance of dredging, while not required for permitting, may have assisted the contractor in planning for this variability. In this case, a turbidity curtain was deployed at the discharge to serve as a final clarifier and to capture any unretained solids during system adjustments. A small dredge was deployed to remove any solids that built up inside the turbidity curtained area of the marina; however, the amount of dredging required here was very small, less than 1200 CY, and this volume likely includes material that was already present in the berth.

Since the material contained relatively low levels of contamination, the use of the turbidity curtain as a clarifier was seen as a necessary sacrifice to allowing the dredging project to move forward efficiently. With more contaminated sediment, this may not be a viable option. In this case, despite effluent quality being variable, samples of the water just inside the turbidity curtain revealed that there was likely no increase in concentrations of contaminants of concern relative to ambient concentrations in the bay. In fact, ambient bay concentrations were often higher than those near the discharge point for TSS and PCB congers (Figures 7 and 8). While this does mean that water quality in this shallow bay continues to suffer from ongoing sources of contamination (primarily stormwater), there is no evidence that the project impacted water quality.

Weather Delays

Considerable difficulty was experienced with both types of equipment due to cold weather. While the permit restrictions prohibited in water work after December 31 (a nine-day work extension was granted in Phase I), work was significantly curtailed in all three phases as the weather became colder. Freezing conditions resulted in mechanical difficulties and reduced the drainage efficiency of the geosynthetic tubes. Cold weather has been shown in other projects to affect project schedules and dewatering efficiency (Howard, 2019).

Small Footprint

Working on the small footprints of the two sites, as well as scheduling constraints, proved to be the greatest challenges faced by the project team. With limited sites available, and other uses being prevented during site occupancy, there was considerable pressure to complete the project as rapidly as possible. As it was, both sites had to be utilized despite the additional site preparation time and alternating techniques that were required. Proximity to local residences and working within an operating marina also required sensitivity and flexibility on the part of the contractor. In addition to noise and light concerns, limiting night-time operations; additional public scrutiny meant strict attention to the appearance of the site and maintenance of site screening. Truck traffic was carefully monitored and street cleaning was required to keep sediment off the roadways.

Operationally, there was limited room for keeping redundant equipment or moving components of these complex treatment systems. There was also no room for additional holding space of effluent to allow for reprocessing should the system not achieve performance specifications or permit requirements. The large amount of sediment processed in Phase III required that geosynthetic tubes be stacked. While this is considered an appropriate way to increase field capacity according to the manufacturer, it does increase on-site logistical and safety concerns as well as increasing the difficulty in monitoring material status and when removing the sediment once dewatered.

Schedule

The project duration of slightly more than three years is not indicative of the number of actual dredging/processing days due to the highly restrictive work windows allowed by the dredging permit. Dredging was prohibited by permit between January 1 and June 30. In addition, the high recreational boating traffic in the Shark River Bay from Memorial Day to Labor Day makes maintenance operations challenging, if not dangerous. Consequently, dredging operations were limited to the last four months of the year. The actual number of dredging days for the entire project was 133; the number of dewatering days was 509, and the number of days for transporting material was 103. For Phase I and III, the dredging and dewatering initially occurred simultaneously, but dewatering continued for a considerable period after dredging ceased. For Phase II, dewatering and transportation were concurrent with dredging. Taking all of this into consideration, the dredging, processing, and placement of 68,417 CY took a total of 561 days over the course of three years between December of 2015 and November of 2018.

Cost

The cost of the project was relatively high for shallow draft navigation, with a combined per CY price of $107.61. The unit cost for Phase I was $113.00, for Phase II was $98.00, and for Phase III was $127.00. This does not include the cost of transportation of the material to the beneficial use site, which was provided courtesy of Monmouth County in exchange for the material. However, the cost does reflect the need for three mobilizations. Although Phase I and Phase II utilized the same footprint, the treatment techniques were different and required completely different equipment and use of the site.

SUMMARY

- Both active and passive mechanical dewatering techniques can be utilized in a navigational dredging contract on a small footprint in close proximity to residences.
- Episodic reductions in dredge efficiency should be anticipated, but overall project efficiencies were not significantly impacted.
- Experience and familiarization with the equipment and treatment is essential.
- In preparation for adjustments in treatment train, redundant equipment may be stored off-site.
- Additional sampling of the sediment beyond what is required by permitting agencies may help to prepare for changes in sediment characteristics over the course of the project.
- Turbidity curtains can be used to increase the footprint of the treatment train, provided the material being dredged is essentially free of contaminants.
- Weather delays can be significant
- Careful attention to housekeeping, noise, and truck traffic management are required.

REFERENCES

Averett, DE and TJ Estes. 2011. "Physical separation process demonstrations," ERDC TN-DOER-T10. Dredging Operations and Environmental Research Program, US Army Corps of Engineers, Vicksburg, MS.

Douglas, WS, MJ Marano, S Flanigan, D Fanz, and S Mars. 2019. "Ensuring sustainable marine transportation by beneficially using dredged material to support marsh ecosystems in coastal New Jersey" *Proceedings of the Western Dredging Association Dredging Summit & Expo '19, Chicago, IL, USA*, June 4-7, 2019.

Howard, E. 2019. "Stabilization of dredged materials in Ohio: an investigation of mechanical, chemical and biological dewatering techniques." University of Akron, Akron, OH.

HOW MUCH IS TOO MUCH? SAMPLING DENSITY IN STRATIFIED SEDIMENT BEDFORMS FOR ESTIMATING SURFACE-AREA WEIGHED AVERAGE CONCENTRATIONS

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ABSTRACT

Supplemental Remedial Investigations and Feasibility Studies (SRI/FS) are being conducted for Operable Unit 5 of the Allied Paper, Inc./Portage Creek/Kalamazoo River Superfund site, namely the Kalamazoo River in Kalamazoo and Allegan Counties, Michigan. Sediment sampling for the SRI/FS has been completed for Area 5, a 9.1-mile stretch of the Kalamazoo River. To efficiently cover this large reach of river, an innovative and cost-effective stratified, random sampling design was developed based on results of field reconnaissance. The sampling design provided an appropriate sample density in coarse-grained sediment bedforms (one strata) and in fine-grained sediment bedforms (the second strata). Sample results were used to develop surface-area weighted average concentrations (SWACs) which relate to fish exposures and tissue recovery time projections performed as part of the FS. This study aimed to evaluate the sediment sampling results and to assess the value of the stratified sample design using river bedforms. The sample design was based on the conceptual site model (CSM) developed as part of two field reconnaissance activities. Reconnaissance activities included collection of high resolution topographic/bathymetric data, sediment thickness, sediment particle size distributions, and polychlorinated biphenyl (PCB) concentrations in standardized depth intervals in a limited number of sediment cores. Sediment bedforms were mapped using the topographic/bathymetric surface and geomorphological/fluvial properties. The bedforms were grouped into two categories based on multivariate statistical evaluations of the physical data collected during field reconnaissance. Group 1 bedforms consisted of higher-energy environments with coarser gradations and thinner sediment, while Group 2 bedforms were in more depositional environments with finer gradations and thicker sediment. Phase I sediment core sample densities were determined based on observed PCB variability within each bedform group plus additional samples as a safety factor. Evaluation of PCB concentration distributions by sediment bedform group showed two dramatically different populations. While bedform groups were defined by physical characteristics, PCB concentrations in Group 2 bedforms were typically greater and more variable than those in Group 1. SWACs and upper confidence limits (UCLs) were calculated using the bedform groups for three geomorphologically defined river sections. An evaluation on the SWAC and 95% UCL was performed to test if fewer samples could be collected in the future to arrive at approximately the same SWAC and UCL. The evaluation showed that, in general, reasonable estimates of SWAC and UCL could be estimated with 40% fewer samples such that large safety factors on the sample count were not necessary.

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Keywords: Geomorphology, sample design, multivariate statistics, cluster analysis, contaminated sediment.

BACKGROUND

A Supplemental Remedial Investigation (SRI) is being conducted for Area 5 of Operable Unit 5 (OU5) of the Allied Paper, Inc./Portage Creek/ Kalamazoo River Superfund Site (Site) in Kalamazoo and Allegan Counties of southwest Michigan. Area 5 is an approximately 9.1-mile stretch of river (Figure 1). The SRI presents the nature and extent of polychlorinated biphenyl (PCB) concentrations within sediments and floodplain soils along Area 5. Sediment and soil samples were collected during multiple field events, including a Reconnaissance I (Recon I), Reconnaissance II (Recon II), Phase I and Phase II. Data collected during these events included high-resolution topography/bathymetry data using Light Detection and Ranging (LiDAR) and multibeam sonar, total Aroclor PCB concentrations, and particle size distributions using sieve analysis and Sediment Imaging (SedImaging). Analytical data were reported using standardized depth intervals: Interval 1 from 0 to 6 inches, Interval 2 from 6 to 12 inches, Interval 3 from 12 to 24 inches, continuing in 12-inch intervals.

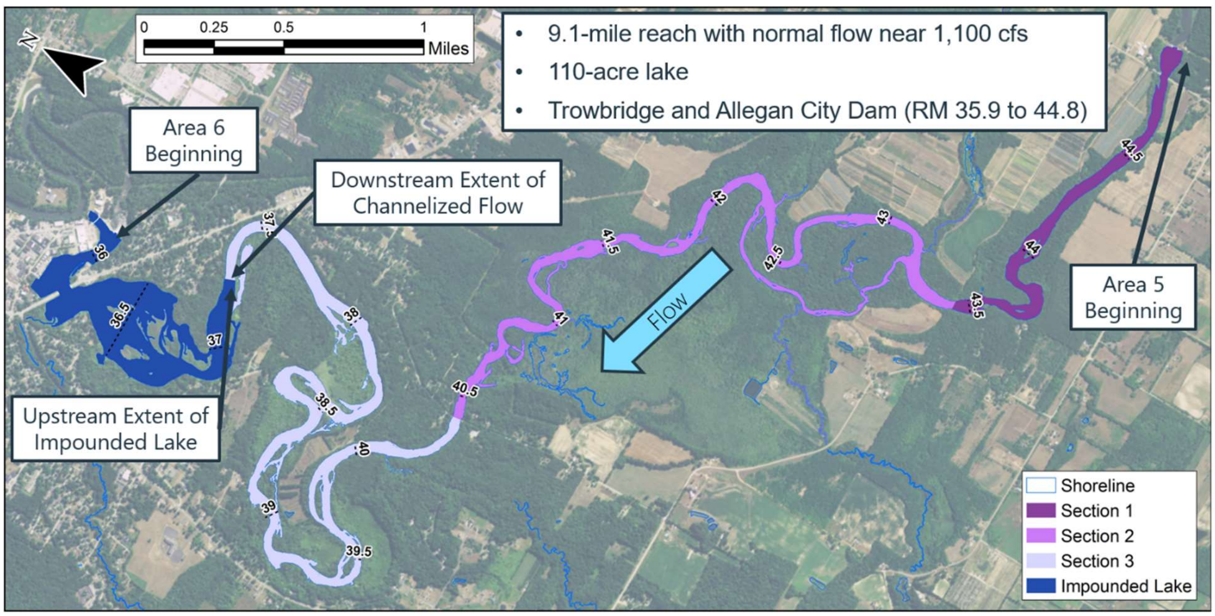

Figure 1. Map of Area 5 of the Kalamazoo River.

Area 5 can be conceptualized as two regimes: a free-flowing channelized flow regime from approximately RMs 37.25-44.9 (referred to as channelized flow), and an impounded regime from approximately RMs 35.9–37.25 (referred to as the impounded lake). The channelized flow regime is divided into three sections based on changes in geomorphology and water level gradient.

An innovative and cost-effective stratified, random sampling design was developed for Phase I and Phase II based on the conceptual site model (CSM) developed as part of the two field reconnaissance events. The CSM for Area 5 indicates that PCB contaminants tend to be associated with organics bound to fine-grained sediments. PCB concentrations are often low in coarse-grained sediments, whereas concentrations tend to be more variable in fine-grained sediments. The sampling design provided an appropriate sample density in coarse-grained sediment bedforms (one strata) and in fine-grained sediment bedforms (the second strata) while reducing potential data gaps that would likely arise with more traditional approaches. This study aimed to evaluate the sediment sampling results and to assess the value of the optimized stratified sample design using river bedforms. The following sections provide the methods and statistical evaluations towards development of the Phase I sample design.

BEDFORM MAPPING

Bedform mapping was completed primarily with the high-resolution digital elevation model (DEM) representing the bare earth topography and bathymetry and other derived terrain features. The DEM was created using LiDAR and multibeam sonar clipped to the extent of the river shoreline, yielding a bathymetry-only raster. Areas of similar bathymetry and riverbed characteristics were grouped into bedform classifications. Guidance for the bedform mapping was provided by Malmon et al. (2017), Merwade (2017), and Richardson et al. (2017).

Terrain Features

Terrain features were generated from bathymetry data using Spatial Analyst Tools in ArcToolbox (ArcGIS 10.3, ESRI). Seven lines of evidence were used to map bedforms:

1. Bathymetry – riverbed elevations (Area 5 LiDAR/multi-beam sonar results)
2. Elevation contours – riverbed topography, 1-foot (ft) contour interval
3. Water depth – feet (ft) below water surface, measured Nov. 11, 2016; LiDAR water surface minus DEM elevation
4. Slope – first derivative of a surface (bathymetry); related to rate of movement downhill
5. Curvature – second derivative of a surface (bathymetry); related to rate of acceleration downhill
6. Aspect – cardinal direction/orientation of a plane, defined by azimuth (0 to 360 degrees) of the face of a plane
7. Hillshade – artificial shadowing on bathymetry from a predefined orientation of a light source

Bedform Classification

Bedforms were manually drawn in ArcMap by subdividing riverbed surface within the shoreline, based on clear boundaries evident in the terrain feature maps. Bedforms were classified as one of the following:

- **Anabranch** – stable side channel within channelized flow of the river; may occur in areas with split thalweg
- **Anthropogenic** – human-influenced regions, often due to dams or bridges
- **Backwater** – stagnant or slowly flowing water; may be drainage/tributary feature; thalweg not adjacent to feature
- **Glide** – areas of shallow positive slope leading out of a pool and into a riffle
- **Island** – generally above water except during high river stage events; may be formed by sediment deposition or through river erosion around hard bed features
- **Mouth bar** – geomorphic feature of river deltas, bar feature in impoundment
- **Oxbow** – geomorphic feature of meandering, channelized flow; a meander can become so curved that the river meets itself and creates a faster flow path via avulsion
- **Plane bed** – hydrodynamically uniform region based on river velocity, depth, and sediment size; bathymetry is relatively flat.
- **Point bar** – geomorphic feature of meandering channelized flow; commonly on the inside of a meander bend (lower velocity, shallower water depth)
- **Pool** – areas of both negative and positive slopes, meeting at zero slope point where the river's deepest water is located
- **Riffle** – areas of steeper, generally negative slope and shallower water depth with a rough substrate; occurs immediately downstream of glide

- **Ripple marks** – visibly rippled/wavy region of sediment based on river velocity, depth, and sediment size
- **Run** – areas of slightly negative slope and deeper water depth leading into a pool
- **Scour trough** – small, localized areas of deep bathymetry
- **Sediment bar** – bar feature or region of sediment accumulation along a relatively straight segment of a river
- **Side channel** – subaqueous channel within impounded area; may have split thalweg
- **Steep side slope –** rapid bathymetric variations over short lateral distance

Certain bedform features do not exist in both channelized flow and impounded lake river regimes. For instance, the channelized flow does not contain the mouth bar bedforms that are only present in the impounded lake. While meandering river conditions are dynamic, evidence suggests that the main channel is generally geomorphologically stable. Aerial photographs from 1938 onward show that the channel has not migrated significantly. Surficial regional geology is glacial in origin, and glacial moraines in Sections 1 and 3 have allowed the channel to be stable. Sediment texture measured during reconnaissance is generally vertically consistent throughout the sediment cores. Further, the focus of bedform mapping and grouping was to efficiently sample the site while still providing high quality SWAC estimates over the sampling timeframe (2017-2019).

Bedform Mapping Example

Figures 2 and 3 show the general concept for delineating bedform boundaries using the various terrain features. On the following figures, the floodplain hillshade is shown in gray with a specific terrain feature overlaid and the bedform outlines for RMs 38.8–38.9.

Figure 2 shows bathymetry, which is especially helpful in identifying river areas of relatively lower elevation (pools, glides) versus higher elevation (backwaters, point bars, anabranches). Colors of bathymetry represent relative elevations, with browns being higher elevations and greens and blues being lower elevations. In addition, the fine resolution aids in delineation of riffle-run-pool-glide sequences. Final bathymetry voids appear as a crosshatch pattern.

Figure 3 shows a bedform map colored by bedform classification. No single terrain attribute provides enough evidence to draw bedform boundaries; rather, all attributes together provide a holistic delineation of bedforms.

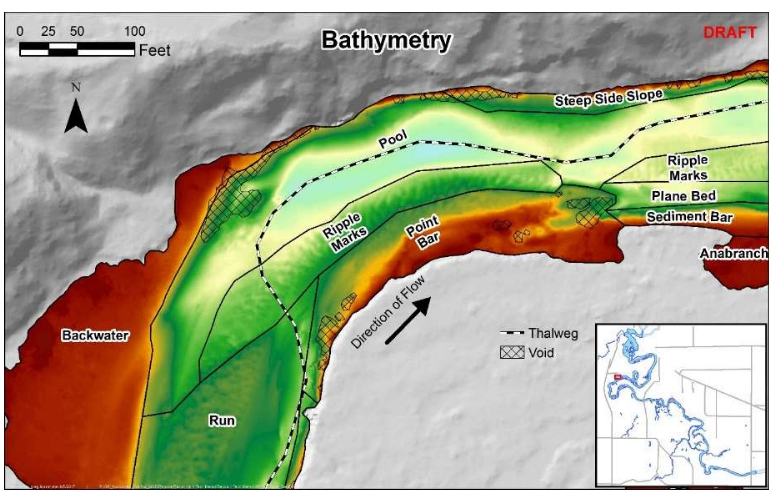

Figure 2. Bathymetry with superimposed bedform outlines.

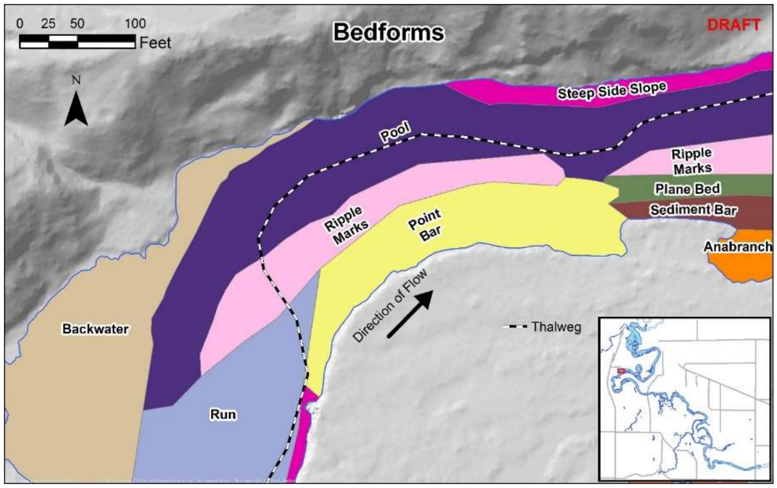

Figure 3. Colored individual bedforms within channelized flow.

MULTIVARIATE STATISTICS

A multivariate analysis of variance (MANOVA) and a hierarchical cluster analysis were used to simplify individual sediment bedform classifications into groups to support the preparation of a stratified, random sampling approach for the channelized flow during Phase I. The river bedforms were classified into two major sampling strata: sets of bedforms that are primarily coarse textured (Group 1) and those that are primarily fine textured (Group 2). The classifications of the two major sampling strata were based on the following physical features at each of the 10 Recon I and 45 Recon II sediment locations:

- Sediment thickness (1 parameter)
- Interval 1 gradation results (4 parameters)
- Hydrodynamic modeling results (20 parameters)

The grouping of sediment bedforms focused on physical data alone and did not consider PCB concentrations.

Bedforms

Bedforms of the riverbed were first mapped during the Recon I data evaluation. Seventeen individual bedforms were mapped through a detailed evaluation of various terrain features derived from the topographic/bathymetric data. Prior to Recon II, the 17 individual bedforms were grouped into three simplified categories by surface grain size texture using professional judgement: likely coarse, likely fine, likely coarse and fine. Available Recon I data were used to support this grouping; however, Recon I data were located within a small section of the impounded lake. A major goal of the sampling design Recon II data collection within the channelized flow was to further evaluate the groupings of the individual bedforms. Bedforms were revised throughout Area 5 using data and field observations gathered as part of Recon II.

Sediment Thickness

Soft sediment thickness was measured as part of Recon I and Recon II activities. Sediment thickness is measured by pushing a metal rod into the soft sediment until refusal. The difference between push probe depth and water depth is recorded as that location's sediment thickness. During Recon I, 143 locations in the impounded lake were probed for sediment thickness. Sediment probing locations collocated with Recon I sediment Ponar samples and upstream of RM 37 were retained for the multivariate statistics, which yielded 10 locations. During Recon II, a total of 60 sediment thickness measurements were collected. Recon II sampling locations upstream of RM 37 were included in the multivariate statistics, which yielded 45 locations.

Gradation Parameters

The multivariate statistical evaluation required quantitative values for any samples in the analysis. Laboratory gradation analysis of all sediment samples collected during reconnaissance was not practical, however valuable qualitative information is included within each core log. This qualitative information was leveraged to provide numerical approximations for samples not sent for gradation analysis.

Specifically, the Recon I event produced 46 particle size distributions (PSDs) assumed to represent Interval 1 because samples were collected with Ponar, and the Recon II event produced 80 PSDs in Intervals 1-7. After the two Recon field events, a USCS classification was assigned to the lab results (lab-based USCS classification) and the log description (log-based USCS classification) following ASTM D2487 (2011). Population statistics from the 126 total PSDs were computed for each lab-based USCS classification in four percent-by-size classes: fines (smaller than 0.075 mm); fine sands (0.075-0.42 mm); medium sands (0.42-2.0 mm); and materials coarser than 2.0 mm. The motivation for investigating the match between a sample's core log description and its corresponding gradation analysis was to apply the four percent-by-size class values to Recon II gradation data gaps to provide numerical approximations for each sediment core standard interval.

Two types of data gaps were populated: (1) intervals logged the same as an adjacent interval in which gradation data exist; and (2) intervals logged differently than an adjacent interval in which gradation data exist. To populate data gap Type 1, the four percent-by-size class values from a given adjacent interval, in which gradation data exist, were directly applied to the corresponding data gap. To populate data gap Type 2, the interval's log-based USCS classification was established. Then, the four percent-by-size class values for that USCS classification were given to the corresponding data gap. In this scenario, the median value for each percent-by-size class was used based on the distribution of lab-based USCS classifications. This methodology yielded a numerical value for each of the four Interval 1 gradation parameters.

Hydrodynamic Model Results

A hydrodynamic model was developed for Area 5 using DELFT3D-FLOW during the Recon I data evaluation. A detailed, 2-dimensional, depth-averaged flow model was constructed, and flow simulations were run for various pseudo-steady-state conditions with existing dam-in bathymetry. Model results for the following return periods were generated:

- Typical normal flow (median flow; 1,100 cfs)
- Bankfull (geomorphic; 1.3-year return period 3,200 cfs)
- 2-year return period (4,900 cfs)
- 16-year return period from 1985 event; maximum flow since 1950s (8,400 cfs).
- 100-year return period (12,000 cfs)

Results included depths, water surface elevations, velocities, and bed shear stresses. Each run modeled a constant upstream inflow and constant corresponding downstream water surface elevation. The modeled water depth, water surface elevation, velocity, and bed shear stress for each of the five flow scenarios were reported for each Recon I and Recon II sediment location using spatial join in ArcGIS. This yielded 20 total parameters for each discrete location. Available hydrodynamic data were retained as inputs to the multivariate statistics.

Multivariate Statistical Methods

The data described above were organized into a single input dataset for multivariate statistical analysis. Each data type (e.g., sediment thickness, percent fine sand, water velocity for 3,200 cfs scenario) is considered a variable within the analysis. In total, 25 parameters were used in the analysis. Available Recon I and Recon II surface sediment locations upstream of RM 37 (the upstream boundary of the impounded lake at the time of this evaluation) were included in the evaluation. A total of 53 Recon I and Recon II sediment sampling locations were used in the analysis because hydrodynamic model results were not available for two locations.

Individual bedform classifications were used within the MANOVA to assess the similarities in the average physical characteristics of individual bedform groups. Conversely, individual bedform classifications were not included as an input to the hierarchical cluster analysis. The hierarchical cluster analysis was used to test the accuracy of each sample's individual classification as well as to group samples into simplified bedform groups.

The MANOVA tests were performed using the Statistics and Machine Learning Toolbox in MATLAB (Mathworks 2017). The data were standardized using z-score transformation, which returns a centered, scaled version of each dependent variable prior to running the MANOVA.

Hierarchical cluster analysis is a multivariate statistical method that groups individual observations into clusters of increasing levels of similarity. The method is like MANOVA where data are clustered into hierarchical groups based on similarities. However, with hierarchical cluster analysis, individual data are evaluated without consideration of their assigned individual bedforms. This allows for a semi-quantitative, independent check on bedform classification while also identifying similar bedform classifications. For instance, if an individual sample located in a predominately fine bedform (e.g., anabranch) clustered with samples in generally coarse bedforms (e.g. riffles, runs), then this would indicate the sample's individual bedform classification may be incorrect and more inspection may be warranted. Methods and procedures follow guidance presented in the Statistics and Machine Learning Toolbox for Matlab (Mathworks 2017).

Results

Results of the MANOVA test are shown in the dendrogram on Figure 4. The dendrogram clusters individual sediment bedforms with similar means for the 25 variables in the input dataset. The height of each branch of the dendrogram represents the level of dissimilarity, with short branches indicating low levels of dissimilarity (i.e., similar mean values for both bedforms). Dissimilarity is measured as distance between bedforms, with larger numbers indicating higher degrees of dissimilarity. For instance, the Glide and the Run bedforms are clustered together with low measures of dissimilarity suggesting that the average sediment thickness, hydrodynamic model results and surface gradation data are very similar. Conversely, the Glide and the Backwater bedforms are highly dissimilar suggesting the mean values for the input variables are quite distinct for each bedform. Broadly speaking and based on the variation of input data, the results of the MANOVA test identified two primary groups of individual sediment bedforms, one that is predominately higher energy with coarser sediments and another that is lower energy with finer sediments.

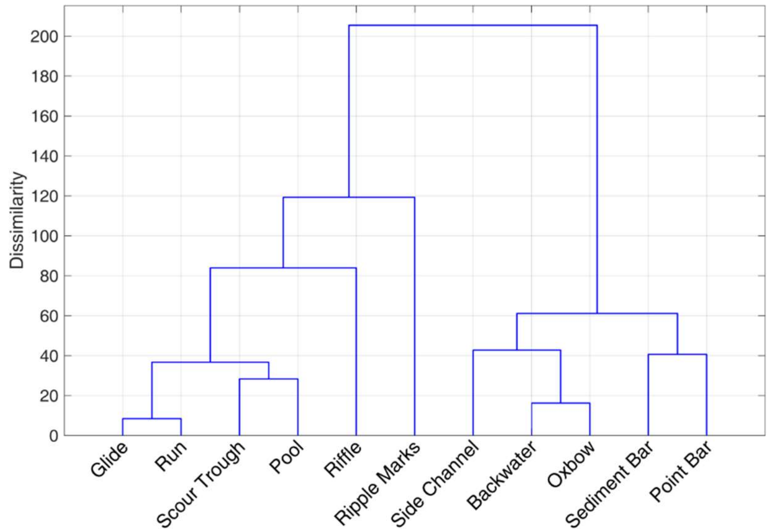

Figure 4. Dendrogram of MANOVA results.

Results of the hierarchical cluster analysis are shown in the dendrogram on Figure 5. The dendrogram is interpreted in the same manner as for MANOVA test above; however, the hierarchical cluster analysis groups individual sample locations rather than the mean values by individual sediment bedform. In this test, the individual sediment bedform definitions were not included as input. Rather, the test grouped the observations based on the individual sample's physical data. The dendrogram presented on Figure 5 was produced using standardized data. The pairwise distance was calculated using squared Euclidean distance, and the linkage distance was calculated as inner squared distance (also known as minimum variance algorithm or ward algorithm). The cophenetic correlation coefficient for this dendrogram model is 0.66. Alternative distance calculation algorithms were evaluated and produced similar results.

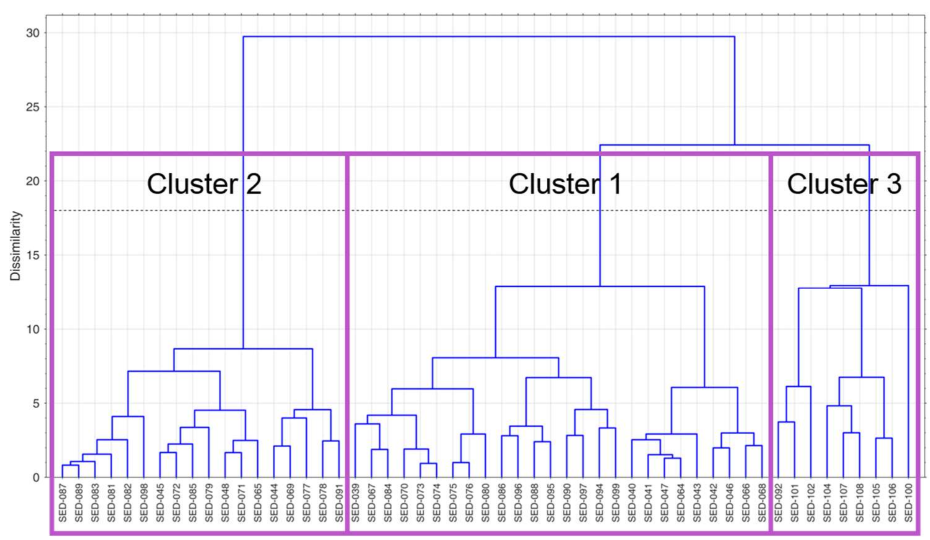

Figure 5. Dendrogram of hierarchical cluster results with individual sampling locations.

The dendrogram presented on Figure 5 shows varying hierarchical levels of clusters. Three clusters are shown at a distance cutoff between 13 and 22. Two clusters are shown at a distance cutoff of 22 or greater. The optimal distance cutoff is determined using professional judgement. At the individual sample level, sampling locations SED-087 and SED-089 have low levels of dissimilarity and are clustered together (i.e., similar sediment thickness, hydrodynamic model results, gradation data), while SED-087 and SED-100 have very high levels of dissimilarity. At the larger cluster levels, three distinct clusters are evident at a distance cutoff between 13 and 22. These clusters are highlighted as purple boxes on the figure. Cluster 1 is the largest cluster, and locations within it have generally coarse-grained sediments in moderate to high velocity areas. Cluster 2 is the second largest cluster, and locations within it have generally fine-grained sediments in slower velocity areas. Cluster 3 is the smallest cluster, and sampling locations within it have generally the coarsest grained sediments in the highest velocity areas.

Clusters 1 and 3 have similar sediment characteristics and could be considered the same cluster if the distance cutoff was moved to be greater than 22. In this scenario, there would be two clusters, one for relatively coarser-grained sediments (Clusters 1 & 3) and one for finer-grained sediments (Cluster 2).

Table 1 lists the sample counts by individual sediment bedform and by cluster group. Samples within Cluster 2 are in the backwater, oxbow, point bar, sediment bar, or side channel bedforms. Samples in Cluster 1 and 3 are in the sediment bar, scour trough, run, ripple marks, riffle, pool, point bar, or glide bedforms. The sediment bar and point bar bedforms have samples in both cluster groups, which suggest sediments in these bedforms could have either finer gradation or coarser gradation.

Table 1. Sample counts for hierarchical cluster results by cluster group.

	Cluster 1	Cluster 2	Cluster 3
Steep Side Slope	0	0	0
Side Channel	0	1	0
Sediment Bar	0	1	1
Scour Trough	3	0	1
Run	8	0	3
Ripple Marks	2	0	0
Riffle	2	0	0
Pool	9	0	1
Point Bar	0	2	2
Plane Bed	0	0	0
Oxbow	0	2	0
Mouth Bar	0	0	0
Island	0	0	0
Glide	2	0	1
Backwater	0	12	0
Anabranch	0	0	0

	Cluster 2	Cluster 1 & 3
Steep Side Slope	0	0
Side Channel	1	0
Sediment Bar	1	1
Scour Trough	0	4
Run	0	11
Ripple Marks	0	2
Riffle	0	2
Pool	0	10
Point Bar	2	2
Plane Bed	0	0
Oxbow	2	0
Mouth Bar	0	0
Island	0	0
Glide	0	3
Backwater	12	0
Anabranch	0	0

Final Grouping

The results of the MANOVA test and hierarchical cluster analysis were used to support the stratification/grouping of individual sediment bedforms within the channelized flow sections of Area 5. Individual sediment bedforms with similar physical characteristics were grouped into one of two strata:

- Group 1: Generally coarser-grained sediments, located in higher energy bedforms with lower sediment thickness
- Group 2: Generally finer-grained sediments, located in lower energy bedforms with higher sediment thickness

Table 2 presents how each individual bedform was simplified into one of the two groups. Generally, the groups presented are consistent with the results of the hierarchical cluster analysis presented in Table 1 with the notable difference of the sediment bar and point bar being included in Group 2. These individual bedforms had samples that appeared to fall into either cluster group, and to be conservative, the individual bedforms were included in Group 2. Additionally, the anabranch and the island sediment bedforms were also included in Group 2. There were no Recon II samples within these individual bedforms, but it was reasonable and conservative to expect sediments in these areas to have similar physical characteristics as other bedforms in Group 2. Conversely, the steep side slope and the plane bed were included in Group 1. These individual bedforms also lacked Recon II data, but the physical characteristics of the sediments in these features was consistent with other bedforms in Group 1.

Table 2. Revised bedform acreages, individual and grouped categories.

Simplified Bedform Group	Individual Sediment Bedform	Acres*	
Group 1 (coarse)	Anthropogenic	5.5	145.7
	Glide	8.9	
	Plane Bed	4.5	
	Pool	49.4	
	Riffle	21.3	
	Ripple Marks	7.2	
	Run	44.1	
	Scour Trough	3.7	
	Steep Side Slope	1.2	
Group 2 (fine)	Anabranch	11.6	75.6
	Backwater	21.1	
	Island	4.3	
	Oxbow	10.2	
	Point Bar	18.1	
	Sediment Bar	10.3	

*Acres are for bedforms upstream of the Impounded Lake (RM 37.25).

PHASE I AND PHASE II SAMPLING RESULTS

Upon reviewing Phase I and Phase II sampling results, PCB concentration distributions by sediment bedform group showed two dramatically different populations. While bedform groups were defined by the physical characteristics of 45 sampling locations, results from 1,132 samples demonstrated that Group 2 bedforms (725 samples) typically had greater and more variable PCB concentrations than Group 1 bedforms (407 samples). These results confirmed that statistical bedform grouping did in fact reflect PCB concentration distributions. Figure 6 displays boxplots of Recon II, Phase I, and Phase II PCB concentrations by bedform.

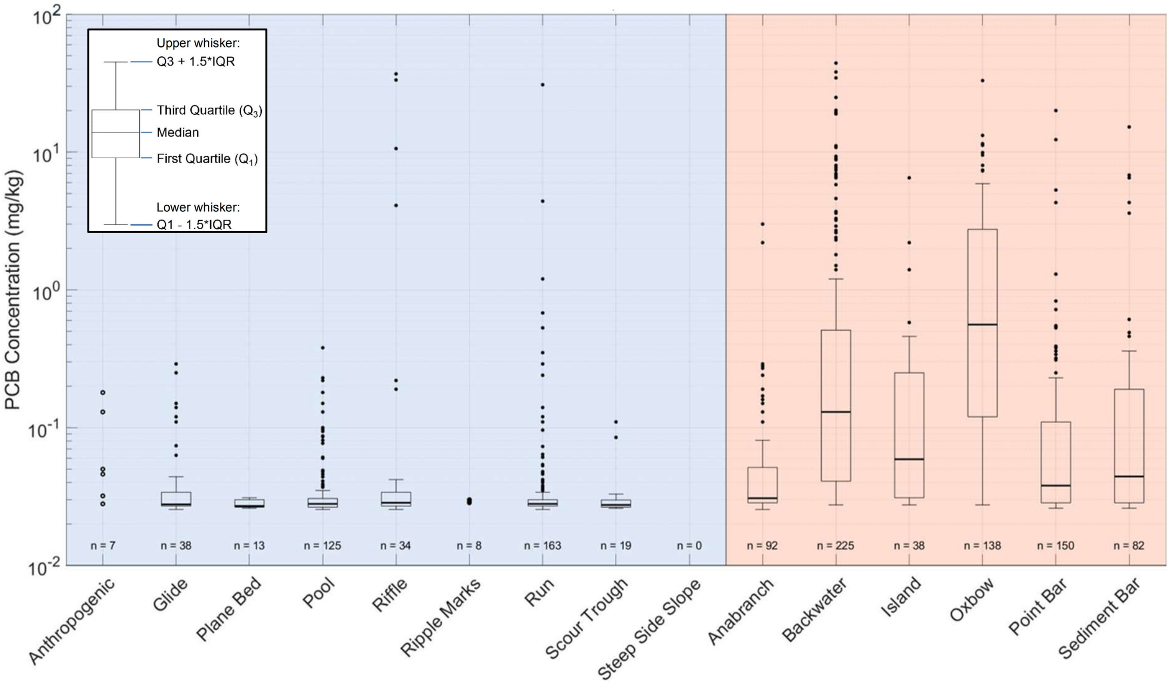

Figure 6. Boxplots of Recon II, Phase I, and Phase II PCB Concentrations by Bedform.

SWACs and upper confidence limits (UCLs) were calculated using the bedform groups for three geomorphologically defined river sections. The 95% UCLs were calculated using Chebyshev and bootstrap methods.

A sensitivity analysis on the SWAC and 95% UCL was performed to test if fewer samples could be collected in the future to arrive at approximately the same SWAC and UCL. The evaluation performed 1,000 simulations of new sample populations using a random resampling of 10-30 Group 1 (coarser group) samples and all Group 2 (finer group) samples. The Section-specific SWAC and UCL were then calculated for each simulation. Since fewer Group 1 samples were resampled during the simulations and this varied across the simulations, the sensitivity analysis could assess how informative additional Group 1 samples were toward estimating the SWAC and UCL. Figures 7, 8, and 9 show results of the sensitivity analysis for Interval 3 in Sections 1, 2, and 3, respectively.

Results shown on Figure 7 indicate that the SWAC (black line) and UCL (blue line) were reasonably estimated regardless of the number of Group 1 samples used in the simulation. Both statistics closely match the baseline values calculated using all available data. This suggests that the SWAC and UCL could be estimated with 10 Group 1 samples and that additional samples in Group 1 would not lead to less reliable estimates of the SWAC or UCL. Figure 8 shows that as additional Group 1 samples were included in SWAC and UCL calculations, the 25th to 75th percentile estimates of each statistic narrowed slightly, indicating more reliable estimates of the SWAC and UCL with increasing number of Group 1 samples. However, the SWAC and UCL values themselves closely match the baseline values within 0.1 mg/kg, which is sufficient for risk management decisions in the FS. Results of the sensitivity analysis indicate that reasonable estimates of SWAC and UCL could be made with fewer Group 1 samples.

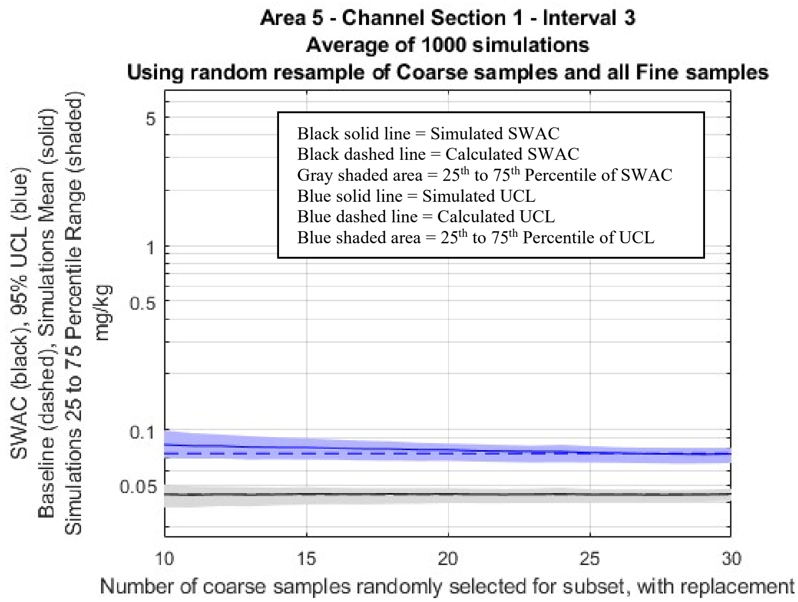

Figure 7. Section 1, Interval 3 SWAC and 95% UCL

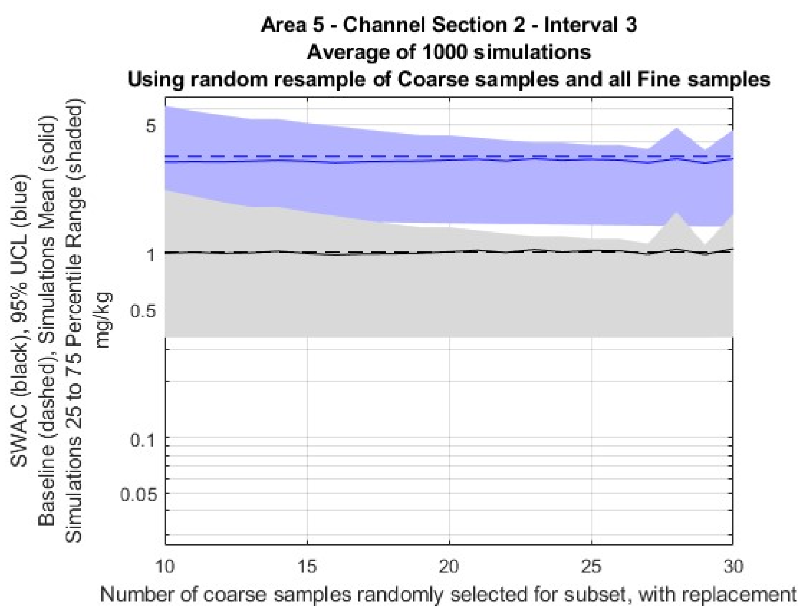

Figure 8. Section 2, Interval 3 SWAC and 95% UCL

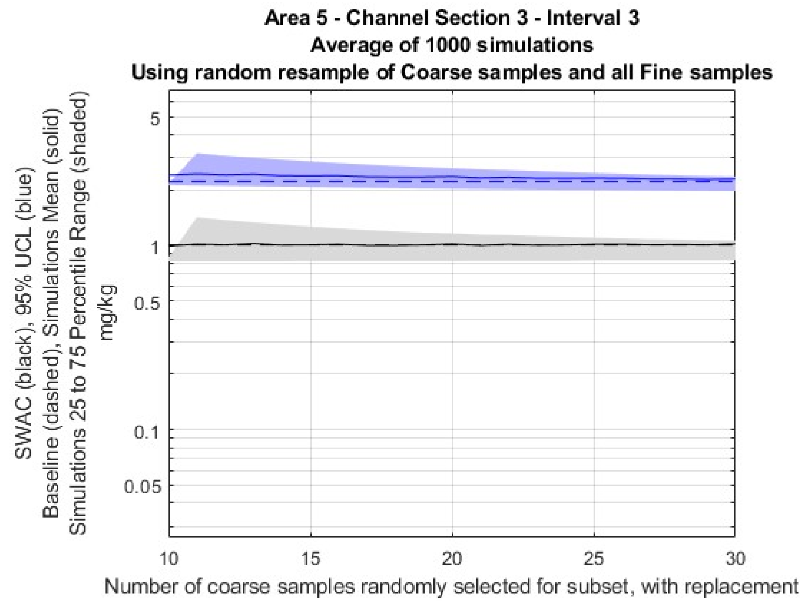

Figure 9. Section 3, Interval 3 SWAC and 95% UCL

CONCLUSIONS

Through multivariate statistical analyses of river bedforms (independent of associated PCB concentrations), two groups of bedforms showed distinct levels of variability in PCB concentrations; Group 1 samples have lower PCB concentrations and lower variability, while Group 2 samples have a larger range and higher variability of PCB concentrations. Therefore, bedform mapping and grouping was successful. Bedform groups proved to be an efficient stratified sampling approach, where the low variability bedform group was sampled at a comparatively lower density and the high variability bedform group was sampled at a higher density. Future sediment sampling events at this and other sites with sufficiently mapped river bedforms will require fewer samples while still providing reliable SWAC estimates, ultimately saving time and money.

REFERENCES

Amec Foster Wheeler. (2017). "Area 5 Draft Reconnaissance II Technical Memorandum Appendix F. OU-5 Allied Paper, Inc./Portage Creek/ Kalamazoo River Superfund Site."

ASTM. (2011). "Standard D2487: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM International, West Conshohocken, Pennsylvania, USA. DOI: 10.1520/D2487-11, www.astm.org

Malmon, D., Burnet, P., Moreen, E., Prestbo, K., and Gariglio, F. (2017). "Geomorphic and Stratigraphic Approaches to Riverbed Characterization: Example from the Coeur d'Alene River, Idaho." *Battelle Ninth International Conference on Remediation and Management of Contaminated Sediments*, New Orleans, Louisiana, USA.

MathWorks. (2017). "Statistics and Machine Learning Toolbox: User's Guide (R2017a)." Retrieved June 5, 2018 from https://www.mathworks.com/help/pdf_doc/stats/stats.pdf

Merwade, V. (2017). “GIS and River Channels” PowerPoint Presentation. *Center for Research in Water Resources*, University of Texas, Austin, USA.

Richardson, D., Schrotenboer, B., and Bigsby, M. (2017). “Using Bathymetry and Geomorphic Surfaces to Evaluate Contamination in River Systems.” *Battelle Ninth International Conference on Remediation and Management of Contaminated Sediments*, New Orleans, Louisiana, USA.

Sokal, R. R. and F. J. Rohlf. (1962). “The comparison of dendrograms by objective methods.” *Taxon*, 11:33-40

CITATION

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DATA AVAILABILITY

Some data, models, and code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

SAND PARTICLE SIZE ANALYSIS BY SEDIMAGING IN A FIELD LAB

G. Horstmeier[1], J. Eykholt[2], C. Kempf[3], A. Ventola[4], R. Hryciw[5]

ABSTRACT

SedImaging is an innovative alternative particle size analysis method developed to obtain high-resolution particle size distributions (PSDs) of sands. It was developed at the University of Michigan (UM) and is based on wet processing and digital image analyses of fine to medium sands. This work summarizes a variant of the SedImaging method, named FieldSed, which was first applied in a field lab setting for a sediments site by the authors and colleagues in October 2017. The goal of this work was to detect subtle variations in the fine sand and fines compositions as a pilot test at a field laboratory, without use of a sieve set or oven drying. The testing program included replicates, independent testing by UM, and other quality control measures. Sediment processing included wet-removal of fines and particles larger than coarse sand; preparation of the sample in a pre-sorter tube followed by sedimentation in a tall, water-filled column to sort the sands; and the collection and analysis of high-resolution digital imagery of the settled sand. The FieldSed method included variations to estimate mass percentages of oversized (> 2 millimeters [mm]) and undersized (< 0.075 mm) sediments, and throughput improvement. Wet sieving and air drying were used to separate and prepare oversized sediments for weighing. Multiple decants of sediment-water mixtures were used to wash out more dispersive fines. Decanted fines contents were estimated by differences in wet weights and by specific gravity approximations. Digital images were analyzed and used to generate high-resolution PSDs, which typically included more than 80 size bins from 2 mm to less than 0.050 mm. The FieldSed method was successful in clearly distinguishing coarse and fine material, as well as defining the gradient between medium sands, fine sands, and coarse silts. Color, angularity, and other grain characteristics from the digital imagery were noted. With further testing to improve processing rates and efficiencies, the method could be applied to provide same-day field decisions. More efficient and faster processing could be achieved for characterization of cleaner sands, and applications could be expanded further, such as to assess suitability of post-dredge sand cover materials in the field.

Keywords: innovative technology, grain size, image analysis, sediment bedforms, contaminated sediment.

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INTRODUCTION

As part of a geoenvironmental investigation of a river site, sediment samples were collected and analyzed. The goal of the testing program was to rapidly obtain accurate particle size distributions (PSDs) and support detailed mapping of fine sediment bedforms. The testing and analysis were performed using the first field application of SedImaging (short for sediment imaging) method developed at the University of Michigan (UM) for particle size analysis based on wet processing and digital image analyses of fine to medium sands (Ohm and Hryciw 2014). The digital image is analyzed by wavelet transform algorithms, and the computed particle sizes are sorted from largest to smallest to form a volume-based PSD. Ventola and Hryciw (2019) developed FieldSed (Figure 1), a lightweight field-portable version of the hardware for SedImaging. The results and method are also detailed in Ventola, et al. (2020). The field method does not require ovens or a sieve set and eliminates the need to ship specimens to distant geotechnical or analytical laboratories. Therefore, FieldSed can provide high-resolution PSDs of sands within hours of sample collection.

Although sieve and hydrometer testing is common, other alternatives exist to obtain PSDs. Chadwick and Arias (2014) demonstrated an in-situ friction-sound probe for characterization of sediments in San Diego Bay and a sand cap pilot study in the Anacostia River in Washington, DC. This cone-based technology is based on the principle that, as a cone penetrometer is advanced into sediment at a controlled speed, friction sound (acoustic energy) intensity is proportional to the grain size of the particles in contact with the cone. The friction sound probe amplitudes were lower for fine sands and silts, and the amplitudes were greater for coarser sands. The system requires a hydraulic ram on a heavy frame to advance the cone at a steady rate, but it can be used to quickly distinguish different sands (fine, medium, coarse) with vertical resolution (grain-size depth profiles). Laboratory testing of grab samples is also used for calibration, within the method. The two main limitations of the method are lower resolution for PSDs and vessel and rigging requirements to use the cone technology. Other techniques may include electrical resistivity geophysical surveys (sands and gravels are typically more electrically resistive than fine sands, silts, and clays) and digital photography analysis techniques for characterizing streambed particle sizes (Buscombe, 2013).

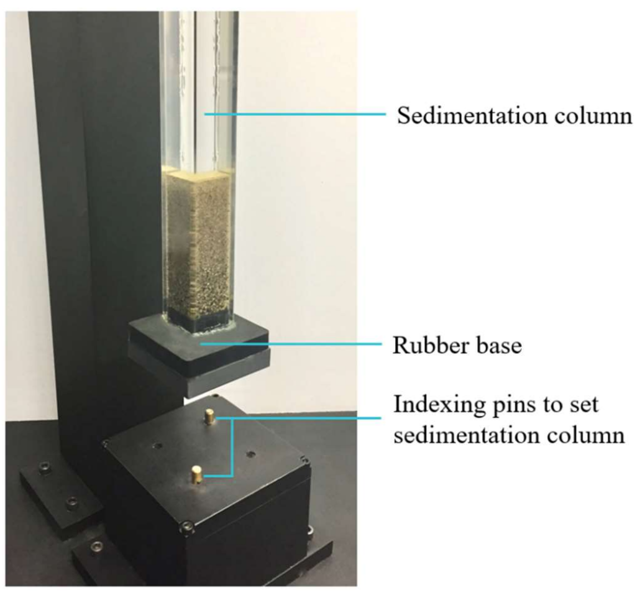


Figure 1. FieldSed device at imaging station.

SedImaging has the advantage of providing high-resolution PSDs from grab sample, because fines and oversize materials that may interfere with image analysis are screened out with preprocessing steps, and sands are sorted by sedimentation prior to imaging. Results from processing the high-resolution digital image can yield hundreds of size 'bins' and the digital image can also be analyzed for color, porosity, angularity, and other features (Zheng and Hryciw 2016a and 2016b). SedImaging is an ex-situ technique and, therefore, less sensitive to site access or the method of sampling.

SedImaging methods, including the FieldSed method, have been shown to have excellent agreement with sieve analysis for sands (Ohm and Hryciw, 2014; Ventola, et al. 2020). Coarse particles (> 2 mm) can be imaged but, for the field version of this method, are not efficiently separated for the selected sedimentation column length and cross-sectional area and, therefore, are removed with a pre-screening step. Fines, with diameters less than 0.075 mm (75 micrometers), need to be largely removed as the camera magnification is not set high enough for their characterization. Fines removal is accomplished by preparatory steps and, for cleaner sands (e.g., < 5% fines), can be accomplished simply by the sedimentation process without preprocessing. For quantification of percent fines, an approximate method is provided in Ventola et al. (2020) and summarized below. While particles as fine as 40 micrometers may be imaged, the general method is not targeted to characterize fines. The method could be coupled with other technologies in the future to collect and analyze fines, perhaps with other optical methods, passive sampling vessels, or by filtering and extractions/digestions of fines for chemical analyses.

The FieldSed technology is available for additional studies through Prof. Roman Hryciw and Andrea Ventola, at the Department of Civil and Environmental Engineering, University of Michigan in Ann Arbor, Michigan. More recent developments have also included changes to the sedimentation column and imaging method, as well as other steps to refine the method.

METHODS

SedImaging was originally developed for the analysis of sands (Ohm and Hryciw 2014); however, the method has been modified to allow for the analysis of sediment with fines. The main steps of SedImaging are: 1) field pre-processing, including preparing a sample for the sedimentation column; 2) image collection; and 3) generation of PSDs. Methods for SedImaging and its field implementation, FieldSed, are described more completely in Ventola, et al. (2020), and the FieldSed method is summarized below.

For the first application of the FieldSed technology (Eykholt, et al. 2019, Ventola and Hryciw 2019), sediment cores were collected and transported to the field processing station. The FieldSed laboratory (Figure 2) was enclosed and had electricity and water but was without temperature control. Sediment samples were selected for SedImaging by staff geologists. Most samples were selected to distinguish between samples described as "sands [without fines]" (< 5% fines), "sands with silt/clay" (5-12% fines) and "silty/clayey sands" (12-49% fines), or to more carefully examine fines content. In the field, visual inspection alone makes it difficult to distinguish the wide gradient between sands [without fines] and sandy silts. Eighty sediment samples were analyzed in eight field days.

Wood staff completed the pre-processing and digital image collection in the on-site field laboratory. The digital images were sent electronically to the UM where the images were analyzed, and PSDs were generated. However, no computer limitations prevented the analysis of images at the field lab. The final PSDs were adjusted by considering the mass fraction of coarse sand (> 2 millimeters [mm]) and gravel material and decanted fines (< 0.075 mm) found during sample pre-processing. UM also analyzed replicates to evaluate the repeatability of the FieldSed test and the agreement of the results with traditional sieving.

Figure 2. FieldSed field laboratory.

Field Pre-Processing

First, coarse sands and gravel were removed (if present). Samples were then sieved using a #10 (2 mm aperture) sieve. The portion retained on the sieve was air dried and weighed (W_1) with a bench top digital scale. The portion passing the sieve was loaded into a pre-sorter tube. Once the sediment sample was loaded, water was added to a pre-set mark on the tube, and the tube mass (W_{pre}) was recorded.

The next step involves removing dispersive fines from the material in the pre-sorter tube. The sediment was mixed, and the suspensions allowed to settle for set times (T_1 and T_2). Most particles remaining in suspension were decanted as waste. After the suspension settles, multiple decants were usually required to achieve a relatively clear suspension. The first set of decants were performed with a settling time of 2 minutes (T_1 = 2 minutes), which was long enough for fine sand-sized particles to settle, but quick enough for the more dispersive fines to remain in suspension. The final decant was performed after a settling time of 30 seconds (T_2 = 30 seconds), which was quick enough to decant most dispersive fines while retaining sands and some coarse silts. The suspension was poured over a #200 sieve (0.075 mm aperture). Sand collected on the sieve was returned to the pre-sorter tube. The pre-sorter tube was filled again with water to the pre-set mark, and the mass (W_{post}) and number of decants was recorded. A diagram of the pre-processing procedure is shown on Figure 3. Figure 4 shows an example of a sample in the pre-sorter tube before and after decanting fines (left and right images, respectively).

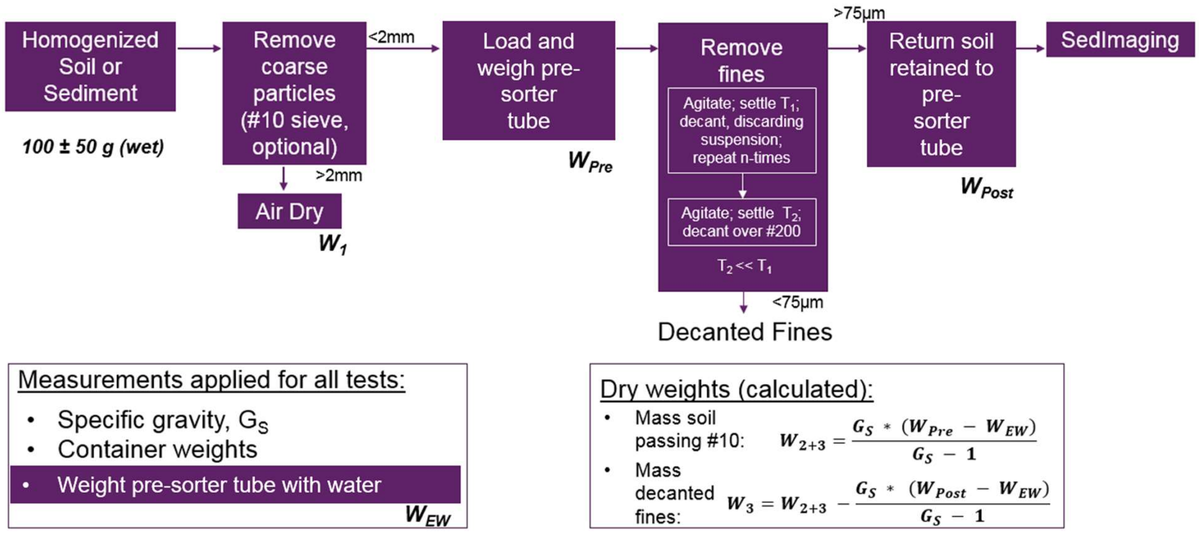


Figure 3. Flowchart for pre-processing procedure.

Figure 4. Sample in pre-sorter tube before (left) and after (right) decanting fines.

The method uses measurements on a wet mass basis to determine the fines percentage, but it is a differential method that assesses the loss of fines from the bulk sand (rather than a direct measurement of the mass of fines). Fines were intentionally removed from the imaged fractions but not lost in the process. Fines were collected and delivered to process wastes. To reduce the volume of process wastes, process water was recycled by filtration, stored in containers marked as non-potable, and reused for FieldSed tests.

Mass measurements are noted on the process diagram (Figure 3), where W values refer to mass (grams), not weight. Measurements include the mass of air-dried solids retained on the #10 sieve (W_1), and masses of the filled pre-sorter tube before and after decanting fines (W_{pre} and W_{post}, respectively). The mass of the pre-sorter tube, without sediment, filled with water to a standardized height (pre-set mark) is W_{EW}. Other than air-drying, which was necessary for the portion retained on the #10 sieve, no sample drying was required. Instead, dry weights were calculated with field measurements and an assumption for specific gravity (G_s). For these test results, the specific gravity was assumed to be 2.55 based on previous specific gravity measurements of site sands. The water temperature was recorded for each test to allow a density correction for dry weight calculations.

After pre-processing, samples were loaded into the sedimentation column. A rubber balloon was used to seal the open end of the pre-sorter tube. The balloon was deflated before being attached to establish a slight vacuum seal, the tube was inverted, and the sediment and water fell to the balloon-sealed end. The balloon was carefully removed, and the vacuum held the sediment and water in the column. The pre-sorter tube was placed over a settling column into a connector (a circular tube connected to a square column adapter), and the vacuum was released by removing a stopper on the top of the tube.

With the stopper removed and the vacuum released, the sediment fell into the water-filled settling column. Larger particles settled faster than finer particles. This size segregation is central to the method because the digital image analysis is much more accurate when nearby particles have similar sizes. Most settling occurred within 2 minutes, but the columns were typically left for hours before the images were collected.

The settling columns, constructed of clear acrylic measuring 6 feet by 1 inch by 1 inch, were mounted in a rack (Figure 2). Care was taken to make sure the columns were secured and mounted vertically.

Imagery

Columns with settled sediment were moved to a separate assembly for imaging. The assembly locks one column in place and sets a specified distance from a high-resolution camera. The outer surface of the column was wiped clean to remove dust. The camera was focused on the few inches of settled sand, and its distance was adjusted forward or backward if a desired focal length was needed. Further details are discussed in Ventola, et al. (2020).

Digital imagery was collected two or four times (i.e., on either 2 or 4 sides of the column). Collecting four-side imagery generally improved accuracy (as PSDs are determined from averages) but collecting two-side imagery improved throughput. The final digital image sets were reviewed, saved, and electronically sent to UM for analysis. On-site image analysis was possible, however, if a more rapid analysis was needed.

PSD Generation

The UM team analyzed the images offsite using a computer algorithm for volume distribution, on a flexible schedule. The UM lab provided cropped digital images and unadjusted PSD values for the imaged fraction of the sediment samples. Unadjusted PSD outputs from the computer analyses were high resolution: hundreds of percent passing value bins for diameters ranging from 0.040 mm (40 micrometers) to 2 mm. The PSD results from each image (side of column) were numerically averaged at each size bin to generate a composited PSD (result).

Wood analyzed the unadjusted PSDs to complete the analysis and reporting. Two percent passing values, calculated from masses as shown on Figure 3, were used to adjust computer-generated PSD values into a PSD that considers oversized (> 2 mm) and undersized (< 0.075 mm) materials. The percent of decanted fines was calculated by the following equation:

$$P_{DF} = \left(\frac{W_3}{W_1 + W_{2+3}}\right) \tag{1}$$

The percent finer than 2 mm was calculated by the following equation:

$$PP_{2mm} = \left(\frac{W_{2+3}}{W_1 + W_{2+3}}\right) \tag{2}$$

In this analysis, the adjusted PSD value (PP_{adj}) was calculated by the following equation:

$$PP_{adj} = P_{DF} + \left(\frac{PP_{2mm} - P_{DF}}{100\%}\right)(PP_{raw}) \tag{3}$$

where:

PP_{adj} = percent passing value, adjusted to consider oversized and undersized materials

P_{DF} = percent of decanted fines

PP_{2mm} = percent finer than 2 mm

PP_{raw} = percent passing value from raw, computer-generated PSD, calculated from analysis of digital images.

Further details on the adjusted PSD calculations, with an example, are presented in Ventola, et al. (2020).

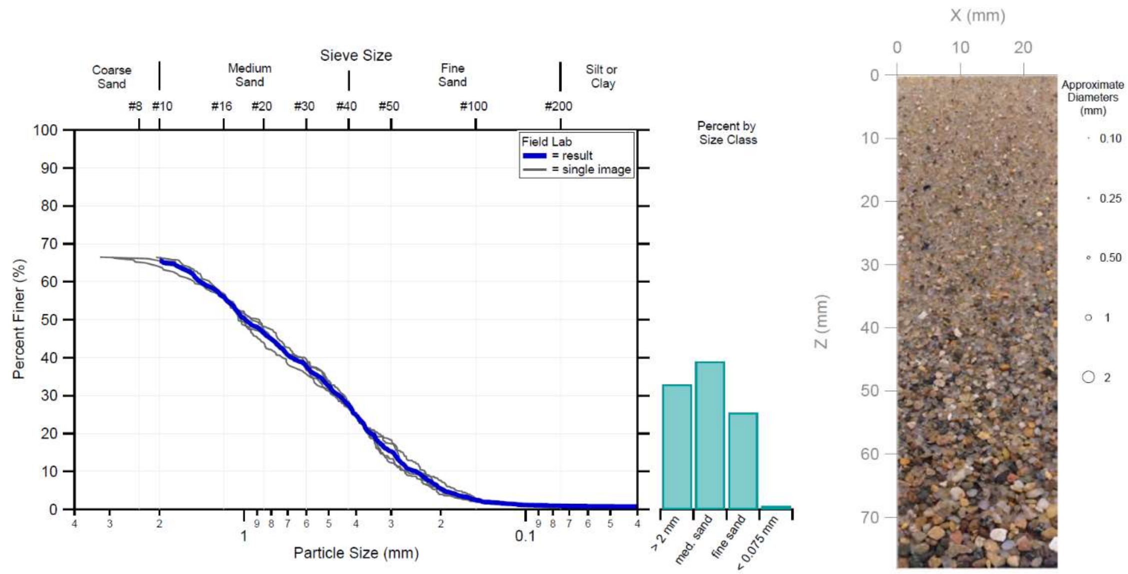
RESULTS

Samples tested ranged from 0 inches to 72 inches below the sediment-water interface in the following intervals, with interval frequency usually decreased with depth:

- Interval 1 from 0 to 6 inches
- Interval 2 from 6 to 12 inches
- Interval 3 from 12 to 24 inches
- Continuing in 12-inch intervals

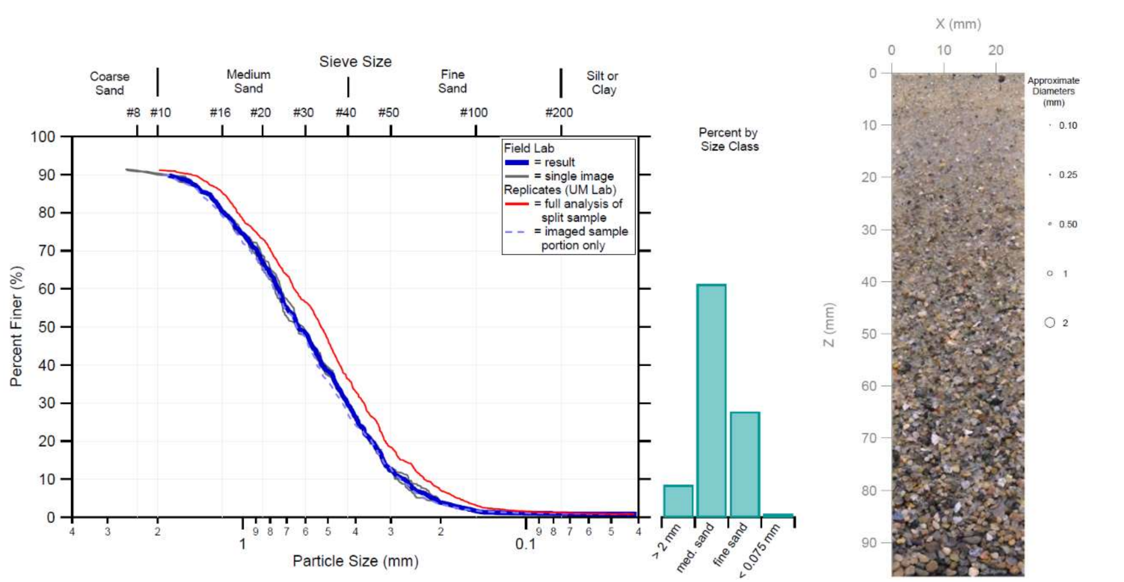
Of the samples imaged, 43 samples were sands with trace (< 5%) fines, 18 samples were sands with 5-12% fines, 18 samples were silty sands with > 12% fines, and one sample was silt (> 50% fines). Numerous sand types were analyzed and there is a large spread in the dataset. For example, the coarse sand fraction ranged from 32-100% passing the #10 sieve (2 mm). The fines fraction ranged from 0-61% passing the #200 sieve (0.075 mm). Grading also varied. Of the 43 sands with trace fines, 32 samples were poorly graded and 11 samples were well graded. Of the 18 sands with 5-12% fines, 14 sands were poorly graded and 4 samples were well graded.

Representative examples are show in Figure 5, Figure 6, and Figure 7. Note that the values reported in the boxes below the image and PSD are of the composited PSD (result).



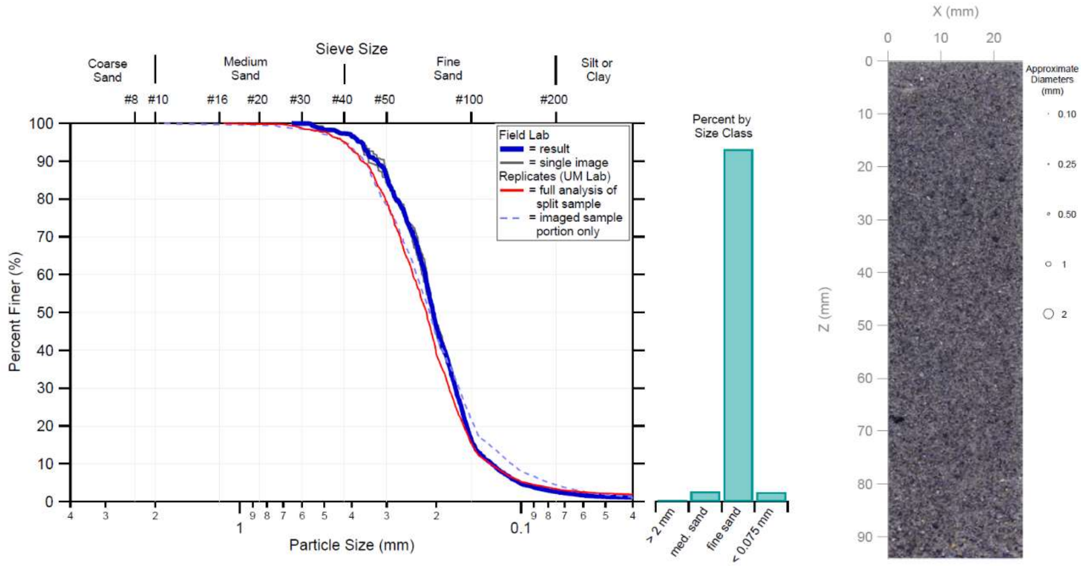
Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.25	D_{50}: 0.99	C_u: 5.8	< 2 mm	= 65.6%	medium sand or finer
D_{20}: 0.36	D_{60}: 1.43	C_c: 0.6	< 0.420 mm	= 26.9%	fine sand or finer
D_{30}: 0.46	D_{80}:		< 0.075 mm	= 0.9%	fines, total
				= 0.2%	fines, as imaged
				= 0.8%	fines, decanted

Figure 5. Example 1 – grain size summary from FieldSed analysis.



Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.27	D_{50}: 0.64	C_u: 2.8	< 2 mm	= 90.2%	medium sand or finer
D_{20}: 0.35	D_{60}: 0.75	C_c: 0.9	< 0.420 mm	= 29.2%	fine sand or finer
D_{30}: 0.43	D_{80}: 1.16		< 0.075 mm	= 0.9%	fines, total
				= 0.1%	fines, as imaged
				= 0.9%	fines, decanted

Figure 6. Example 2 – grain size summary from FieldSed analysis.



Effective Diameters (mm)		Coefficients	Summary of Particle Size Distribution		
D_{10}: 0.13	D_{50}: 0.21	C_u: 1.7	< 2 mm	= 100.0%	medium sand or finer
D_{20}: 0.16	D_{60}: 0.22	C_c: 1.1	< 0.420 mm	= 97.3%	fine sand or finer
D_{30}: 0.17	D_{80}: 0.28		< 0.075 mm	= 2.6%	fines, total
				= 1.5%	fines, as imaged
				= 1.1%	fines, decanted

Figure 7. Example 3 – grain size summary from FieldSed analysis.

Replicate Analysis

Two types of replicates were analyzed by the UM lab. The first type was for samples that were already pre-processed, imaged, recovered from the settling column, and re-bagged. Five replicates of this type were used to test variations from the camera being operated in a different environment and by different operators. The second type was for split samples requiring pre-processing and imaging. Six samples of this type were meant to test variations in pre-processing and imaging. Analyses conducted at UM were performed independently.

As shown in Figure 6 and Figure 7 for two representative samples, results of replicate analyses show strong agreement with parent samples. Minor variations are attributed to a small number of coarse particles shifting the curve, but the curves' shapes and locations are approximately equal. These results suggest a high level of reproducibility.

Bedform Application

Environmental contamination in sediments generally follows fine-grained sediments. While contaminant concentrations are often reliably low in coarse-grained sediments, there is a higher probability of variable contaminant concentrations (including non-detect concentrations) in fine-grained sediments. Efficient measurements of fines and sand characteristics are important for site characterization, and field lab determinations may be helpful for promoting adaptive sampling decisions. Therefore, a stratified sampling plan, in which sampling density is higher in fine-grained sediment beds, is beneficial.

To inform the stratified sampling plan, individual sediment bedforms were mapped along the surface of the riverbed using bathymetry data collected in November 2016 and April 2017. In a riverine (non-impounded lake) section, these individual bedforms were grouped for sampling purposes into either coarse-grained bedforms in the main channel (coarse group) or fine-grained bedforms in likely depositional areas (fines group), typically off or along the edges of the main channel. In addition to the bathymetric evaluations, the bedform classifications were further refined using gradation data and statistical analysis of physical characteristics.

At the sediment site, FieldSed-tested grain sizes for samples were collected along one stretch of the river, including an impounded lake area. Of the samples imaged, 26 samples were in the impounded lake and 54 samples were in the channelized flow. This dataset was combined with other grain size results, of which samples were tested via lab-based SedImaging, sieve, and hydrometer.

In the impounded lake, 323 total sediment gradation samples were collected. These samples were selected to be representative of the impounded lake both spatially and with depth. In general, the impounded lake has a variety of grain sizes, with most grain-size samples classified as silty fine sands or silts. The impounded lake has more varied surficial sediment gradation, but clear patterns exist. The main channel and side channels contain coarser surface sediment, whereas channel edges, mouth bars, and backwaters consist of finer surface sediment. Subsurface sediments throughout most of the impounded lake tend to be heterogenous with depth. Median particle diameters (determined from each sample's PSD) were consistently fine sand or silt, with two exceptions that were medium sand.

In the riverine section, 239 total sediment gradation samples were collected. In general, the coarse bedform group with 62 grain size samples contained sands and, to a lesser extent, sands with silt. Gravels and fine-grained sediment were significantly less frequent. In general, the fines bedform group, with 177 grain-size samples, contained silty sands and silts, and to a lesser extent contained gravels. With this fines group, there is a wide range in gradation but with a noticeable tendency toward fine sands and silts. The statistical-based sampling design for the analytical sampling program was well-supported by the effective bedform classifications, and reliable estimates were achieved for surface-weighted average concentrations and other contaminant concentration trends by bedform.

CONCLUSIONS

In summary, FieldSed played an important role for refining bedform classifications and quantifying grain size variations in sediment reaches. Bedform-based groupings of sediments, supported by physical features of grain-size, bathymetry, and geomorphic classifications, were an effective way to reduce overall uncertainty in average contaminant concentrations and concentration variance by reach.

Although the SedImaging method is not a standard particle size analysis method, many benefits exist that are not afforded to sieve and hydrometer testing. SedImaging offers a high resolution, quantitative field laboratory measurement of PSD with an especially well-defined gradient between coarse sand and coarse silt particle sizes. Visual inspection alone makes it difficult to distinguish the wide gradient between sediments classified as sand [without fines] and sediments classified as sandy silt. FieldSed reduces the uncertainty of sediment classifications based solely on visual inspection. Time and money savings are possible because SedImaging does not require oven drying or shipment of samples to an off-site laboratory. Multiple sedimentation columns in parallel can increase testing throughput. Further refinements and automations, some currently being developed at UM, are increasing throughput and quality of the PSDs. Further analytical options of the high-resolution digital imagery present unique opportunities. For example, color, roundness, angularity, porosity of particles may be summarized from the imagery.

Further application of FieldSed is encouraged for the analysis of sands and sandy sediments. For example, dredge passes can be improved with higher resolution, rapidly obtained grain size data. This is especially applicable when physical data are paired with chemical analytical data for residual management decisions. In addition to the goal of achieving high-resolution PSDs for sandy sediments (the goal of this work), the technology should be highly proficient for checking the suitability of post-dredge sand cover materials, understanding differences between upstream river sands and runoff of fill-sands, or for the detection of urban debris (plastics, glass, and other debris).

The FieldSed method is targeted to the analysis of sandy sediments, although approximations for percent fines were achieved in a practical manner. FieldSed analysis of clayey and silty sediments is technically possible, but more time-consuming and inefficient for low sand contents. The current FieldSed method generates fines as a separate waste stream that is not analyzed. However, for sandy sediments with significant fines, the overall utility of the FieldSed method might be improved if it were also coupled with separations and analysis methods for the fines. Unlike standard hydrometer methods which use chemical dispersants or high-energy mixing (e.g., waring blender), fines analyses coupled with FieldSed could be more representative and practical.

REFERENCES

Buscombe, D. (2013). "Transferable Wavelet Method for Grain-size Distribution from Images of Sediment Surfaces and Thin sections, and Other Natural Granular Patterns," *Sedimentology*, doi: 10.1111/sed.12049.

Chadwick, D. B., and Arias, E. (2014). "Demonstration of an In-Situ Friction-Sound Probe for Mapping Particle Size at Contaminated Sediment Sites," Technical Report 2040, *SSC Pacific*, San Diego, CA, April 2014.

Eykholt, J., Horstmeier, G., Kempf, C., Hryciw, R., and Ventola, A. (2019). "Sand Particle Size Analysis by SedImaging in a Kalamazoo River Field Lab", presentation, *Battelle Tenth International Conference of the Remediation and Management of Contaminated Sediments*, *USA*, January 2019.

Ohm, H-S., and Hryciw, R. D. (2014). "Size Distribution of Coarse-Grained Soil by SedImaging." *Journal of Geotechnical and Geoenvironmental Engineering*, 140(4).

Ventola, A., and Hryciw, R. D. (2019). "On-site particle size distribution by FieldSed." In *Geo-Congress: Engineering Geology, Site Characterization, and Geophysics*, edited by C. Meehan, S. Kumar, M. Pando, and J. Coe, 143–151. Reston, VA: ASCE.

Ventola, A., G. Horstmeier, R.D. Hryciw, C. Kempf, and J. Eykholt, (2020), "Particle Size Distribution of Kalamazoo River Sediments by FieldSed", J. Geotechnical and Geoenvironmental Engineering, 145(12):05020012.

Zheng, J., and Hryciw, R. D. (2016a). "Index Void Ratios of Sands from Their Intrinsic Properties." *Journal of Geotechnical and Geoenvironmental Engineering*, 142(12).

Zheng, J., and Hryciw, R. D. (2016b). "Roundness and Sphericity of Soil Particles in Assemblies by Computational Geometry." *J. Computing in Civil Engineering*, 30(6).

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DATA AVAILABILITY

Some data used during the study are available from the corresponding author by request. Some data or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

VIBRACORE SEDIMENT ACQUISITION MONITORING (V-SAM) FOR REMEDIATION DREDGING DESIGN AT THE PORTLAND HARBOR SUPERFUND SITE

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ABSTRACT

This paper presents selected results and lessons learned from advancing more than 50 sediment cores in 2020 at the U.S. Environmental Protection Agency Portland Harbor Superfund Site in Portland, Oregon, using a recently developed Vibracore sediment acquisition monitoring (V-SAM) system. A specific objective of the coring program was to estimate the depth of contamination (DOC) below mudline (bml) for remediation dredging design. V-SAM provides incremental measurements of the core tube's depth of penetration into the sediment bed and the corresponding incremental measurements of the sediment collected inside the tube. By providing a means to estimate positions of sediment samples in the core tube with respect to in-situ sample depths bml, V-SAM provides improved estimates of DOC for remediation dredging design.

Keywords: Sediment sampling, sample processing, depth of contamination, DOC, sample recovery

INTRODUCTION

Characterizing the nature and extent of contaminated sediment for remediation dredging design involves collecting and analyzing sediment samples at various depths below the sediment bed elevation. Depending on site conditions and sampling media, several methods can be used to collect subsurface sediment cores. These methods, which vary in the mechanism used to advance the cores through the substrate, include direct-push, impact-driven, auger-driven, and vibratory coring.

CONVENTIONAL VIBRACORING

Vibracoring is a vibratory method of advancing a core tube into the substrate to collect continuous subsurface sediment samples. The cores can vary in length and material. For the Vibracore sediment acquisition monitoring (V-SAM) coring conducted at the Portland Harbor Superfund Site, aluminum tubes 15 feet long (~4.6 m) and 4 inches (10 cm) in diameter were driven into the substrate by a high-frequency vibrating head attached to the top of the tube. The high-frequency vibration adds energy to the sediment through the core tube and causes a layer of sediment particles at the interface with the metal core to mobilize, reducing friction and allowing for the tube to be advanced in a continuous fashion. When the core tube has been advanced to full penetration, or has met refusal and will not advance further, the tube is withdrawn from the sediment. After extraction from the bed of the waterway, the tube is generally kept in an upward-oriented position, measured for penetration depth and headspace (the length from the top of the

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core to contact with retrieved sediment), and sectioned into manageable lengths for transport to the core processing location. Each section represents various depth intervals of sediment within the core tube. The samples are submitted for chemical analysis to reveal the types and concentrations of chemicals of concern (COCs) at various depth intervals in the core tube. The laboratory analysis and assigned depth intervals from the core tube are combined to identify the maximum depth of sediment in each core tube where COCs are present at or above regulatory concentrations (COC_{max}). The COC_{max} is then used to estimate the maximum in-situ depth in the sediment bml where COCs are present at or above regulatory action levels. The mudline elevation at each core location can be used to convert depth of contamination (DOC) to elevation of contamination for development of dredge plans.

CORE RECOVERY PARAMETERS

Core recovery is a measure of the amount of sediment acquired in a Vibracore tube upon retrieval of the core tube. The primary parameters used to determine core recovery are the total length of sediment collected in the core tube (L_{ST}) and the total length that the core tube is driven into the sediment bed (L_{DT}). Figure 1 shows how L_{ST} is compared to L_{DT} to establish the percent recovered (%R).

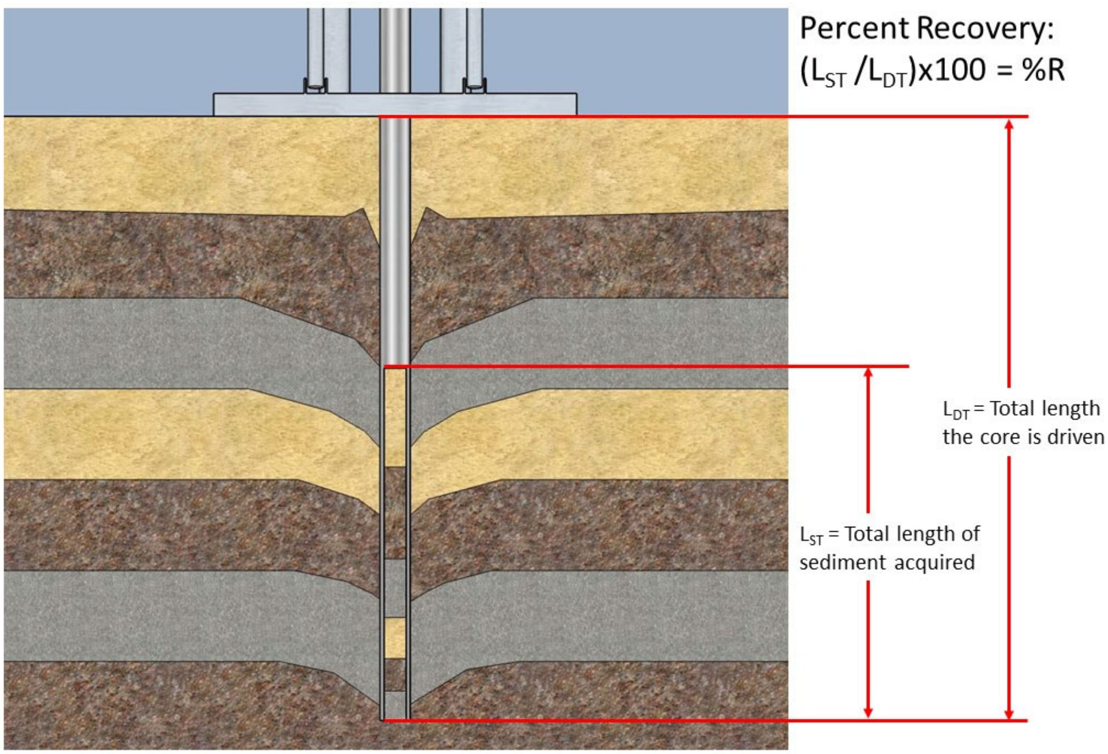

Figure 1. Core recovery parameters.

For example, the percent recovered in a Vibracore tube with L_{DT} = 16 ft (~4.9 m) and L_{ST} = 12 ft (~3.7 m) would be %R = 12 ft ÷ 16 ft x 100 = 75%R. Common values for %R can range from 50% to 100% but are greatly dependent on sediment composition and site conditions.

The conventional coring approach does not provide a mechanism to establish the cause of the difference between L_{DT} and L_{ST}. Incomplete recovery (%R < 100%) may be due to compaction of the sediment in the core tube, development of a plug at the cutting edge of the tube, partial recovery during driving (Figure 2), presence of debris during the drive, loss of sediment from the bottom of the tube during extraction (Figure 3), or some combination of all. Because it is difficult to discern the mechanism that causes the difference between L_{ST} and L_{DT}, uncertainty is inherent in dredge prism design when using conventional coring to estimate the in-situ DOC bml if %R < 100%.

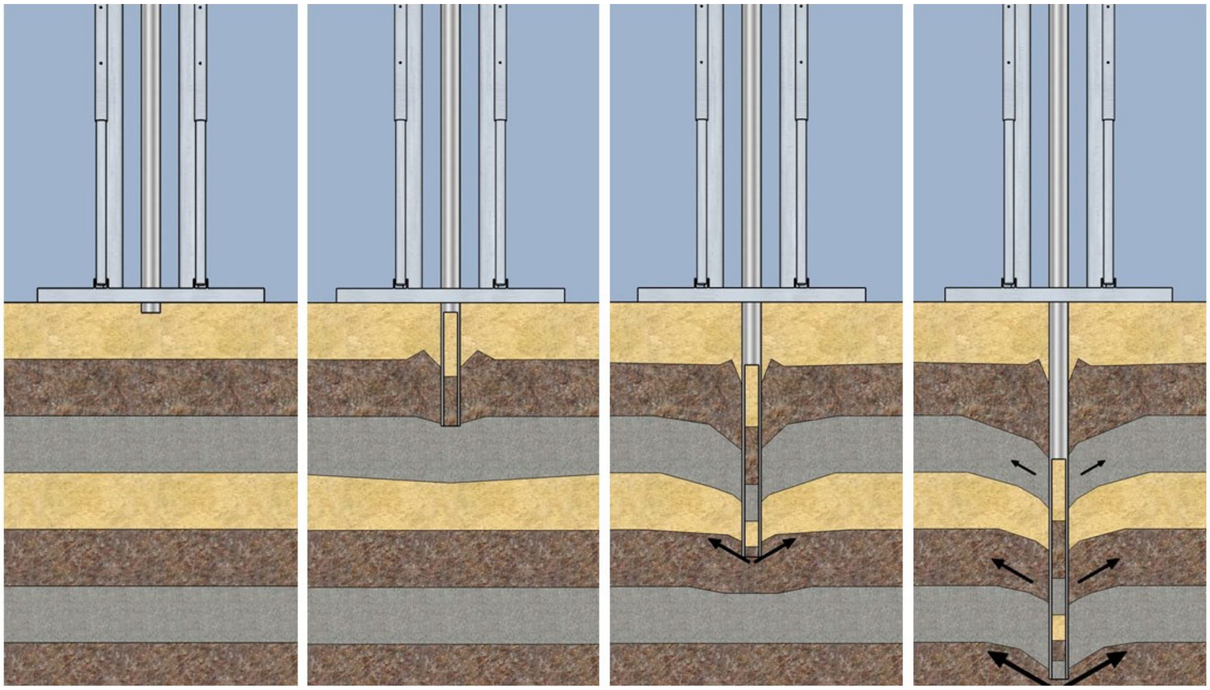

Figure 2. Partial recovery during Vibracoring.

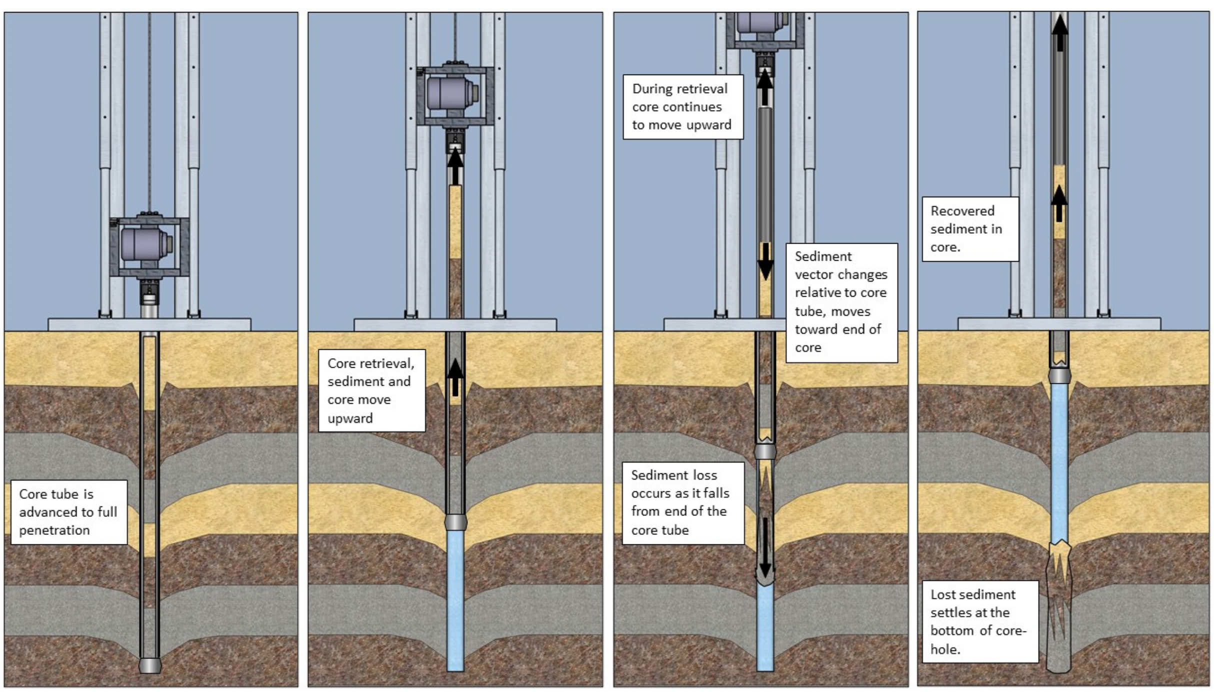

Figure 3. Bottom loss during retrieval.

The following sections discuss uncertainties in establishing DOC with conventional Vibracoring and potential improvements afforded by V-SAM.

UNCERTAINTY OF DOC FROM CONVENTIONAL VIBRACORES

When employing conventional Vibracore methods, the two data points L_{DT} and L_{ST} (defined above) are typically used to estimate the in-situ depths of sediment in a core tube. Two common approaches using these data points to assign estimated in-situ depths bml are the L_{ST} and the %R methods:

- L_{ST} Method. This approach assumes that the estimated in-situ depth bml of a sample is equal to the position of the sample in the core tube (DOC = COC_{max}). For example, a sample located 6 feet (~1.8 m) from the top of the sediment column in the core tube is assumed to represent in-situ sediment at 6 feet (~1.8 m) bml. If the %R is less than 100%, the difference between L_{DT} and L_{ST} is assumed to be due solely to sediment falling out of the bottom of the tube during extraction. If a tube is driven 16 feet (4.9 m) bml with 12 feet (3.7 m) of sediment recovered in the tube, the bottom 4 feet of sediment is assumed to have fallen out of the tube during extraction from the bed, leaving 12 feet of sediment in the core tube representative of the in-situ sediment to 12 feet bml.

- %R Method. This approach assumes that the sediment in the core tube is representative of the full length of the core penetration. For example, if a tube is driven to L_{DT} = 16 feet (4.9 m) bml with L_{ST} = 12 feet (3.7 m) of sediment recovered, resulting in 75%R, each 1-foot increment of sediment in the core tube is assumed to represent 1.33 feet of in-situ sediment (1 ÷ 0.75 = 1.33). The in-situ depth bml of a sample is then estimated as the location of the sample in the core tube divided by %R. With a 75%R, for example, a sample located 6 feet (1.8 m) from the top of the sediment column in the core tube, is assumed to represent in-situ sediment at 8.6 feet (2.6 m) bml (= 6 ÷ 0.75). The difference between L_{DT} and L_{ST} is assumed to be due to uniform compaction and/or uniform partial recovery of the sediment in the core tube proportional to %R, throughout the length of the sediment in the core tube.

Differences in %R values directly influence the in-situ depth assumption associated with COC_{max}. An example is shown in Figure 4 for a core tube driven to L_{DT} = 15 feet (~4.6 m) with a COC_{max} (blue dashed line) of 6.5 feet (~2 m) below the sediment surface in the core tube and six %R values. Each of the six lines in the figure indicates a different %R value, or acquisition-to-penetration relationship. Under the %R Method, the estimated in-situ DOC bml is determined as the point on the X-axis where the respective %R line intersects the COC_{max} at 6.5 ft (~2 m). At 100%R in Figure 4, the estimated DOC is equal to the COC_{max} of 6.5 feet. At 70%R the estimated DOC is 9.3 feet bml, and at 50%R the estimated DOC is 13 feet bml.

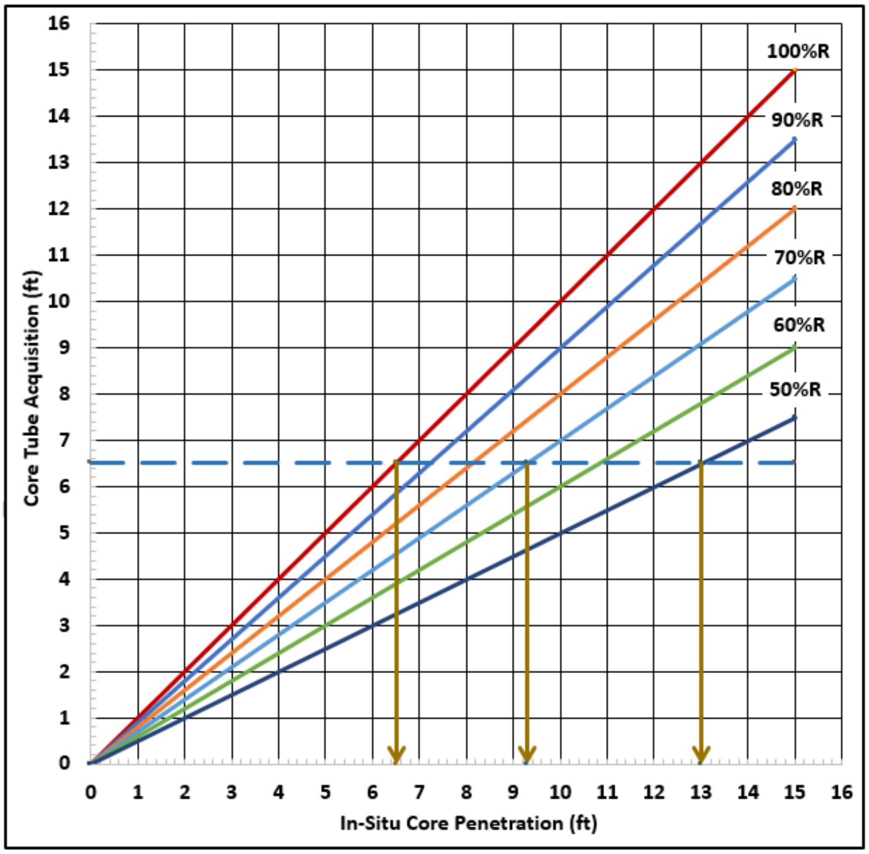

Figure 4. Example DOC estimates by %R method, COC_{max} = 6.5 ft (~2 m)

Estimated DOCs derived using both the %R and the L_{ST} Method to calculate in-situ depths of sediment in the core tube are shown in Table 1 for the six %R values represented in Figure 4. The contrasting results of the two methods—or uncertainty—are shown by the two far right columns of Table 1.

Table 1. Example ranges of estimated DOC based on L_{ST} and %R methods for conventional Vibracoring. Drive length = 15 ft (~4.6 m), COC_{max} = 6.5 ft (~2 m)

			DOC bml (ft)		DOC Difference	
L_{DT} (ft)	L_{ST} (ft)	%R	L_{ST} Method	%R Method	(ft)	as % of L_{ST} DOC[a]
15	15	100%	6.5	6.5	0	--
15	13.5	90%	6.5	7.2	0.7	~10%
15	12	80%	6.5	8.1	1.6	~25%
15	10.5	70%	6.5	9.3	2.8	~45%
15	9	60%	6.5	10.8	4.3	~65%
15	7.5	50%	6.5	13	6.5	~100%

[a] Value rounded to nearest 5%

Whether calculated as an absolute value or as a percent of the value derived using the L_{ST} Method, the DOC difference increases as %R decreases. In this example, the difference as a percent of the L_{ST} DOC ranges from approximately 10% (at 90%R) to 100% (at 50%R).

The uncertainty associated with estimating in-situ DOC bml can limit the efficacy of precision remediation dredging plans, which, in turn, can affect the cost, schedule, and overall success of remedial actions. An overestimated DOC could result in excess dredging and disposal of clean sediment below the actual DOC, and an underestimated DOC could erroneously leave undisturbed residuals in place (Bridges et al. 2008).

V-SAM VIBRACORING

To reduce the inherent uncertainty of conventional Vibracoring, equipment developed by Marine Sampling Systems, LLC was modified to directly measure the sediment acquired in the core tube as well as the corresponding incremental distance that the core tube is advanced. The modified equipment consists of a bottom-sitting Vibracore "A-frame" configured with two specialized fathometers (Figure 5a and 5b). The Penetration Fathometer, mounted on the A-frame drive-head, measures the incremental penetration of the core tube below mudline (l_P) by recording the changing distance as the drive-head advances the core and moves closer to the sediment bed. The Acquisition Fathometer, located at the top of and inside the core tube, measures the incremental length of sediment acquired in the core tube (l_A) by recording the distance to the top of the sediment as the core is advanced into the sediment bed during driving. Recording and comparing the measures of l_P and l_A during Vibracoring is referred to as V-SAM.

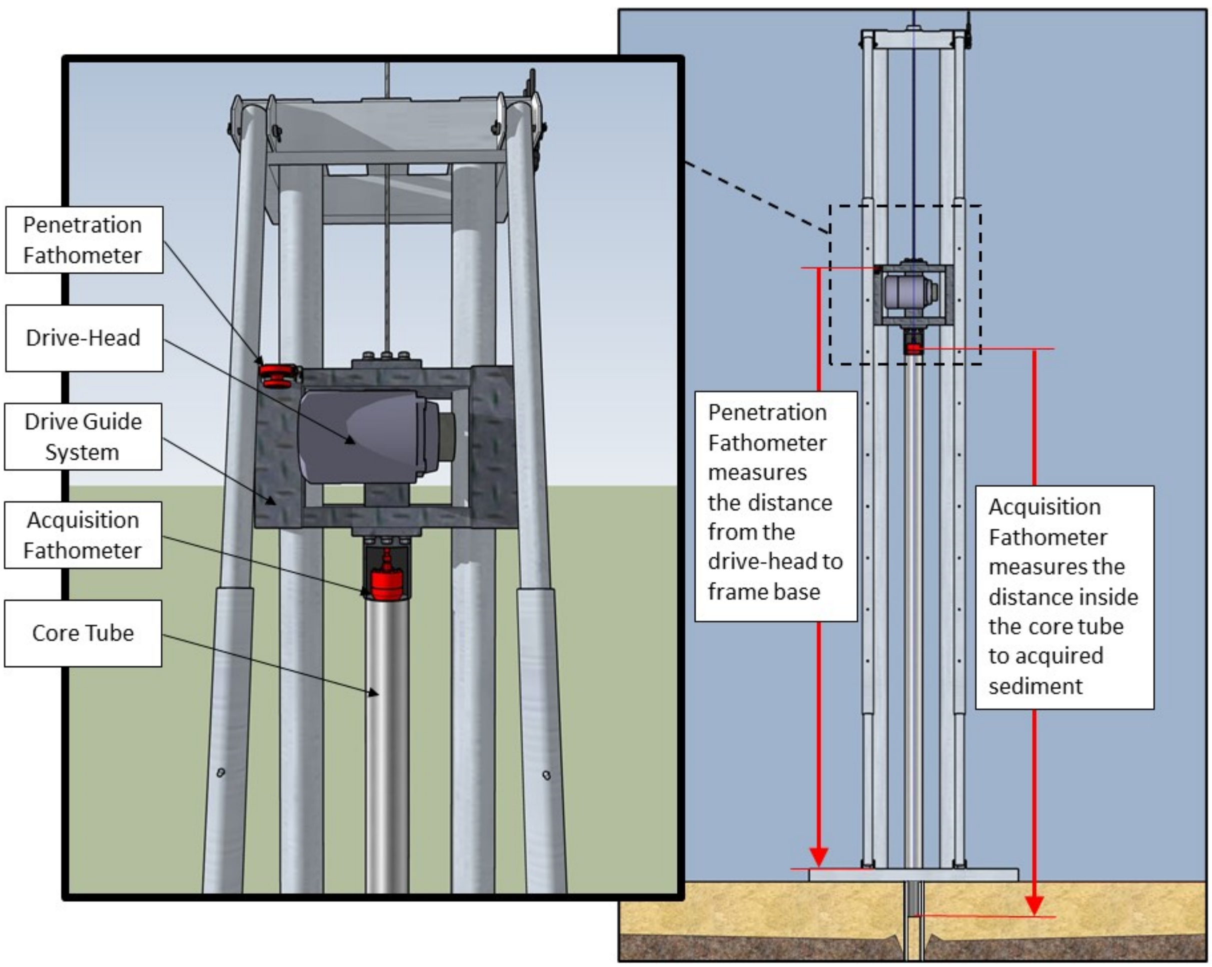

Figure 5a. Marine Sampling System's V-SAM Vibracoring System.

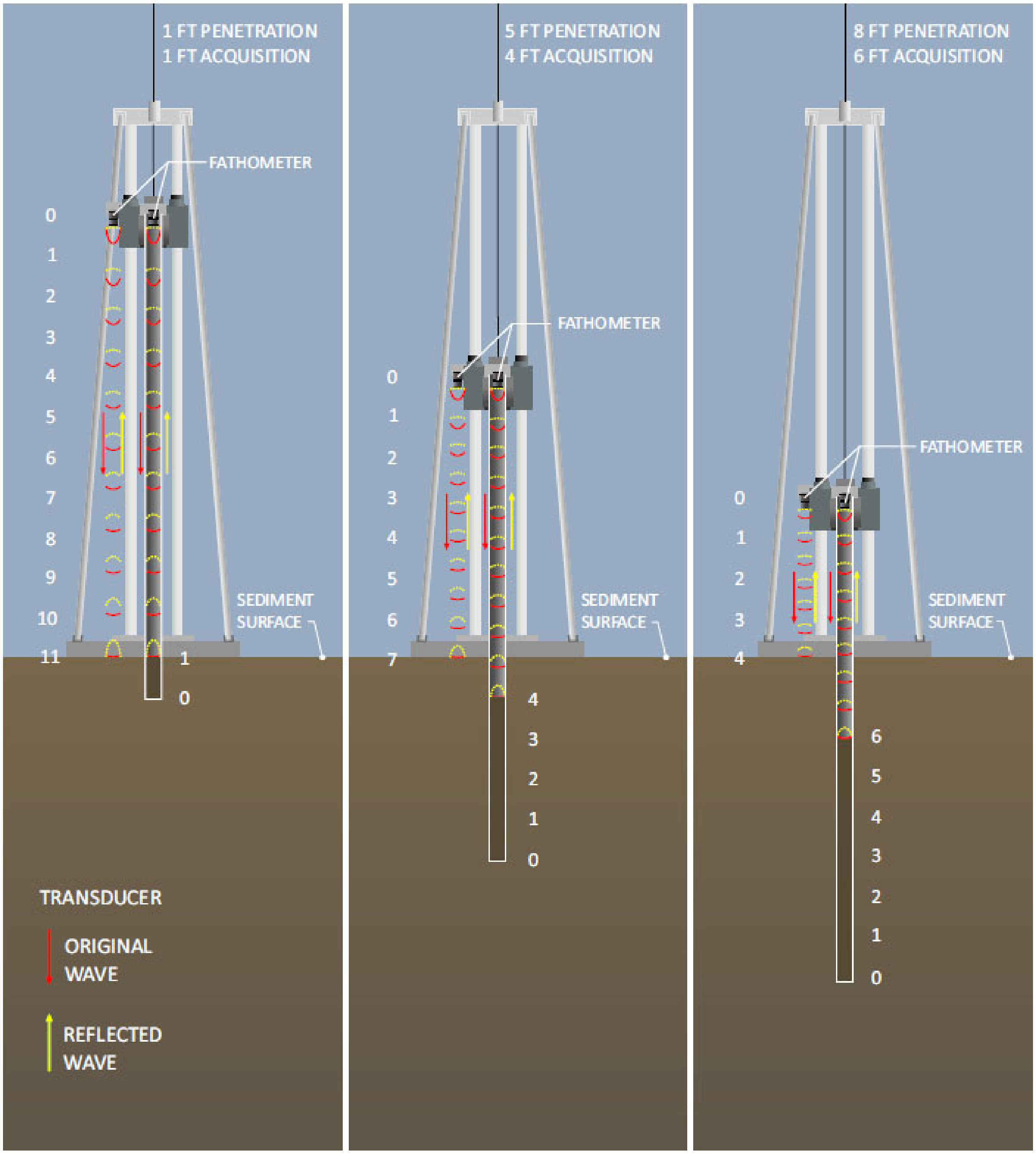

Figure 5b. Marine Sampling System's V-SAM Fathometer System.

During V-SAM, a record of each incremental drive and the associated measure of acquisition is taken and plotted on a curve of acquisition feet per core penetration feet (Figure 6), referred to as a V-SAM acquisition curve.

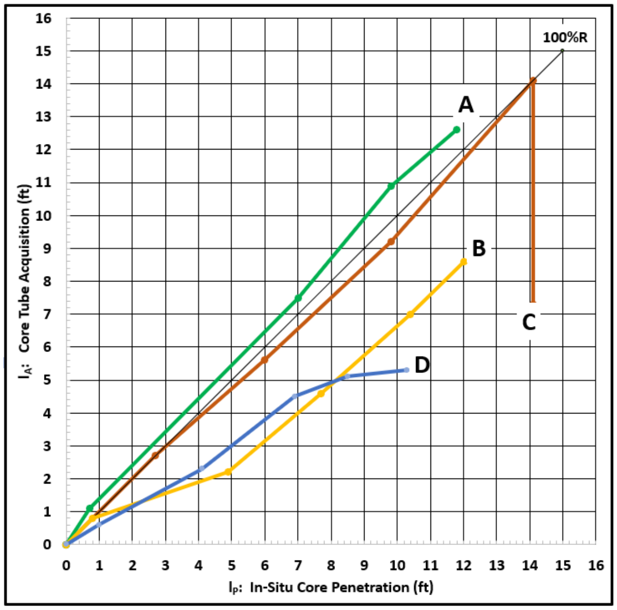

Figure 6. Example V-SAM acquisition curves (A, B, C, D described below).

The 100% R line on Figure 6 indicates the ideal condition where the length of sediment acquired in the core tube is equal to the in-situ core tube penetration. The four acquisition curves shown in Figure 6 represent different conditions obtained during Vibracoring at the Portland Harbor Superfund Site:

A. (111%R). Acquisition curve A indicates sediment that is slightly expanding in the core tube (plotting above the 100%R line), occupying more volume in the tube than it did in-situ. In this case the material in the tube was primarily sand, and excessive energy applied by the vibratory drive-head to dense sand caused the material volume to expand.

B. (72%R). Acquisition curve B indicates a case of reduced acquisition in the core tube (plots below the 100%R line) to about 5 feet (~1.5 m) of in-situ core penetration with just over 2 feet (~0.6 m) of acquisition (45%R); acquisition then increases to 90%R (near parallel to the 100%R line) for the remaining increment of the drive.

C. (100%R then 52%R). Acquisition curve C shows nearly 100%R acquisition for the full depth of the drive to 14 feet (~4.3 m); upon retrieval, however, the vertical drop of the acquisition value on the curve at 14 feet (~4.3 m) of penetration shows 7 feet (~2.1 m) of sediment loss (likely having fallen out of the bottom of the tube during extraction), with approximately 7 feet (~2.1 m) of sediment retained in the tube after extraction.

D. (51%R). Acquisition curve D shows reduced acquisition rates for the full length of the drive, averaging about 65%R to an in-situ core penetration to 7 feet (~2.1 m), and then reducing to about 25%R for the remainder of the drive.

DOC FROM V-SAM COMPARED TO CONVENTIONAL L_{ST} AND %R METHODS

In Figure 7, each V-SAM acquisition curve from Figure 6 is individually plotted with lines representing the L_{ST} Method (fine line at 100%R) and the %R Method (red dashed line) for estimating DOC. In these examples the COC_{max} is at 4.5 feet (~1.4 m), as indicated by a blue dashed line at 4.5 feet (~1.4 m) on the Y-axis. Table 2 tabulates the DOC estimated for each scenario by the L_{ST} Method, the %R Method, and the V-SAM acquisition curve.

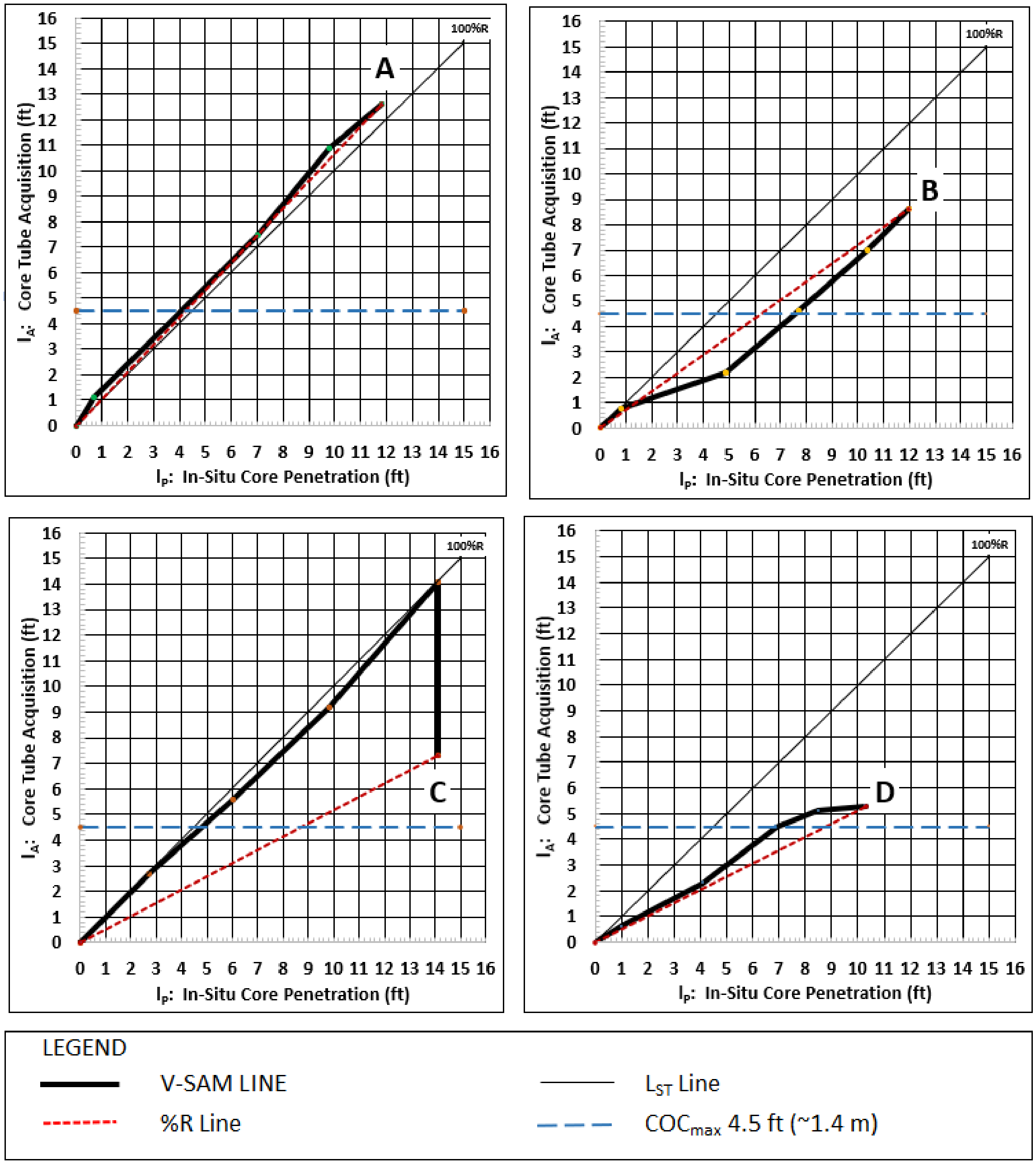

Figure 7. Example V-SAM acquisition curves with L_{ST} line and %R line, COC_{max} = 4.5 ft (~1.4 m).

Table 2. DOC Estimates by LST, %R, and V-SAM Methods, COC_{max} = 4.5 ft (~1.4 m).

Acquisition Curve	%R	COC_{max} (ft)	DOC bml (ft)			Variation of DOCs (ft)
			L_{ST} Method	%R Method	V-SAM	
A	111%	4.5	4.5	4.2	4.1	0.3
B	72%	4.5	4.5	6.2	7.5	3.0
C	52%	4.5	4.5	8.7	4.6	4.2
D	51%	4.5	4.5	8.8	6.8	4.3

The variation in DOC estimates for the four different scenarios is summarized as follows:

A. (111%R). Acquisition curve A shows that when acquisition is close to 100%R all three methods generate very similar values of estimated in-situ DOC bml of 4.1 to 4.5 ft (~1.2 m to 1.4 m).

B. (72%R). Acquisition curve B shows the effect of reduced acquisition at the start of the drive. The estimated value of in-situ DOC bml by V-SAM, 7.5 ft (~2.3 m), is deeper than the less certain estimates of DOC bml by the L_{ST} Method, 4.5 ft (~1.4 m), and the %R Method, 6.2 ft (~1.9 m).

C. (100%R then 52%R). Acquisition curve C shows the effect of sediment loss from the tube upon extraction. The estimated value of in-situ DOC bml by V-SAM, 4.6 ft (~1.4 m), is the same as the less certain DOC bml estimate by the L_{ST} Method, 4.5 ft (~1.4 m), and shallower than the less certain estimate of DOC bml by the %R Method, 8.7 ft (~2.7 m).

D. (51%R). Acquisition curve D shows the effect of a progressive reduction of %R during the drive of the core. The estimated value of in-situ DOC bml by V-SAM, 6.8 ft (~2.1 m), is between the less certain estimates of the in-situ DOC bml by the L_{ST} Method, 4.5 ft (~1.4 m), and the %R Method, 8.7 ft (~2.7 m).

PROCESSING CORE TUBES USING V-SAM ACQUISITION CURVES

The V-SAM acquisition curve can be used to segment the core into representative intervals of estimated in-situ depths bml, as shown in Figure 8. The core penetration depth represented by the X-axis corresponds to the sediment acquisition on the Y-axis through the plotted acquisition curve upon collection of a core. The estimated location in the core tube of acquired sediment representative of a particular in-situ depth can be assigned by referencing a value on the X-axis vertically to the intersection with the acquisition curve and then horizontally to the value on the Y-axis. Figure 8 shows acquisition curve B and the position in the core tube (4 ft.) representative of in-situ sediment at 7 ft bml.

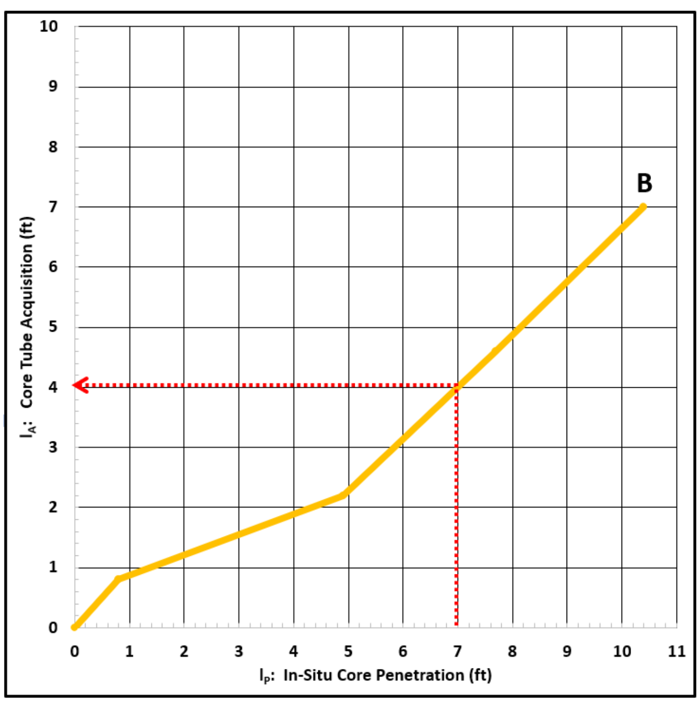

Figure 8. Example establishing core tube positions representative of estimated in-situ depths bml.

The full-length core tubes are cut into shorter sections (~4-ft, ~1.2 m) in the field for easier handling and delivery to the core processing facility. The information from the acquisition curve is used to generate a core tube sampling plan corresponding to targeted in-situ sample depths. Table 3, based on Figure 8, presents a core tube sampling plan targeting 1-ft (~0.3-m) in-situ depths bml. The plan is used during core processing to reference the location of the 1-ft in-situ sediment intervals within the sectioned core tubes and to collect sediment samples for submittal to a laboratory for analysis of COCs.

Table 3. Example core tube sampling plan from V-SAM acquisition curve B.

Core Segment	Target In-Situ bml (ft)	Core Tube Location (ft)
A	1	0.8
	2	1.2
	3	1.6
	4	1.9
	5	2.3
	6	3.2
	7	4.0
	CUT	4.0
B	7	4.0
	8	4.8
	9	5.8
	10	6.6

When processed in this manner, results of laboratory analysis for COCs correlate to the estimated in-situ depths bml and can then be used to estimate the in-situ DOC bml.

LIMITATIONS OF V-SAM

With the first deployment of V-SAM in 2020, a finite amount of experience is available from which to assess limitations of the V-SAM system. Examples of challenges encountered to date are listed below:

- Vibracoring with V-SAM provides an improved method to estimate in-situ DOC bml as compared to conventional Vibracoring. Both methods possess varying degrees of uncertainty in DOC determination due to possible disturbance/distortion of the sediment in the core tube associated with the Vibracoring process. More direct measurement of in-situ DOC can be achieved by drilling methods that collect individual discrete samples at multiple known depths bml for testing (e.g., hollow-stem auger drilling with split spoon or Shelby tube sampling).
- Locating the acquisition fathometer at the top of the core tube precludes the use of a piston in the core tube to improve sample recovery.
- V-SAM does not work in shallow water if the fathometers are not submerged.
- Vibracoring with V-SAM is more labor intensive, has a lower daily production rate, and costs more per day than conventional Vibracoring. However, it also provides more information by which to estimate in-situ DOC bml than conventional Vibracoring.
- Organic sediment can release methane bubbles inside the core tube, resulting in a blinding effect on the acquisition fathometer and an inability to detect the sediment surface as it advances into the core tube. In some cases, a pause in the coring program may allow for the methane bubbles to clear and for the fathometer to again detect the acquired sediment surface.

- Woody debris or other foreign material in the sediment can separate from the sediment as it enters the core tube and float upward in the water column, creating a blinding effect and preventing the acquisition fathometer from reading the top of the sediment column in the core tube.
- Stopping the advance of the core tube to gather incremental fathometer readings can allow the surrounding frictional forces to increase and resist the further ease of advancement of the core tube.
- No automated data collection system is currently available to record l_P and l_A during Vibracoring. Real-time reading and processing of acquisition data is completed manually.

CONCLUSIONS

Relative to conventional Vibracoring, the V-SAM system provides a better correlation between the location of a sediment sample in the core tube and its estimated in-situ sample depth bml. This improved correlation reduces uncertainty in the mapping of in-situ DOC bml for remediation dredging design.

REFERENCES

Bridges, T.S., Ells, S., Hayes, D., Mount, D., Nadeau, S., Palermo, M., Patmont, C., and Schroeder, P. (2008). *The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk*. Technical Report ERDC/EL TR-08-4. Vicksburg, MS: U.S. Army Engineering Research and Development Center.

CITATION

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DATA AVAILABILITY

V-SAM Core Acquisition Logs are available from the corresponding author by request.

NOMENCLATURE

Term	Definition
bml	Below mudline
COC	Chemical of concern
COC_{max}	Maximum depth of sediment in the core tube where COCs are present at or above regulatory levels
DOC	Depth of Contamination. The maximum in-situ depth bml where COCs are present at or above regulatory action levels
L_{DT}	Total drive length of the core tube into the substrate
L_{ST}	Total length of recovered sediment in the core tube
l_A	Incremental length of sediment acquisition in the core tube
l_P	Incremental penetration of the core tube below mudline
%R	Quotient of total length of sediment collected in the tube (L_{ST}) divided by the total length that the core is driven into the riverbed (L_{DT}), times 100

REVISITING HISTORIC DREDGED MATERIAL HABITAT IMPROVEMENT SITES INFORMS THE FUTURE OF BENEFICIAL USE INITIATIVES

J.F. Berkowitz[1], K.D. Philley[1], and N.R. Beane[1]

ABSTRACT

The beneficial use (BU) of dredged materials improves environmental outcomes while maximizing navigation benefits and minimizing costs. As a result, numerous BU projects have been implemented since the 1970s and BU efforts continue to expand within the navigation dredging portfolio. Yet, few studies document mid- to long-term project benefits due to a combination of 1) short monitoring timeframes and 2) the paucity of BU sites that have reached maturity since most BU projects were recently constructed. In response we conducted a survey of six historic (>40 years old) BU locations designed to improve habitat, where initial post-construction data was collected. Conditions at natural reference locations were also documented for comparison. This approach allows for an analysis of the long-term success of BU initiatives and the development of BU trajectory curves. Study sites were geographically diverse (TX, FL, GA, CT, MI, OR) and incorporated data from coastal marshes, freshwater wetlands, and upland habitats. The current analysis reports on habitat diversity and vegetation communities and compares those results with historic data. Results indicate that the BU projects provide valuable habitat for a variety of species in addition to yielding a number of engineering (e.g., shoreline protection) and other (e.g., water quality) benefits. In general, BU locations evolved into the habitat types targeted during construction. However, the specific habitat assemblages at BU locations often diverged from reference conditions. Most BU sites exhibited more diverse habitat distributions than natural reference areas, largely due to construction activities and the establishment of elevation gradients absent from unaltered locations. Experimental plantings conducted post-construction apparently had limited influence on community composition after >40 years of succession, as environmental conditions (elevation, salinity) dictate long term vegetation community dynamics. However, plantings likely play a key role in maintaining the physical stability of recently constructed BU projects and decrease the potential for invasive species establishment. Our findings suggest that establishment of BU success criteria should not over-emphasize replicating reference conditions but should focus on achieving specific ecosystem functions (i.e., energy dissipation) and engineering outcomes (i.e., storm surge reduction). The analysis also highlights the need for additional research into long-term BU project trajectories, especially as new initiatives including Engineering With Nature® continue to expand. The abundance of completed BU projects provides opportunities to conduct chronosequence analysis to document project successes, predict conditions for milestone establishment, and inform the design of future projects to maximize environmental, navigation, and engineering benefits.

Keywords: Engineering With Nature®, Ecosystem functions, Engineering benefits, Restoration trajectory, Chronosequence analysis

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INTRODUCTION

Recent initiatives have focused on the capacity of natural processes to improve ecological endpoints while accomplishing engineering objectives and reducing project costs within a dredged materials management context (Yozzo et al. 2004). The concept of integrating ecosystem and dredged material management is encapsulated by the Engineering with Nature® (EWN) initiative, an intentional alignment of natural and engineering processes to deliver economic, environmental, and social benefits efficiently and sustainably through collaborative processes (Bridges et al., 2014). The beneficial use of dredged material is consistent with EWN.

The incorporation of dredged material beneficial use into navigation channel maintenance portfolios and long-term management plans has increased since the first studied were conducted in the 1960s and 1970s, and additional interest in identifying opportunities to expand beneficial use applications are increasing in the United States and abroad (Sheehan et al., 2012). For example, a recent analysis of shallow draft dredged material projects within the U.S. Army Corps of Engineers Baltimore District area of responsibility demonstrates the increase in beneficial use features over the past four decades (Berkowitz and Szimanski 2020) (Figure 1a). These projects ranged from beach nourishment and restoration efforts to the creation of oyster bays, islands, and wetlands, highlighting the diversity of beneficial use projects (Figure 1b).

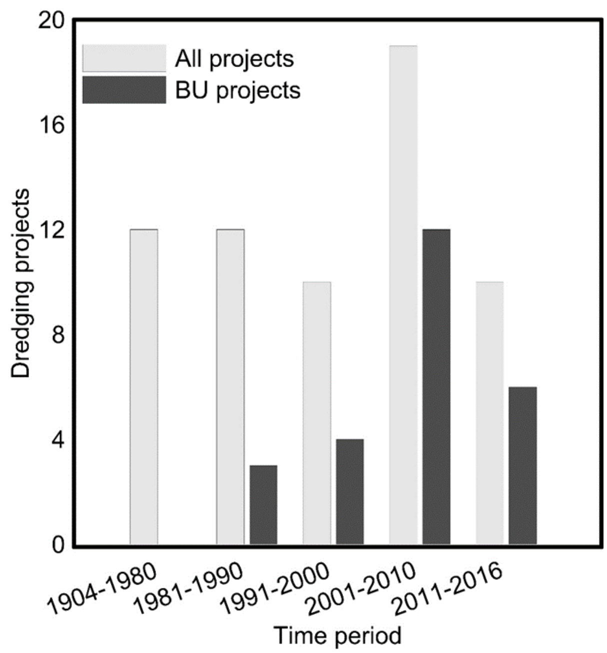

Figure 1a. Temporal distribution of shallow draft dredging projects and associated beneficial use (BU) activities executed by the U.S. Army Corps of Engineers Baltimore District. Note that the abundance and relative proportion of BU projects increased each decade since the 1980s, with BU incorporated into >60% of projects implemented after 2010 (Berkowitz and Szimanski 2020).

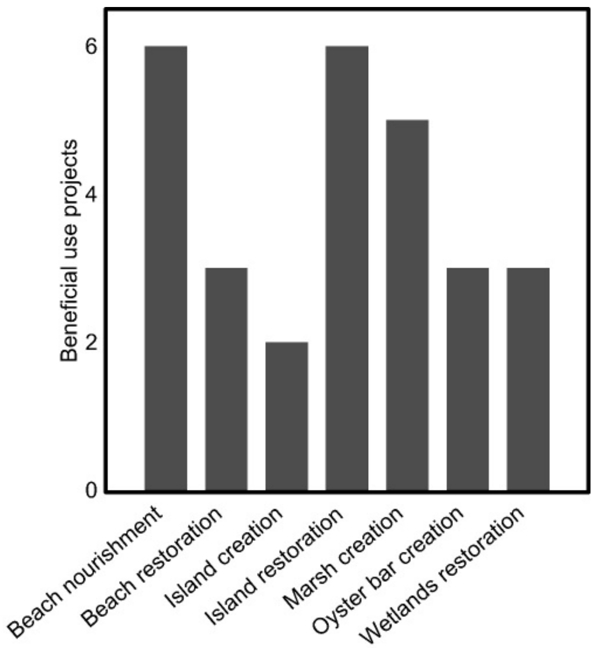

Figure 1b. Distribution of shallow draft dredging beneficial use (BU) project types executed in the U.S. Army Corps of Engineers Baltimore District 1980-2016 (Berkowitz and Szimanski 2020).

Not unexpectedly, the availability of data documenting the outcomes of beneficial use projects has increased as the number of beneficial projects being implemented has expanded. These studies now provide a rich body of literature informing the design, construction, and operation of a variety of beneficial use activities. In particular, the environmental benefits of these projects have been evaluated across multiple disciplines and geographic areas (Edwards and Proffitt 2003). For example, Faulkner and Poach (1996) assessed the functional capacity of created and natural wetlands and identified similarities and differences between natural and built environments; and Mallach and Leberg (1999) evaluated avian community use at natural islands and those created using dredged material composed of varying substrates identifying variables that effected faunal community composition and abundance. Importantly, Streever (2000) highlighted the finding that project designs that incorporate engineering elements that mimic natural processes display ecosystem characteristics similar to natural systems to a greater extent than landscape features created using traditional dredged material management techniques.

Despite the increasing number of beneficial use projects and the associated studies researching project outcomes, the long-term trajectory of beneficial use projects remains unclear. These uncertainties result from the limited period that dredged material management designed for ecosystem improvements have been implemented. In other words, most beneficial use projects are relatively ‘young’ landscape features compared with their unaltered counterparts which evolved over periods ranging from centuries to millennia (Coleman et al. 1998). This limitation precludes the collection and analysis of data from fully “mature” beneficial use study locations.

Additionally, few studies track the trajectory of habitat restoration/creation sites for extended periods, with most monitoring efforts occurring over short durations (often 2-5 years) which D'Avanzo (1989) and others recognize is not sufficient for documenting the long-term benefits and outcomes of restoration/creation projects. The paucity of information reflecting the mid- to long-term ecological conditions at historic beneficial use sites represents a significant knowledge gap, limiting our ability to account for project benefits over decadal (or longer) timescales and develop data driven trajectory curves used to develop ecological success criteria and project milestones.

The absence of long-term datasets also represents an ecological trajectory gap that persists between documenting conditions at recently constructed beneficial use projects and projecting those conditions across project lifespans (Figure 2). Without that information our capacity to develop accurate project lifecycle analysis, including long-term benefit-cost determinations remains constrained. In response, a research effort was initiated to evaluate conditions at six of the oldest dredged material beneficial use projects for which historic data is available in order to evaluate the long-term ecological trajectory of engineered systems and compare them with their natural counterparts.

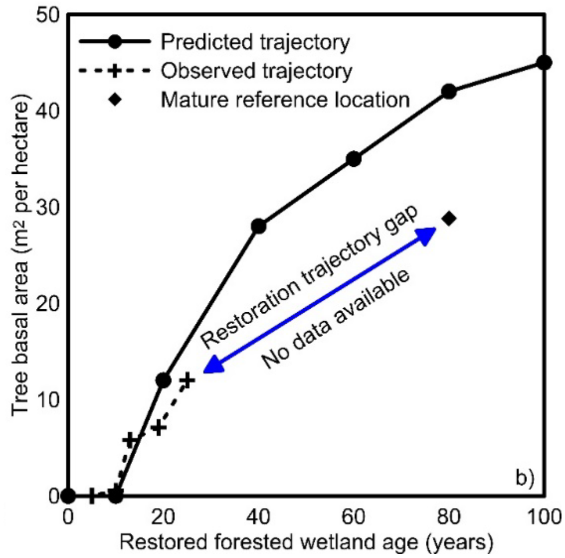

Figure 2. Example of a restoration trajectory curve evaluating tree growth following implementation of habitat restoration projects. This highlights the knowledge and ecological trajectory gaps between conditions documented at mature natural reference areas (◆), observations at established habitat improvement projects (✚), and estimated conditions under post construction scenarios (●). Adapted from Berkowitz (2019).

STUDY LOCATIONS AND APPROACH

During 2019, researchers conducted natural resource assessments at six historic dredged material beneficial use projects constructed between 1974 and 1977, where earlier studies were completed as described in Landin et al., (1989) and others. These project locations represent some of the earliest beneficial use sites with available post construction monitoring data in the United States. As a result, the projects sites provide a unique opportunity to investigate the mid- to long-term outcomes of early dredged material beneficial use initiatives. Additionally, the projects occurred across a range of geographic locations and target habitat types (e.g., marsh, upland meadow), allowing for the evaluation of outcomes across the nation and in a variety of ecological settings (Figure 3).

Figure 3. Location (●) of the six historic beneficial use projects evaluated.

The U.S. Army Corps of Engineers Dredged Material Research Program funded construction or the six project sites. A monitoring program was initiated under the U.S. Army Corps of Engineers Dredging Operation Technical Support (DOTS) Program to document the stability and successional changes of the projects, and relate the observed conditions at the project sites to natural, reference systems (Newling and Landin 1985). The monitoring program concluded in 1987. Notably, the projects focused on improving habitat at each location and the historic monitoring efforts did not consider engineering benefits or other factors that are now recognized within broader contexts such as the EWN initiative.

The following section provides a general overview of each beneficial use project and outlines the construction and initial monitoring results for each study location. Subsequent sections describe the results of the 2019 data collection effort and compare results to both 1) the early (1974-1987) study data and 2) conditions observed at reference systems. To the extent possible, researchers applied the same monitoring techniques utilized during the historical monitoring efforts to support these comparisons.

Accordingly, the 2019 assessment effort established triplicate vegetation sample points within representative locations of each plant community observed within the beneficial use sites and at corresponding reference locations (Figure 4). Meter square quadrats were used to estimate percent cover by species and 0.25 m2 quadrats were used to calculate stem densities at each vegetation sampling location. The results of three triplicate measurements were averaged for reporting purposes. In some cases, transects were established to stratify sampling across elevation gradients and associated plant community types (e.g., low marsh, high marsh, transitional zones, herbaceous upland, forested upland).

Plant communities were classified based on dominant and/or diagnostic species assemblages. Values for community composition and species abundance that were reported in historic monitoring studies were compared to current data to assess contemporary conditions and development and maintenance of target ecological outcomes (Allen et al. 1978; Landin et al. 1989; Newling & Landin 1985; Webb et al. 1978).

Additionally, data on avian species assemblages and soil properties were collected, but those results are not presented herein and will available following publication of a comprehensive technical report (Berkowitz et al., In Review) and journal paper. The following provides a brief description of each beneficial use project, focusing on the objectives of construction, target habitat types, and other supporting information.

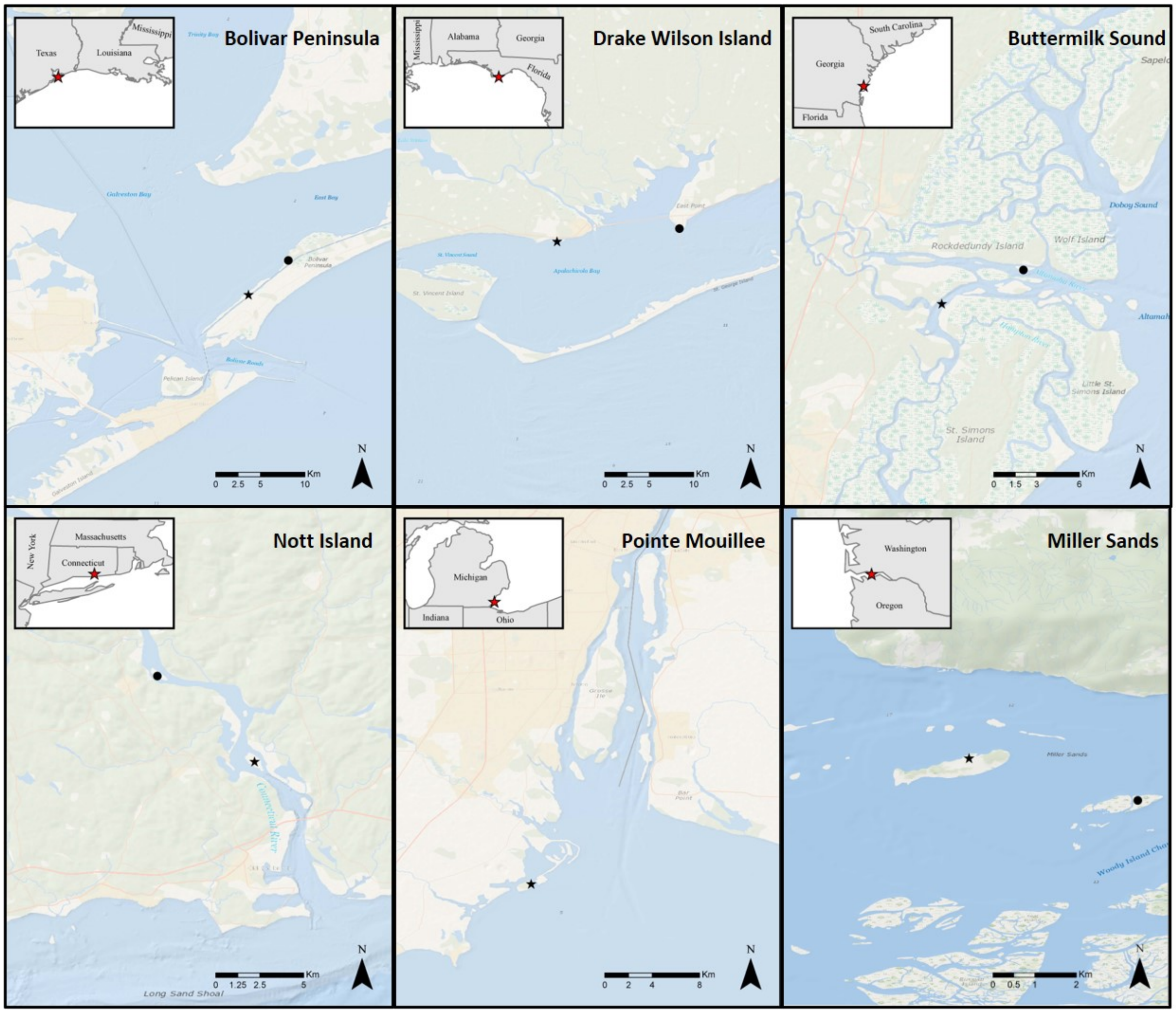

Figure 4. Beneficial use study locations (★) and reference sites (●) evaluated during the study.

Bolivar Peninsula, TX

The Bolivar Peninsula beneficial use project is located adjacent to the Gulf Intercoastal Waterway near the Houston Ship Channel. The location was selected because it exhibited representative conditions observed at many of the dredge material placement sites in coastal Texas and the Gulf of Mexico (Allen et al. 1978). In 1976, a 11.1 ha area of dredged materials previously deposited on the peninsula were contoured using construction equipment to create an elevation gradient capable of supporting the establishment of upland, high marsh and low marsh/intertidal habitats oriented perpendicular to Galveston Bay. A temporary sandbag dike was constructed to protect the dredged material placed into a lower intertidal marsh environment from the erosive forces of waves and encourage stabilization/consolidation of the dredged materials. Vegetation plantings were established in 1976 and 1977 in both wetland and upland areas using different fertilizer treatment and plantings. A reference marsh, Pepper Grove, was identified east that had similar wind and wave characteristics as the beneficial use project location.

Differences in elevation between the beneficial use site and the reference marsh were identified as important during the historic studies. These early reports indicated that plant growth equaled or exceeded values at the Pepper Grove reference area; however, root biomass remained lower than observed in the unaltered natural marsh. General findings of the early monitoring efforts indicated that smooth cordgrass and saltmeadow cordgrass can be established on dredged materials, but that elevation gradients strongly influenced species survival and vigor and should be incorporated into project design and implementation.

This project adheres to the principles and objectives of EWN because it mimicked natural elevation gradients to establish a variety of habitats and target vegetation community types based upon observations made at natural, unaltered locations in the region. Additionally, the project avoided the inclusion of hardened engineering features (e.g., riprap) and, following initial construction, allowed for natural tidal processes and natural patterns of succession and landform change to drive the projects evolution.

Drake Wilson Island, FL
Drake Wilson Island was developed in 1976 using sandy dredged material derived from the adjacent Two-Mile Channel, a navigation route used to access the city of Apalachicola Florida, the Gulf Intercostal Waterway, Apalachicola Bay, and the Gulf of Mexico. The navigation channel is utilized by the local commercial fishery fleet, recreational boaters, and those transporting materials through northeast Florida waterways. In early 1976, the 5-ha project sought to develop an emergent marsh by placing hydraulically pumped dredged material into an intertidal environment. The location was selected because it typifies the northeast Gulf Coast intertidal islands in the region. Prior to dredged material placement, a temporary dike and weir was installed adjacent navigation channel to prevent erosion until consolidation occurred. This allowed intertidal exchange and protected the newly established marsh vegetation. During construction, fine-grained silty dredged material was pumped into the site, covering older course-grained sandy dredged material deposited during previous dredging operations. Planting was conducted and the site was fully vegetated by 1978. Later monitoring efforts reported that the site was heavily utilized by wildlife in 1986 (Landin et al. 1989). A reference marsh, Cat Point, was located east of the study site.

This project adheres to the principles and objectives of EWN because it utilized fine grained sediments that occur in the natural marshes within the region to cap the older sandy dredges materials, encouraged natural patterns of marsh inundation using the weir during the initial post construction phase, and allowed natural processes to degrade the weir and dike needed for initial stabilization ensuring tidal exchange would continue. Plantings utilized locally sourced materials selected based upon appropriate landscape positions and salinity/inundation tolerances. Additionally, the project avoided the inclusion of hardened engineering features and, following initial construction allowed natural processes (e.g., tides, species succession) to drive the evolution of the project area.

Buttermilk Sound, GA
The 2.1-ha beneficial use project at Buttermilk Sound was developed in 1975, adjacent to the Atlantic Intracoastal Waterway near the mouth of the Altamaha River, GA. The area is used by the local fishing community, those transporting goods along the intercostal waterway, and those accessing the barrier islands and open ocean from the nearby cities of Brunswick and Darien, GA. The beneficial use project site was selected because it was representative of a South Atlantic sandy dredged material disposal sites in the region that buried natural salt marshes. The objectives of the project were to: 1) convert the ~5m high dredged material sand mound to a intertidal marsh habitat; 2) document changes in the field site over time; and 3) demonstrate that a stable marsh could be created using sandy dredged material. The area was graded to a 3.7% slope and planted with vegetation. A nearby reference marsh location, Hardhead Island, was selected to assess vegetation and site characteristics of a naturally evolved wetland ecosystem in close proximity to the project. Within five years of construction, the project is reported to be visually indistinguishable from unaltered marshes (Landin et al., 1989).

This project adheres to the principles and objectives of EWN because it re-established the environmental gradient of elevation, inundation, and salinity observed in unaltered areas in the region. Also, the project allowed for natural processes (e.g., tidal creek evolution and migration) to occur while avoiding the use of hardened engineering features.

Nott Island, CT

The Nott Island beneficial use site is located on the Connecticut River, one of the state's most vital waterways servicing recreational harbors and commercial waterfronts in Essex, Lyme, Hartford, Haddam, and other communities. The 3.2-ha project was developed in 1974. Nott island had been used a dredged material placement area during periodic channel unvegetated mound of sand, substantially raising the elevation of the island. The location was selected because it reflected conditions at many islands in the northeastern United States where navigation channel maintenance dredging deposited materials on top of natural landforms. The sandy dredge material deposits were low quality habitat and poor vegetation established on the sites due to nutrient limitations, course soil textures, and steep grades. The beneficial use project incorporated fine grained dredged materials into the sandy substrate. Temporary dikes were built to contain the fine-grained materials during dewatering and homogenization using construction equipment and farming implements (e.g., disking). Follow substate mixing, the site was treated with lime and fertilizer. Vegetation was planted to create a nesting and feeding meadow for mallards, Canada geese, and other species. In general, the grasses were successfully established, with approximately 80% of the planted area vegetated within the first growing season. Eustasia Island was selected as a reference monitoring site due to its similar geomorphology, substrate, and proximal location to Nott Island.

This project adheres to the principles and objectives of EWN because it incorporated finer grained sediments into the sandy dredged material deposits to mimic soil textures found in unaltered habitats in the region, encouraged the establishment of plant communities of high habitat value, and allowed natural patterns of plant species succession to occur following initial construction and planting efforts. Additionally, the project avoided the inclusion of hardened engineering features and attempted to diversify the variety of habitat types found within the project area.

Pointe Mouillee, MI

The Pointe Mouillee beneficial use project is located adjacent to the western shore of Lake Erie, Michigan. Historically, the area included a barrier beach, which protected an extensive marsh from wind and wave driven erosion. However, the barrier beach was destroyed in the 1960's by a series of high energy storm events coinciding with a period of high lake levels. Following degradation of the barrier beach extensive erosion decreased the spatial extent of the marsh. Concurrently, sediments from the Huron River that historically supported and nourished the Pointe Mouillee marshes and barrier beach were reduced by the construction of dams and reservoirs that prevented sediment transport and deposition. This resulted in the degradation and inundation of >1618 ha of marshes and an expansion of open water. In response, 148-ha were diked in 1963 to protect and maintain the remaining marsh habitats. In 1967, a Confined Disposal Facility (CDF) was constructed at Pointe Mouillee to hold dredged materials removed from the Lake Erie Ship Channel and protect provide additional protection for the degraded adjacent marsh. The CDF was strategically situated and designed to match the configuration of the historic barrier island to support revitalization of the degraded marsh. Dikes facing the open expanse of Lake Erie were armored with riprap to protect the feature from erosion, and a system of culverts and water control structures were used to manage water levels within the project area.

The objectives of the project were to: 1) protect and stabilize the wetlands and shoreline and an adjacent wildlife management area; 2) reestablish the degraded marsh through sedimentation and plant colonization; 3) establish a multiuse site on both the CDF and the wildlife management area that includes a visitors' center and supports multiple recreational activities; and 4) provide opportunities for the deposition of dredged material from western Lake Erie harbors and channels as part of re-occurring maintenance dredging operations. Vegetation communities inside the CDF included emergent cattail and bulrush wetlands, and a high marsh component dominated by common reed. Vegetation data indicated that plant colonization took place within three growing seasons after construction (Landin et al. 1989). No reference monitoring location was selected near the Pointe Mouillee beneficial use site.

The Pointe Mouillee project adheres to the principles and objectives of EWN because it protected the existing marshes to the west, while providing habitat and recreational opportunities and maintaining the capacity to manage dredged materials and navigation channels within the western Lake Erie basin. Unlike the other projects examined in the study, the Pointe Mouillee project did utilize hard infrastructure including protected dikes to stabilize project features and prevent wind and wave erosion from occurring. However, the development of infrastructure was needed to replace the ecological functions (i.e, wave energy attenuation) and engineering benefits (i.e., shoreline stabilization; storm surge reduction) provided by the eroded barrier beach that previously protected the surrounding marshes.

Miller Sands, OR
The Miller Sands beneficial use project is located in close proximity to the Columbia River navigation channel near Astoria, OR. The site is a large, horseshoe-shaped dredged material island within the freshwater intertidal reach of the river. The original island was constructed with dredged materials in 1932 and continued to receive additional dredged materials during maintenance operations at approximate 4-year intervals (Landin et al. 1989). The beneficial use project resulted in development of three distinct habitats including 1) upland meadows, 2) wetland marshes, and 3) dunes on the sand spit designed to protect the adjacent wetlands and other features from wind and wave driven erosion. In 1974, the upland portion was disked using farming implements and heavy machinery to prepare a seed bed, followed by planting; portions of the islands were graded to an intertidal elevation and planted to support development of the wetland habitats; and the sand spit was planted with beachgrass interspersed with sand fencing, rapidly inducing the formation of dunes. A nearby marsh, Snag Island, was select as reference location for comparison with the wetland portions of the beneficial use project.

This project adheres to the principles and objectives of EWN because it was designed to provide a variety of habitat types (uplands, wetland, dune) common in the region based on the gradient of elevations and associated inundation patterns. Additionally, the project utilized natural processes (e.g., erosion of the sand berm and dunes, sediment accretion in wetlands) to naturally contour and shape the island after construction, while providing for the management of dredged materials in the Columbia River navigation channel. Plantings materials were selected based upon appropriate landscape positions and inundation tolerances to establish a variety of habitats and target vegetation community types using observations made at natural, unaltered locations in the region. Additionally, the project avoided the inclusion of hardened engineering features and, following initial construction, let natural processes drive the ecological evolution of the project area.

RESULTS AND DISCUSSION

The beneficial use projects successfully developed the target habitat types described in the project objectives and historic monitoring reports, and 13 of the 15 target habitats continue to persist more than four decades after project construction (Table 1; Figures 5a and 5b). The vegetation community data collected during the 2019 survey demonstrates that the beneficial use projects continue to provide a variety of habitat, physical/hydrology, and biogeochemical cycling functions important to ecological processes that can be linked with associated engineering benefits.

Table 1. Summary of target vegetation community types, success of sustained development over >40-years, challenges, and management opportunities to improve conditions at the study locations.

Location	Habitat type	Present after >40 years	Sustainable without intervention	Challenges	Management opportunities
Bolivar Peninsula	Low marsh	No	No	Erosion	Sediment placement
	High marsh	Yes	Yes	None	None
	Herbaceous upland	Yes	Yes	Undesirable species	Selective species control
	Woody upland	Yes	Yes	Species planted outside of native range, poor survival	Selective species control
Drake Wilson Island, FL	Low marsh	Yes	Yes	Land surface decrease	Sediment placement
	High marsh	Yes	Yes	Land surface decrease	Sediment placement
	Woody upland	Yes	Yes	None	None
Buttermilk Sound, GA	Low marsh	Yes	Yes	None	None
	High marsh	Yes	Yes	None	None
	Un-vegetated upland	Yes	No	Woody species	Selective species control
Nott Island, CT	Upland meadow	Yes	Yes	Undesirable species, poor soil quality	Selective species control, soil amendments
Pointe Mouillee, MI	Freshwater marsh	Yes	No	Woody species, ongoing management	Selective species control
Miller Sands, OR	Upland meadow	Yes	No	Poor soil quality, woody vegetation	Selective species control, soil amendments
	Tidal marsh	Yes	Yes	Erosion, Invasive species	Selective species control
	Dune	Yes	No	Lack of sediment	Sediment placement

Notably, the spatial distribution of habitat components and/or the suite of vegetation species present today differs from the conditions observed during post-construction and early monitoring surveys at some study locations. For example, a number of the vegetation species planted and/or initially established at the Bolivar Peninsula are either absent or occur as minor components of the plant community. The shift in species composition following construction is not unanticipated as ecological succession occurs in response to biotic and abiotic factors that drive the success of individual species and plant communities over time (Zedler 2000).

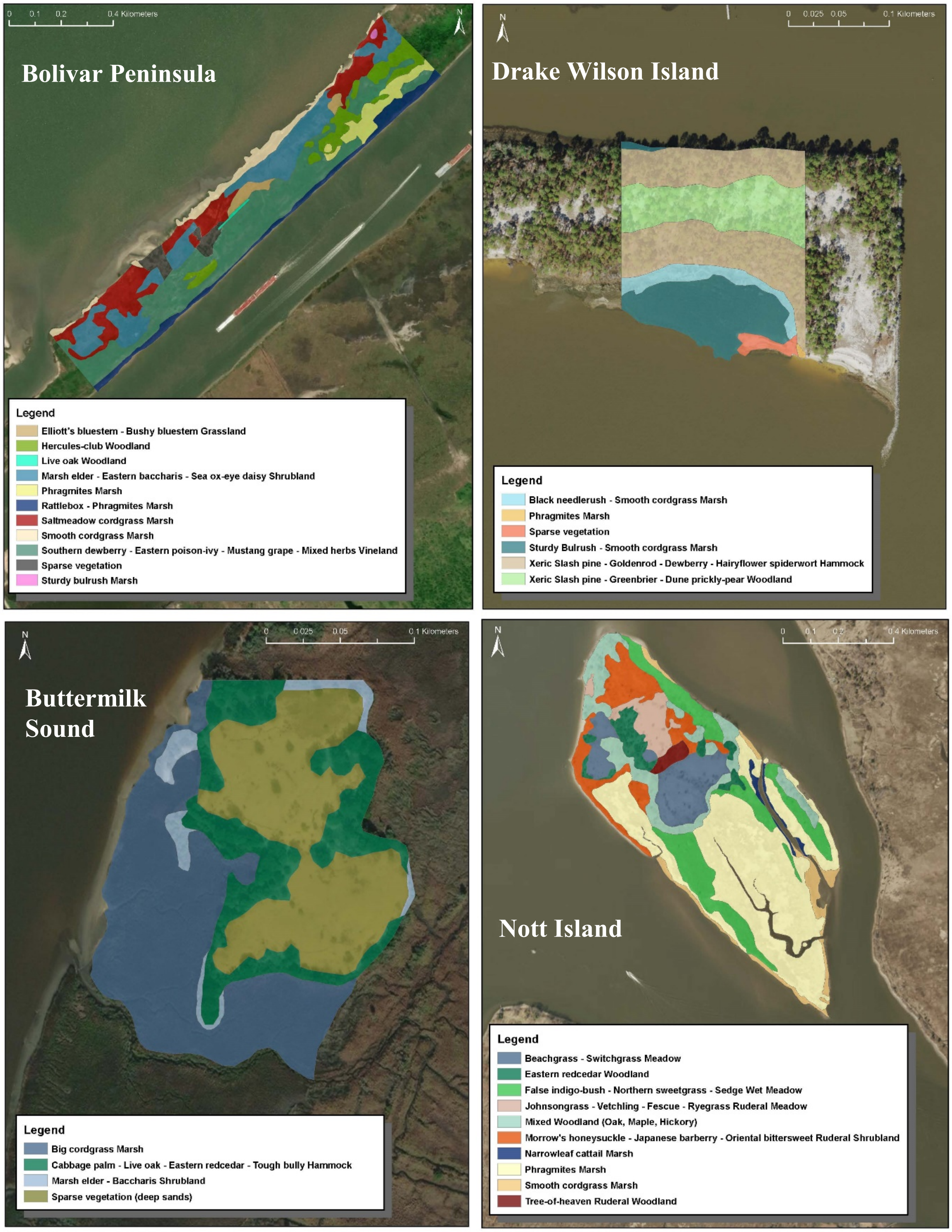

Figure 5a. Vegetation community composition at beneficial use projects after >40 years.

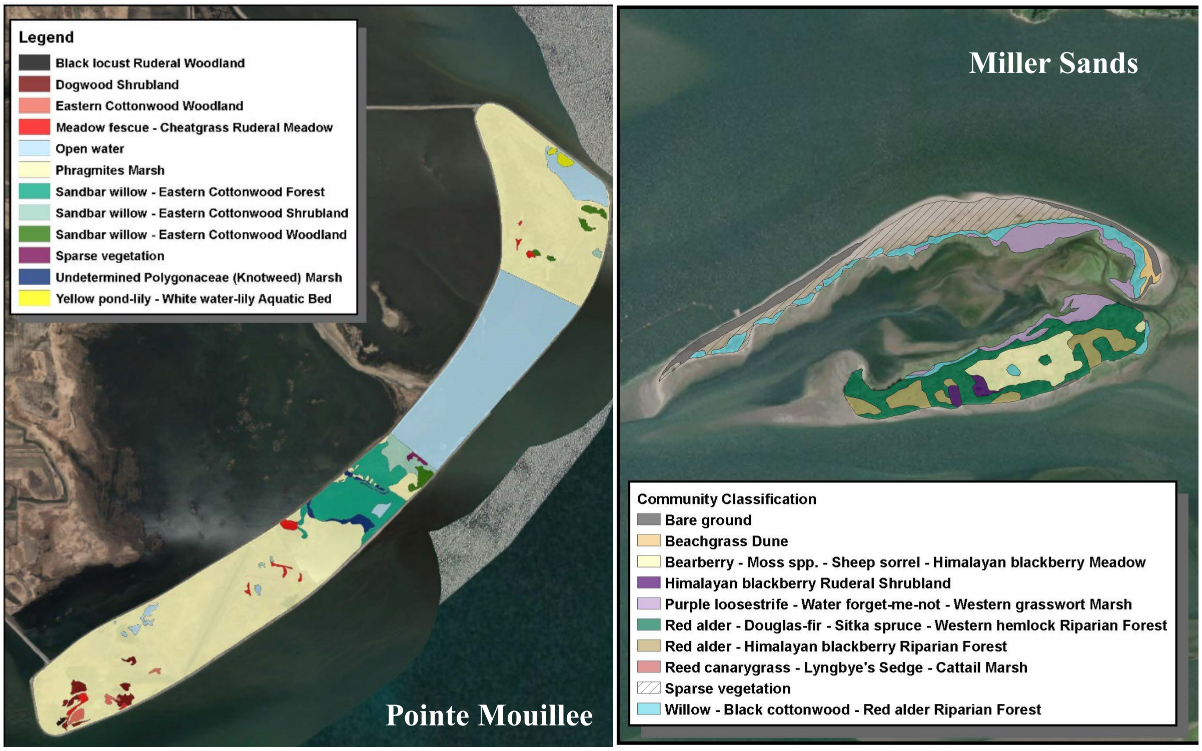

Figure 5b. Vegetation community composition at beneficial use projects after >40 years.

In some cases, the disconnect between project designs and steady state conditions can be attributed to inappropriate species selection, including the planting of some species (e.g., sand pine in coastal TX) outside of their native ranges. At other project locations, target habitat communities may not be sustainable without further interventions to maintain favorable conditions. For example, additional periodic sediment placement may be required to maintain low marsh communities (Bolivar, TX), woody plant removal would help sustain open sandy habitats (Buttermilk Sound, GA), and soil amendments would help improve the conditions for vegetative growth and habitat development in areas subject to nutrient limitations (Miller Sands, OR). Additionally, nuisance, invasive, and non-native species pose a significant challenge to achieving ecological goals across many of the study sites, as well as a number of the reference locations evaluated. In general, the number of undesirable species and their abundance has increased during the post construction period in both beneficial use and reference monitoring areas.

The available data suggests that initial planting efforts had limited effects on the persistence and distribution of plant species after 40 years of ecological succession, and some studies have inferred that in areas with rapid natural recruitment post restoration plantings may not be necessary (Mitsch et al 1998). In the current study, plantings of saltmeadow cordgrass and smooth cordgrass at Drake Wilson Island, FL have become components of more complex communities, as other species that were not planted have been recruited. In other cases, planted species (e.g., black needlerush at Buttermilk Sound, GA) are no longer observed within the project area, or occur to a much lower extent.

Despite the absence of some planted species at beneficial use locations >40 years after construction, establishing appropriate species following project construction likely has advantages even if those plant communities do not persist or undergo alteration over decadal timescales. Initiating vegetative growth after disturbance has been shown to stabilize soils and sediments, accelerate dewatering, provide habitat, retain sediment and build elevation, improve soil health, and promote ecological functions and engineering benefits (Bailey et al. 2019). Additionally, establishing plant communities can influence the trajectory of restoration areas, even if the initial species introduced fail to persist, migrates in response to environmental conditions, or becomes integrated into a more diverse plant assemblage (Simonstad et al. 2006). The establishment of desirable species has also been shown to preclude the invasion of non-desirable species and may provide other ecosystem functions and engineering benefits as site maturation and succession takes place.

The major trends and findings of this study that can help inform the development of future beneficial use projects are highlighted below.

1) The habitat complexity of study locations generally increased over time, as observed at Bolivar Peninsula, TX which exhibited six distinct vegetation communities during the 1988 assessment, increasing to 10 vegetation communities in 2019 (Table 2). The increase in complexity over time is not unexpected given natural patterns of vegetation recruitment, response to disturbance, and the adjustment of plant communities to local conditions following four decades of ecological succession. Increases in species complexity following restoration have been reported in other studies, especially as seed banks become enriched over time. Baldwin (2004) provides a model outlining patterns of plant distribution following restoration, planting, colonization, and expansion of clonal perennials in restored/created marsh habitats. As outlined in the model, observed increases in species richness are not expected to continue indefinitely as the project sites reach equilibrium, however species composition will continue to respond to disturbances (e.g., floods, fire) and changes in ecological conditions (e.g., climate; invasive species introduction) in the future. These changes reflect natural and anthropogenic drivers occurring in both beneficial use locations and reference communities.

Table 2. Summary of vegetation community characteristics. NA = no data available.

	Vegetation community assemblages (count)		Dominant species richness in target community types (count)			
Location	Beneficial use (BU) site	Reference location	Habitat type	BU (2019)	Historic	Reference (2019)
Bolivar Peninsula, TX	10	1	Low marsh	4	2	2
Drake Wilson Island, FL	6	8	Low marsh	2	2	2
Buttermilk Sound, GA	4	2	Marsh	3	4	3
Nott Island, CT	10	4	Meadow	16	5	NA
Pointe Mouillee, MI	7	NA	Marsh	7	4	NA
Miller Sands, OR	7	1	Marsh	18	17	15

2) The vegetation community assemblages observed in the beneficial use sites were more ecologically complex than the reference areas, with the exception of the Cat Point reference area which exhibited barrier beach features absent at the Drake Wilson Island study location (Table 2). The increased complexity results from a combination of factors including the wider degree of topographic relief within the constructed project areas relative to the reference areas. This finding may seem counterintuitive, as other studies have identified the lack of topographic heterogeneity (e.g., microtopography) as a limitation on many restoration projects (Bruland and Richardson 2005). However, within the locations examined, one of the driving factors behind the restoration design was to create appropriate ecological gradients that would support a variety of habitats. This included the intentional establishment of upland, transitional, high marsh, and low marsh target habitats with ecologically based landforms and hydropatterns.

3) The number of species in target communities has generally remained stable or increased over time and display higher species richness than the reference locations examined. This finding suggest that the beneficial use projects have reached a moderate level of maturity yet do not directly mimic the plant community assemblages of reference areas. The differences in species richness aligns with other studies that report engineered or restored areas often exhibit more species than their natural counterparts (Ehrenfeld 2000). The differences in species composition and richness may include intentionally or unintentionally introduced plants, the response of plant communities to varying substrate conditions, or reflect disturbance patterns associated with restoration design and implementation (Baldwin and Derico 1999). While the beneficial use projects have trended towards conditions observed in reference areas, differences continue to persist after more than four decades of plant succession.

4) Both beneficial use locations and reference areas appear to be responding to environmental conditions in similar ways despite the observed differences in species composition and structural complexity. More invasive species were observed at the study locations and reference areas during 2019 than during previous investigations and those species appear to be increasing in abundance. This trend has been reported in other areas and at larger spatial scales, where anthropogenic landscape alterations coupled with natural patterns of disturbance and plant dispersal are leading to increased alien invasions (Richardson et al 2007). Additionally, stem densities in both restored and reference areas follow similar patterns over the multi-decadal assessment period despite the observed differences in species composition and habitat complexity (Figure 6). This further suggests that the vegetation communities at beneficial use locations are exhibiting similar responses to changing environmental conditions that impact plant distribution and growth at reference areas.

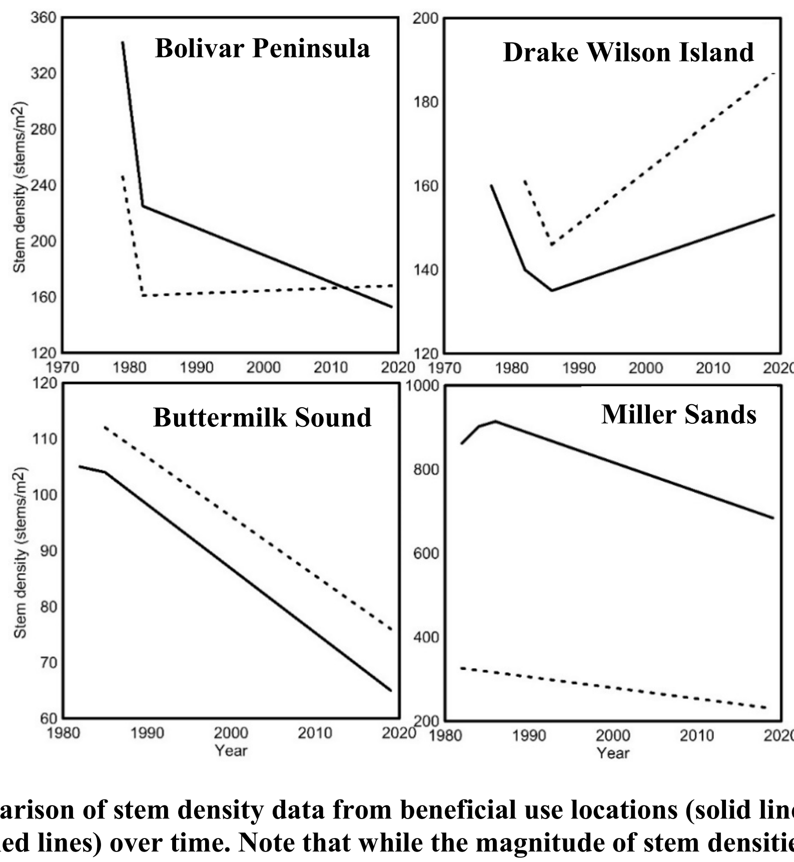

Figure 6. Comparison of stem density data from beneficial use locations (solid lines) and reference areas (dashed lines) over time. Note that while the magnitude of stem densities varies, the constructed and reference locations display similar patterns and responses to environmental conditions over time.

In summary, these findings suggest that the vegetation communities established at the beneficial use sites undoubtedly improved habitat. The project areas generally reflect the conditions at reference locations and have become more similar to reference conditions with age, but do not replicate the conditions observed in un-engineered systems. The study locations are effectively providing habitat for a number of species and represent stable features that will persist into the future, yielding a variety of ecological functions and engineering benefits. Notably, these study locations have persisted over more than 4 decades without the need for intervention, highlighting the sustainability of beneficial use projects that incorporate ecological drivers (i.e., hydroperiod, salinity tolerance, and topography) into project design and execution. Results also indicate that additional management activities could further improve site conditions especially with regard to selective species management, and in some cases the implementation of periodic disturbance regimes (e.g., additional sediment deposition) may improve the sustainability of some landscape features including low marshes and coastal fringe wetlands.

RECOMMENDATIONS AND CONCLUSIONS

Our findings indicate that beneficial use projects improve habitat, while providing ecological functions and engineering benefits, for multiple decades when designs consider ecosystem factors such as topography and hydrology. However, these projects highlight the fact that environmental factors, not initial planting activities, determine long-term vegetation community composition; and that while the projects trended toward reference location conditions over time, they continue to maintain distinct differences in both habitat type and species composition. The beneficial use projects are more structurally complex than reference areas due to increased topographic heterogeneity and other factors, resulting in additional habitat diversity and a wider range of ecological functions and engineering benefits. This suggests that mimicking reference conditions should not be over-emphasized when evaluating project success and establishing monitoring milestones. Instead practitioners should focus on maximizing the ecological benefits and engineering functions that can be achieved through beneficial use activities.

Management opportunities exist to improve a subset of the beneficial use projects examined projects with periodic interventions, including additional sediment placement and selective species control. Additionally, the historic beneficial use projects examined herein can be placed within the context of the Engineering With Nature® initiative, providing a mechanism to conduct chronosequence analysis through incorporation of newer projects to support life-cycle analysis to promote further integration of beneficial use projects into the navigation management portfolio. Ongoing research will place these results in a framework to better evaluate ecological functions and associated engineering benefits resulting from beneficial use project implementation.

REFERENCES

Allen, H.H., Clairain, E.J., Jr., Diaz, R.J., Ford, A.W., Hunt, L.J., and Wells, R. (1978) “Habitat Development Field Investigations, Bolivar Peninsula Upland and Marsh Habitat Development Site, Galveston Bay, TX; Summary Report”. US Army Engineer Waterways Experiment Station. Technical Report D-78-15.

Bailey, P., Miller, S.J., Cary, T.J., Bourne, S.G. and Sekoni, T.A. (2019) “Plant community approach to establishing vegetation on DMPAs and CDFs”. US Army Engineer Research and Development Center. ERDC-TN EWN-19-2.

Baldwin, A.H. and Derico, E.F., (1999). “The seed bank of a restored tidal freshwater marsh in Washington, DC”. *Urban Ecosystems*, 3(1), 5-20.

Baldwin, Andrew H. (2004) "Restoring complex vegetation in urban settings: the case of tidal freshwater marshes." *Urban Ecosystems,* 7(2), 125-137.

Berkowitz, J.F., Beane, N.R., Philley K.D., Jung J.F., and Hurst N.R. (In Review). "An assessment of long-term, multi-purpose ecosystem functions and engineering benefits derived from historical dredged sediment beneficial use projects". US Army Corps of Engineers, Environmental Laboratory. ERDC-TN EWN-21-X.

Berkowitz, J.F. (2019). "Quantifying functional increases across a large-scale wetland restoration chronosequence". *Wetlands*, 39(3), 559-573.

Bridges, T.S., Lillycrop, J., Wilson, J.R., Fredette, T.J., Suedel, B.C., Banks, C.J. and Russo, E.J. (2014). "Engineering With Nature Promotes Triple-Win Outcomes". *Terra et Aqua,* 135, 17-23.

Bruland, G.L., and Richardson, C.J. (2005). "Hydrologic, edaphic, and vegetative responses to microtopographic reestablishment in a restored wetland." *Restoration Ecology.* 13(3), 515-523.

Coleman J.M., Roberts H.H., Stone G.W. (1998). "Mississippi river delta: an overview". *J Coast Res.* 14, 698–716.

D'Avanzo, C. (1989). "Long-term evaluation of wetland creation projects. In: Wetland creation and restoration: The status of the science volume 2: perspectives". Kusler JA and Kentula MA (Eds). US Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Edwards, K.R. and Proffitt, C.E. (2003). "Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA". *Wetlands*, 23(2), 344-356.

Ehrenfeld, J.G. (2000). "Evaluating wetlands within an urban context". *Ecological Engineering,* 15, 253-265.

Faulkner, S.P. and Poach, M.E. (1996). "Functional comparison of created and natural wetlands in the Atchafalaya Delta, Louisiana". U.S. Army Engineer Waterways Experiment Station, WRP-RE-16.

Landin, M.C., Webb, J.W., and Knutson, P.L. (1989). "Long-Term Monitoring of Eleven Corps of Eleven Corps of Engineers Habitat Development Field Sites Built of Dredged Material, 1974-1987". US Army Corps of Engineers, Environmental Laboratory.

Mallach, T.J., and Leberg, P.L. (1999). "Use of dredged material substrates by nesting terns and black skimmers". *The Journal of wildlife management*, 137-146.

Mitsch, W.J., Xinyuan W., Nairn, R.W., Weihe, P.E., Wang, N., Deal, R., and Boucher, C.E. (1998). "Creating and restoring wetlands." *BioScience,* 48(12), 1019-1030.

Newling, C.J., and Landin, M.C. (1985). "Long-Term Monitoring of Habitat Development at Upland and Wetland Dredged Material Disposal Sites, 1974-1982". US Army Engineer Waterways Experiment Station. Technical Report D-85-5.

Richardson, D.M., Holmes, P.M., Esler, K.J., Galatowitsch, S.M., Stromberg, J.C., Kirkman, S.P., Pyšek, P., and Hobbs, R.J. (2007). "Riparian vegetation: degradation, alien plant invasions, and restoration prospects." *Diversity and distributions* 13(1), 126-139.

Sheehan, C., Harrington, J. (2012). "Management of dredge material in the Republic of Ireland–A review". *Waste Management*, 32(5), 1031-1044.

Simenstad, C., Reed D., and Ford, M. (2006). "When is restoration not?: Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration." *Ecological Engineering,* 26, (1), 27-39.

Streever, W.J. (2000). "Spartina alterniflora marshes on dredged material: a critical review of the ongoing debate over success". *Wetlands Ecology and Management*, 8(5), 295-316.

Webb, J.W., Dodd, J.D., Cain, B.W., Leavens, W.R. and Hossner, L.R. (1978). "Habitat Development Field Investigations, Bolivar Peninsula Marsh and Upland Habitat Development Site, Galveston Bay, Texas. Appendix D. Propagation of Vascular Plants and Post-propagation Monitoring of Botanical, Soil, Aquatic Biota, and Wildlife Resources". Texas Agricultural Experiment Station.

Yozzo, D.J., Wilber, P., and Will, R.J. (2004). "Beneficial use of dredged material for habitat creation, enhancement, and restoration in New York–New Jersey Harbor". *Journal of Environmental Management*, 73(1), 39-52.

Zedler, J.B. (2000). "Progress in wetland restoration ecology". *Trends in ecology & evolution*, 15(10), 402-407.

CITATION

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DATA AVAILABILITY

Additional data supporting the results and conclusions presented herein will be available in a forthcoming technical report and may be obtained from the corresponding author by request.

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BENEFICIAL USE: ESTUARINE ISLAND CREATION WITH INTRACOASTAL WATERWAY MAINTENANCE DREDGED MATERIAL IN LAKE WORTH LAGOON; PALM BEACH COUNTY, FLORIDA

Y. Siddiqui[1], L. Brownell[2], E. Anderson[3], J. Vannoy[4] and M. Crosley[5]

ABSTRACT

The Florida Inland Navigation District sponsored a project to maintenance dredge the Intracoastal Waterway channel to -10 feet (ft) Mean Lower Low Water, its federally authorized depth, in a 4.5-mile section from the Port of Palm Beach to the Town of Palm Beach docks in Palm Beach County, Florida. The original permitted project involved hydraulically dredging and pumping to the District-owned Peanut Island, a 17-Acre Dredged Material Management Area located north of Lake Worth Inlet. However, to maintain valuable upland storage capacity and leverage beneficial sand sources for Palm Beach County's Tarpon Cove restoration project, Taylor Engineering facilitated coordination between the County and District to modify the placement area to Palm Beach County's beneficial use site. Palm Beach County had previously obtained permits authorizing restoration and enhancement of Tarpon Cove — a 46-acre site located approximately 1.2 miles south of the Town of Palm Beach docks — by creating seagrass, mangrove, and oyster reef habitat where poor sediment quality and dredged holes otherwise prevented development of high-quality habitats. Orion commenced dredging on a 24-hour, 7-days per week schedule in March 2019 and ended in May 2019. Orion mechanically dredged and transferred 85,000 cubic yards of material from the Intracoastal Waterway channel to the Tarpon Cove restoration project.

Following the completion of the maintenance project, the County created a second intertidal island with sand acquired from another local area project to create a total of 2.40 acres of coastal habitat and 3 acres of shallow water seagrass habitat. Since the initial placement of the IWW material in 2019, these islands have provided an essential nesting habitat for the American Oystercatcher Least Terns, and Black Skimmers. This project demonstrates that through proper planning, design, and coordination with the relevant stakeholders, maintenance dredging projects may provide sediment for environmental restoration with economic benefits to the navigation authority, local government, and the community at large.

Keywords: Dredging, navigation, beneficial reuse, dredged material disposal, island creation, public-private partnerships.

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INTRODUCTION

The Florida Inland Navigation District (FIND) — local sponsor for the 407-mile federally authorized Florida Atlantic Intracoastal Waterway (AIWW), Intracoastal Waterway (IWW) and the eastern 98 miles of the Okeechobee Waterway (OWW) — sponsored a project to maintenance dredge the IWW channel to -10 feet (ft) Mean Lower Low Water (MLLW), its federally authorized depth, in a 4.5-mile section from the Port of Palm Beach to the Town of Palm Beach docks in Palm Beach County, Florida (Figure 1). This portion of the IWW channel had not received maintenance dredging since its construction in the 1960s. The project removed shoals impeding navigation and restored the channel to its federally authorized dimensions.

Figure 1. Project area limits

FIND formulated the project to provide recreational boaters and commercial vessels safer access to the area's marinas, boatyards, and shipping facilities. Partnerships between project stakeholders and environmental regulatory agencies — including the FIND, the Port of Palm Beach, Palm Beach County (County), state and federal permitting agencies, local boating and commercial industry groups, as well as the FIND Engineer (Taylor Engineering, Inc.) and the dredging contractor (Orion Marine Construction, Inc. [Orion]) — ultimately led to a successful project outcome.

FIND's IWW channel dredging permits authorized upland containment of dredged material in FIND's Peanut Island Dredged Material Management Area (DMMA). However, to support an overall cost-effective strategy to leverage beneficial sand sources for Palm Beach County's Tarpon Cove restoration project, Taylor Engineering facilitated coordination between the County and FIND to modify FIND's permits to allow placement of the IWW material in the county's restoration site. Palm Beach County had previously acquired Florida Department of Environmental Protection (FDEP) and Department of the Army (from the U.S. Army Corps of Engineers [USACE]) permits authorizing restoration and enhancement of Tarpon Cove — a 46 acre site located approximately 1.2 miles south of the Town of Palm Beach docks — by creating seagrass, mangrove, and oyster reef habitat where poor sediment quality and dredged holes otherwise prevented development of high-quality habitats. Orion commenced dredging on a 24-hour, 7-days per week schedule in March 2019 and ended in May 2019. Orion mechanically dredged and transferred 85,000 cubic yards (cy) of material from the IWW channel to the Tarpon Cove restoration project.

PARTNERSHIP HISTORY

The Lake Worth Lagoon (Lagoon) estuary in Palm Beach County runs approximately 20 miles along the southeast coastline of Florida. The Lagoon is an urban estuary that has suffered extensive loss of estuarine habitats and degraded water quality due to human development activities over the past century. Approximately 81% of the Lagoon's shoreline is developed with seawalls associated with private residences and businesses (PBC ERM, 2016). Decades ago, dredging of sediments throughout the Lagoon supported local development. The dredging created large benthic 'holes' that now impair the Lagoon's ecosystem as they are well below adjacent grade, often anoxic, and generally do not support seagrass or other submerged resources. Additionally, canals that drain into the Lagoon have introduced fine-grained, silty sediments that settle in these holes, hinder recruitment of seagrasses, and diminish water quality.

FIND and Palm Beach County Department of Environmental Resources Management (PBC ERM) are two members of the Lake Worth Lagoon Initiative (Initiative), a multi-agency effort to increase awareness, support, and funding assistance for projects to improve and protect natural resources within the watershed of the Lagoon. The Initiative has successfully promoted interagency coordination and commitment to Lagoon restoration and protection. The Initiative was the genesis to the FIND and PBC ERM partnership that enabled IWW maintenance dredged material placement at the County's Tarpon Cove restoration project.

FIND has historically supported County restoration and public use projects by providing dredged material for beneficial reuse, or through project grant funding cost-share participation via FIND's Waterway Assistance Program. For example, 1.2 million cy of material from Peanut Island DMMA transferred to the Snook Islands Natural Area in 2003-2005 created 100 acres of shallow water estuarine habitat for seagrass, mangroves, spartina, and oyster reefs. In 2009-2010, 47,000 cy of material from FIND's Juno Dunes DMMA area supported creation and enhancement of 14 acres of mangrove habitat and created 3.2 acres of shallow water seagrass area accompanying the construction of boardwalks, floating docks, an observation tower, and picnic areas. The excavated materials created wetlands and filled dredged holes to create intertidal mangrove islands at the County's South Cove Natural Area in West Palm Beach. Also, in 2010, FIND expedited and completed a small (16,250 cy) IWW maintenance dredging project in West Palm Beach to provide fill for the South Cove Natural Area project for its beneficial reuse of dredged material.

The successful completion of restoration of dredged holes at Snook Islands and South Cove Natural Areas did not rely solely on a partnership with FIND to provide material; the local marine community (i.e., Rybovich Marine Center, Palm Harbor Marina, and Lockheed Martin) also provided material for the projects as a cost-effective disposal alternative for beneficial use of dredged materials. Seeing the positive results of these public-private partnerships, the County saw a need to have additional dredged holes, such as Tarpon Cove, permitted for future restoration and beneficial use of dredged materials.

PERMITTING AND DESIGN

IWW Maintenance Dredging

Taylor Engineering began permitting the dredging project in 2015. State and federal agencies issued environmental permits in 2018, and Taylor Engineering secured permit modifications for alteration of the final placement area in 2019. Taylor Engineering faced significant permitting and design challenges, which resulted in a two-year permitting timeframe, stemming from (1) modification of the original project from a deepening to a maintenance dredging project, (2) identification of seagrass and hardbottom impacts, (3) surveying and performing diving investigations for thirty-two utility crossings, and (4) modification of the final dredged material placement area. Technical resolution of these issues and ultimate permit acquisition focused on developing alternative strategies that optimized channel design while balancing the economic return to the local area community, minimizing environmental impacts, and providing environmental restoration benefits.

A March 2001 USACE Detailed Project Report (*Palm Beach Harbor Lake Work Access Channel Expansion Section 107 Small Navigation Project; Palm Beach County, Florida*) made a case for a 5.2 mile long — inclusive of the area between the Port of Palm Beach and Town of Palm Beach Docks — deepening project that would increase the channel depth from -10 ft MLLW to -18 ft MLLW. To reevaluate the project need, nearly two decades later, FIND and Taylor Engineering evaluated several channel design alternatives. One of the alternatives included an existing adjacent federally authorized 2.8-mile side channel and basin (USACE, 1971) east of the IWW that extended between Lake Worth Inlet and the shoreline of the Town of Palm Beach. Evaluation criteria included variable project lengths, dredge quantities (as compared to the Peanut Island DMMA capacity of 366,000 cy), conflicting submerged utility crossings, and submerged natural resource impacts. The 2001 USACE Detailed Project Report recommendation entailed the greatest dredging volume (1.2 million cubic yards) at -18 ft MLLW, 32 possible utility crossings, and submerged natural resources impact. Based on a current lack of substantial marina and mega-yacht facilities south of the Port of Palm Beach, the requirement to relocate 16 of the 32 identified utilities, and impacts to submerged environmental resources, FIND elected to forgo the deepening and move forward with a project to maintenance dredge 4.5 miles of the existing IWW channel to a depth of -10 ft MLLW (with an additional 2-ft of allowable overdepth) to serve the immediate needs and use of the IWW.

Tarpon Cove Restoration Area

In 2014, the County implemented a scoping effort to identify the dredged holes in the Lagoon and determine potential environmental enhancement projects and options for possible future mitigation needs. The first component of that effort was to create a Sub-Committee from the County's Artificial Reef and Estuarine Enhancement Committee to seek feedback on the potential restoration sites, eliminate from consideration some of the holes that have substantial recreational/fishing value, and arrive at a consensus on which holes to study for potential restoration. The Sub-Committee identified the Tarpon Cove project area as an area with high wave energy associated with an unrestricted wake zone and good shoreline fishing. These conditions offered an ideal area for island creation to provide wetland habitat, protect the adjacent shoreline, and enhance fisheries utilization. The Committee recommended keeping all structures and enhancements 150 ft from the shoreline and noted that clean fill and restoration components would cap fine grain (muck) sediments within the dredged hole and provide for suitable estuarine habitats. Over the next three years, the

County implemented benthic surveys, bathymetric surveys, and seagrass surveys to assess project feasibility. The County then created a conceptual design considering the view from the adjacent neighborhood, navigation, fishing from the seawall, costs, and the development of a large site for the marine community to use for the beneficial placement of dredged material. The project received positive feedback from all the stakeholders, and in May 2017, the County submitted a joint Environmental Resource Permit Application to the FDEP and USACE. The County received the FDEP permit on June 23, 2017, and the federal permit on February 15, 2018.

In general, the 46-acre Tarpon Cove project design fills in a deep dredge hole to restore and enhance critical shallow estuarine subtidal vegetation (seagrass) habitat through the covering of muck. Covering the muck and filling the hole will allow for natural recruitment of seagrasses, including Johnson's seagrass (*Halophila johnsonii*), a federally threatened species, which occurs near the project area. Additionally, the project will result in five intertidal islands consisting of mangrove, emergent (tidal marsh), unconsolidated sand (tidal flat), reef (oyster), and coastal nesting bird island habitats. These islands should support a wide variety of fish, invertebrates, and birds. Other benefits of the project include downstream water-quality improvements, improved wildlife-oriented recreational opportunities, increased protection of shorelines from sea level rise, and increased carbon sequestration capabilities. Methods chosen to achieve this project have been used by the County to successfully restore over 250 acres of high-quality habitat within Lake Worth Lagoon. The project will also serve as a natural buffer between the IWW and existing shoreline, providing for both refuge and safer passage by listed species, such as manatees and sea turtles, outside of the busy IWW channel. Project components:

- Restore 39.9 acres of estuarine habitat
- Cap 15.9 acres of muck sediments while allowing for deep-water refuge landward of the project
- Create 34.8 acres of seagrass habitat
- Create 2.7 acres of emergent islands with intertidal mangrove and spartina habitat
- Create 0.3 acres habitat for coastal nesting birds
- Create 2.1 acres of oyster and artificial reef habitat

The overall project requires approximately 418,600 cy of sand; the FIND IWW Palm Beach Maintenance Dredging project provided 20% of this total. Construction of the Tarpon Cove project began in February 2018 with the placement of beneficial material of opportunity generated from the Town of Palm Beach Channel Maintenance Dredging project and Rybovich Super Yacht Marina Center expansion in West Palm Beach. Construction continued with the placement of the FIND IWW maintenance dredging material in 2019. Future phases of the project will occur as funding and other beneficial use sources of fill material become available.

CONSTRUCTION

Orion completed the construction phase of the IWW Maintenance Dredging project between March 2019 and May 2019, approximately two months before the required completion date. Orion removed 85,000 cy of material over the project duration. The construction phase of the project proceeded smoothly, largely due to Orion's attention to detail and ongoing support from the project stakeholders. A brief description of the equipment, procedures, and stakeholder coordination follow.

Equipment and Procedures

Orion used a mechanical dredge equipped with 14-cy environmental clamshell and 6-cy rock bucket to dredge the channel (Figure 2). A tender tug relocated the dredge during the dredging operation. The environmental bucket minimized sediment suspension, thereby reducing impacts to water quality.

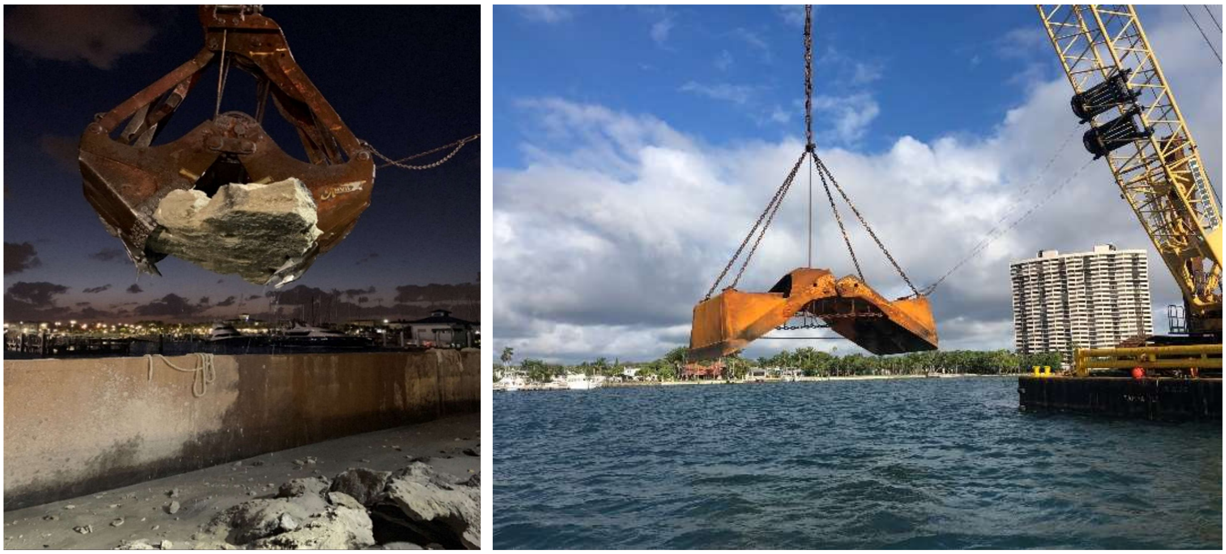

Figure 2. Orion Marine Construction 6 cy rock bucket and 14 cy environmental clamshell bucket

The mechanical dredge — a Liebherr HS 895 HD excavator — was powerful enough to break through the weathered limestone (Figure 3) encountered along some sections of the channel. To facilitate movement of larger vessels during the March 2019 Palm Beach International Boat Show, Orion began dredging in shoal areas targeted by FIND and the marine industry at the south end of the project area. Orion then continued working northward towards Peanut Island.

Figure 3. Weathered limestone encountered within the dredging template overdepth

Hopper barges (260 ft x 52 ft x 12 ft) transported the material from the dredging location to the Tarpon Cove restoration project located about one mile south of the southern project limit. When filled to capacity the hopper barges could hold 3,900 tons of material; however, shallow depths in the offloading area restricted barges to a maximum of 1,850 tons. At the Tarpon Cove restoration project, Orion moored the loaded barges to an offloader barge (Figure 4). The offloader barge — a large excavator equipped with a hydraulic environmental bucket — began placing material from the southern portion of the placement area moving north. A turbidity barrier enclosed the placement area to maintain water quality standards. The excavator released the material below the waterline to further minimize turbidity.

Figure 4. Offloading operations at Tarpon Cove Restoration Area

The contractor experienced substantial variability in daily production rates due to (1) weather and mechanical delays, (2) difficulty in dredging weathered limestone and hard packed sand; (3) mechanically dredging a relatively thin-layer of material spread out over several miles; and (4) increased vessel traffic associated with the Palm Beach International Boat Show.

Stakeholder Coordination

Partnerships between project stakeholders and environmental regulatory agencies — including FIND, Palm Beach County, Marine Industries Association of Palm Beach, Town of Palm Beach, state and federal permitting agencies, local boating and commercial industry groups, and the dredging contractor — had a tremendous, positive project impact. Because the IWW is a key access corridor for many commercial marinas, public outreach and coordination with the local boating and commercial groups was crucial. Providing a daily email update with the construction status, targeted mailings, outreach to the marine industries, public outreach meetings with the historic El Cid neighborhood (lying adjacent to the Tarpon Cove restoration project), and U.S. Coast Guard (USCG) coordination greatly aided in the overall project success.

Maintenance of Marine Traffic

Due to presence of the Port of Palm Beach, coincident timing of the Palm Beach International Boat Show, several adjacent marinas and a mega-yacht service facility, and the existence of numerous private docks, this section of the IWW experiences high volumes of marine traffic. Combined, the dredge and the barge measured approximately 90 ft in width, which substantially reduced the navigable channel width for marine traffic. To buffer potential maintenance of marine traffic issues, Orion provided daily equipment position reports that helped to notify local mariners of the dredging and offloading locations (Figure 5). These reports were shared via email with the engineer, Port of Palm Beach Pilots, USCG, affected marine facilities along the IWW, and other stakeholders or individuals that requested this information.

Figure 5. Example of contractor's forecast location map

Noise and Light Mitigation

Due to the proximity of the El Cid neighborhood, lying approximately 500 feet west of the Tarpon Cove restoration project, Orion had to be cognizant of both noise and light disturbance. To reduce noise during the offloading operations, all equipment operating at Tarpon Cove restoration project had muffler systems in place, and, as much as practical, Orion minimized noises associated with the mechanical aspects of the offloading procedures. Orion also conducted noise monitoring along the El Cid seawall to measure background and construction noise levels. Orion recorded readings in the range of 60 decibels (dB) for passing cars and 80 dB for planes flying overhead. Construction noise levels were measured between 70-75 dB at the seawall located approximately 450 ft from the offloader.

Project construction also considered measures for light mitigation. Orion initially staged the barges in an east to west direction, filling the placement area in rows; once a row reached capacity, the offloader barge moved north to start another row. A few weeks into the dredging operation, the contractor reoriented the barges in a north-south direction (Figure 6). This change (1) reduced light impacts from the tugs on the historic El Cid neighborhood, and (2) resulted in safer offloading with this orientation facilitating the arrival and departure of the tugs and scows in alignment with currents and prevailing winds.

Figure 6. Tarpon Cove Restoration Area during project construction

CONTINUANCE OF TARPON COVE RESTORATION

Following the completion of the IWW maintenance project, Palm Beach County applied an annual marine contract with Vance Construction Inc. to grade 18,700 cy of the IWW material to create adequate elevations for coastal estuarine habitat on the intertidal island. The County also created a second intertidal island (Figure 7) with sand acquired from the Rybovich Marina Expansion project. As a result, the two islands provide a total of 2.40 acres of coastal habitats and 3 acres of shallow water seagrass habitat. To provide adequate shoreline protection, the County purchased and installed 5,600 tons of limestone rock to create 1,400 linear feet of revetment around the two islands; these features created 1.9 acres of intertidal mangrove, spartina, and oyster reef habitat. Additionally, 0.50-acres of sand placed above the tide line created coastal mounds for nesting coastal bird species—American Oystercatcher, Least Terns, and Black Skimmers.

Figure 7. Tarpon Cove Restoration Area, December 2020

In March 2020, nearly 100 volunteers from the community, West Palm Beach Fishing Club, Lagoon Keepers, Palm Beach Day Academy, Conservation Conservatory School, MANG Gear, Lake Worth Waterkeepers, and Florida Fish and Wildlife Conservation Commission helped plant 2,500 mangroves and 4,000 cordgrass plants on the two intertidal islands (Figure 8). Between August 2020 and March 2021, MANG Gear— a local sports apparel company—organized nine additional volunteer planting events and donated over 4,000 red mangroves plants in various sizes ranging from seedlings to 3-gallon pots.

Figure 8. Community volunteer planting event

Since the initial placement of the IWW material in 2019, these islands have provided an essential nesting habitat for the American Oystercatcher, a Florida State-designated threatened species. During the IWW placement, a pair of American Oystercatchers (the fourth pair to successfully nest on designated coastal sand mounds in Lake Worth Lagoon) nested. The unexpected nesting resulted in the County determining to modify the island design to include coastal sand mounds. These features have allowed for successful nesting to continue for three consecutive years. In 2019 the American Oystercatcher pair raised two hatchlings that Florida Fish and Wildlife Commission (FWC) biologists banded as W21 and W22. In 2020, FWC banded one hatchling as W24, and in 2021, FWC expects to band one hatchling. In July 2020, and for the first time at any Lake Worth Lagoon restoration project, two pairs of nesting Black Skimmers successfully nested (Figure 9). In late September, seven Black Skimmers were noted feeding and loafing at the project area. Of these, three were juveniles that successfully fledged from the two nests. These islands continue to provide habitat for a wide variety of shorebird species.

Figure 9. Community nesting black skimmers

Since 2019, Palm Beach County's marine industry has provided nearly 325,000 cy (78%) of the project's estimated 418,600 cy sand requirements through beneficial re-use of dredged material. In partnership with FWC, the County has also acquired $2,100,000 in Federal Funds for the project through the United States Fish and Wildlife Service National Coastal Wetlands Conservation Grant Program, National Oceanic and Atmospheric Administration Hurricane Irma Fisheries Disaster Recovery, and the Florida State Wildlife Grants Program. The County has also secured $1,682,500 in State of Florida Legislature Appropriations, applied along with $1,682,500 in County matched funds.

SUMMARY

Through coordination between stakeholders — FIND, Palm Beach County, regulatory agencies, and the contractor — Taylor Engineering obtained permit modifications, revised the dredging contract specifications, and issued a change order to Orion to place the dredged material as fill at Palm Beach County's Tarpon Cove restoration area. This project demonstrates that through proper planning, design, and co-ordination with the relevant stakeholders, maintenance dredging projects may provide sediment for environmental restoration with economic benefits to the navigation authority, local government, and the community at large.

REFERENCES

Palm Beach County Department of Environmental Resources Management (PBC ERM). 2016. *Summary of Projects and Fiscal Year 2016 Legislative Funding Request*. West Palm Beach, Florida.

U.S. Army Corps of Engineers (USACE). March 2001. *Detailed Project Report. Palm Beach Harbor Lake Worth Access Channel Expansion. Section 107 Small Navigation Project. Palm Beach County, Florida*. Jacksonville, Florida.

U.S. Army Corps of Engineers (USACE). June 1971. *Palm Beach, FL. Side Channel and Basin*. Jacksonville, Florida.

CITATION

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RESTORATION OF HISTORICAL SUBAQUEOUS BORROW PITS FOR MANAGEMENT OF NAVIGATIONAL DREDGED MATERIAL IN COASTAL NEW JERSEY

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ABSTRACT

The New Jersey Department of Transportation's Office of Maritime Resources is responsible for the maintenance of over 200 nautical miles of navigation channels statewide. Traditional sites for management of dredged material, confined disposal facilities, are either at or near capacity and not readily sited or expanded due to their proximity to sensitive coastal resources. Consequently, considerable effort is expended to find innovative beneficial uses for dredged materials. One potential beneficial solution for dredged material placement is to restore subaqueous borrow pits. New Jersey's Atlantic backbay has a large number of these pits resulting from historical mining of sand for coastal development and beach replenishment. Many are located in naturally shallow water embayments, but are many feet deeper than the adjacent benthic habitat, resulting in stratification, hypoxia and reduction of the natural circulation in surrounding waters. In 2013, NJDOT evaluated 122 dredged holes throughout the State. The study identified 5 sites that were considered restoration priorities due to a number of factors including maximum depth, hypoxic or anoxic conditions for part or all of the year, proximity to dredging need and capacity to receive dredged material. In 2018, the NJDOT-OMR began filling Dredged Hole 18, located in the northern Barnegat Bay, with the goal of restoring bottom elevations to match surrounding topography and providing habitat suitable for expansion of surrounding submerged aquatic vegetation (SAV) beds. Dredged Hole 18 was 9 acres in area, had a maximum depth of -22.6' MLW, was characterized as depauperate for benthos and fisheries, and was hypoxic to anoxic at least part of the year. To complete the restoration, 180,000 cubic yards of material was targeted from 11 navigation features, ranging in character from fine silt to coarse sand. A layering strategy ensured that the material in the top two feet would be coarse material similar to that in the surrounding SAV beds and chemically suitable as habitat. Using mechanical dredging equipment, NJDOT contractors began filling Dredged Hole 18 in 2018 and completed work in early 2020. Over 209,000 cubic yards were dredged over the course of 9 months in two dredging seasons. A summary of the design and construction of Dredged Hole 18, including turbidity monitoring during placement and the plans for post placement monitoring will be discussed. This sediment management technique offers a unique opportunity to provide ecological benefits and is considered a proactive adaptation for sediment management practices in coastal waterways.

Key words: dredging, dredged material management, beneficial use, habitat restoration

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INTRODUCTION

The Atlantic coastal region of New Jersey (NJ) is a densely populated and heavily utilized shore ecosystem that not only contains diverse dune, beach, marsh and coastal forest habitats, but also hosts a large and complex marine transportation system comprised of Federal, State and local engineered waterways, berths, marinas and private slips, supporting a $50 billion shore economy. The NJ Department of Transportation (NJDOT) operates and maintains 216 marked channels covering over 200 nautical miles that provide local access to the NJ Intracoastal Waterway and the Atlantic Ocean. These two significant maritime assets have enabled the development of a vibrant shore community with 400 marinas, 325 boat ramps, 235 commercial fishing slips, 57 recreational charters and 250 water dependent businesses as well as 40,000 private boat slips. Maintenance of the transportation system requires nearly continuous dredging to remove accumulated sediment that has historically been placed either on nearby beaches or in confined disposal facilities (CDFs).

Since 2014, OMR has been charged with the restoration and maintenance of the New Jersey Marine Transportation System (NJMTS). In the wake of Superstorm Sandy, OMR determined that more than half of the State's channels were moderately to severely shoaled and over 3 million cubic yards of sediment would need to be dredged to restore the system to full navigability. A quarter of this material can be attributed directly to Superstorm Sandy. Since that time, OMR has restored 58 channels to full navigability. The over 1.1 million cubic yards of sediment dredged to date has been placed on beaches (20%), in CDFs (50%), used for habitat restoration (22%), open water placement (1%) or otherwise used beneficially (7%). While the improvement to the system is significant, much work remains to be done, and a paucity of readily available dredged material management options continues to be problematic.

In years past, it was considered acceptable practice to dredge sand deposits from back bay shallow water habitats and use that material to fill in tidal creeks and wetlands, or open water, to create fast land for development. While this practice has long been prohibited by both Federal and State regulation, the legacy of "dredged holes" remains. These dredged holes sometimes serve as habitat for fish, providing deep water refugia from high summer temperatures. But often, the holes collect sediment and debris, dead plants and animals, and the lack of circulation results in hypoxic conditions which lead to the loss of a natural benthic community. Since as early as the 1960s these holes have been identified as restoration targets, and possible repositories for dredged material from maintenance dredging projects (USACE, 2001). Given the potential for millions of cubic yards of ready capacity, this option is particularly attractive to maritime managers. In addition, there are likely to be water quality benefits from improved circulation, and restoring or enhancing the natural bottom has the potential to increase valuable benthic habitat such as eelgrass beds. Another benefit can be achieved by filling dredged holes deep enough to bury contaminated sediments. While the extent of contaminated sediment in the back bay areas of NJ is minimal, some areas with more commercial and/or agricultural land use can contain hydrocarbons and pesticides. The removal of these contaminants from the ecosystem is desirable and this method may offer a less expensive and more effective way to do so.

Dredged Hole 18 is a subaqueous borrow pit located in upper Barnegat Bay next to the barrier island in Brick Township, Ocean County, NJ. The site was mined for sand used for beach replenishment activities following severe storms in 1962. The depth of the hole was greater than 20 feet and it had nearly vertical sides (Figure 1.). The result of this was a stratified water column due to lack of circulation and poor water quality. Adjacent to the feature are high quality sand flats containing annually recurring beds of SAV including *Ruppia maritima* (widgeon grass). The average depth in this portion of the Bay is less than 4 feet below mean low water. Evaluations of water quality and benthic life performed by Stockton Coastal Resource Center in 2014 and 2015 revealed that dissolved oxygen dropped precipitously inside the feature (Figure 2) and no benthic organisms were present in grab samples.

Due to these conditions, Dredged Hole 18 was targeted for restoration. It was hypothesized that by returning the bottom topography to its original state, water quality would be improved and the amount of available habitat for SAV would be significantly increased. In order to accomplish this, around 180,000 cubic yards of sediment would be placed in the feature and the top layer of material would

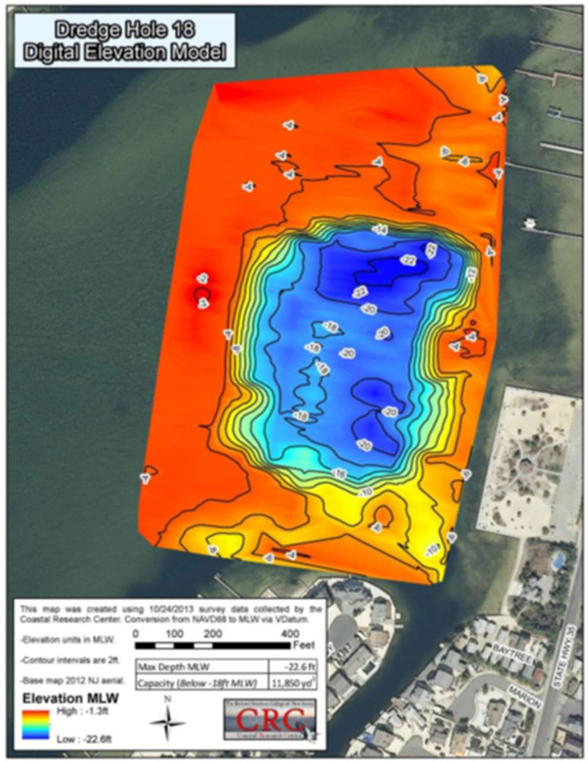

Figure 1. Digital Elevation Model of Dredged Hole 18

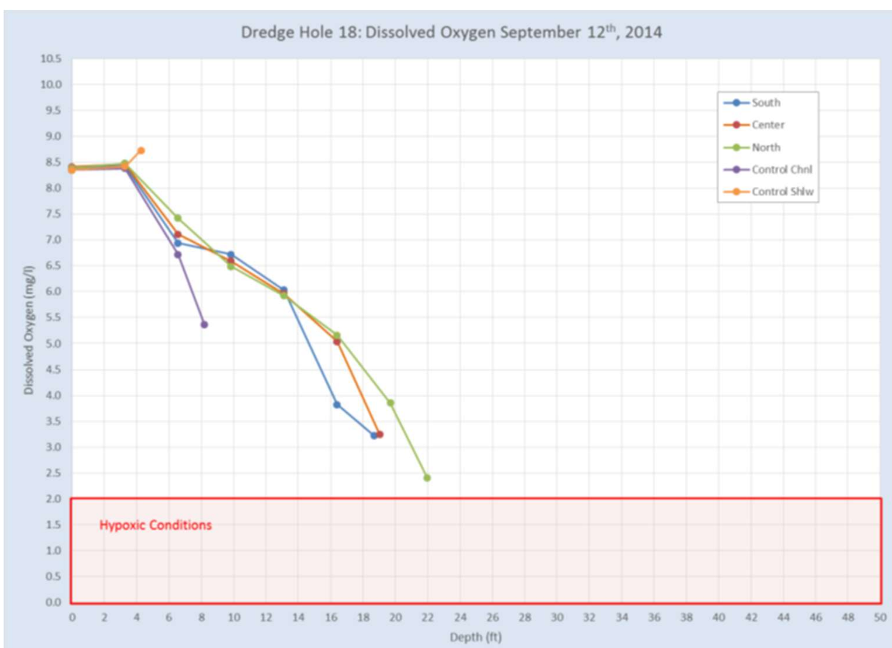

Figure 2. Preconstruction dissolved oxygen measurements in Dredged Hole 18.

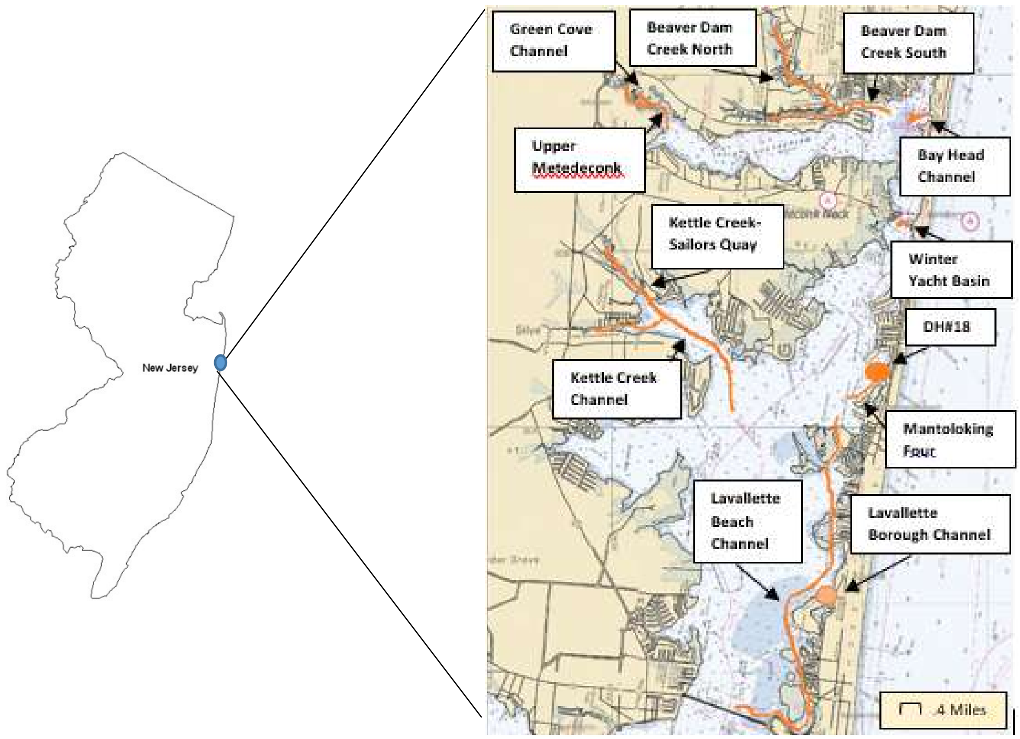

Figure 3. Site location of dredging project.

match the surrounding sediment grain size and quality.

The material targeted for use as restorative fill was located in 10 nearby State navigation channels in northern Barnegat Bay, Ocean County (Figure 3). Additional sandy cap material, should it be needed, was identified in a municipal boat access area in Lavallette Borough. These channels and the public boat ramp serve boaters in 2 Townships and 5 Boroughs.

METHODOLOGY

Preconstruction evaluations

The following evaluation were performed on the targeted restorative fill and at the dredged hole:

<u>Chemistry sampling</u>

Sediment chemistry and physical characteristics were determined in each of the channels providing restorative fill using a Vibracore sampling device. Cores were taken at locations based on the relative amount of material present in each reach and taken to project depth plus one foot. Chemistry was assessed using EPA and ASTM standard methods for grain size, TOC, percent moisture, metals, SVOCs/PAHs, and pesticides. Background sediment samples were also taken adjacent to the dredged hole using a 2” diameter hand core and analyzed for the same parameters.

<u>Benthos sampling</u>

Preconstruction benthic screening at the dredged hole was performed by taking a bottom sample using a hand-held Ponar grab. The material was placed into a plastic tub and evaluated by a biologist.

<u>SAV sampling</u>

Preconstruction SAV sampling at the dredged hole was performed by using a 1m x 1m quadrat divided into sixteen (16) sub-quadrants, a series of three quadrat “throws” were randomly tossed within the sampling point location. Divers then identified the presence of SAV within each of the sixteen (16) sub-quadrants to establish spatial coverage and noted the species type/composition.

Site water

Surface water at the dredged hole was evaluated for total suspended solids on a grab sample.

Dredging method

Dredging was accomplished using either a 3 CY Cable Arm affixed to a barge mounted Sennebogen 850E material handler (Figure 4) or 0.75 CY closed clamshell affixed to a barge mounted CAT 326F material handler (for narrow channel reaches). Real-time positioning was accomplished with cab mounted ClamVision software and visual cues on the cables. Material was placed onto one of seven 120' x 30' scows holding approximately 180 CY each and transported via tug to the dredged hole.

Figure 4. Mechanical Dredging Plant (top) and Placement at Dredged Hole 18 (bottom).

Placement method

Unloading of the material was accomplished using a 5 CY bucket affixed to a CAT 385C material handler (Figure 4). The bucket was lowered below the water surface prior to opening. Due to the variability observed in sediment quality and characteristics, the order of work was described in the permit. In general, material containing slight amounts of contaminants (PAHs and metals) was to be placed first, and the sandiest material was to be placed last (Figure 5). Material from Green Cove was required to be covered with at least 6 inches of material from other locations prior to the end of Season one.

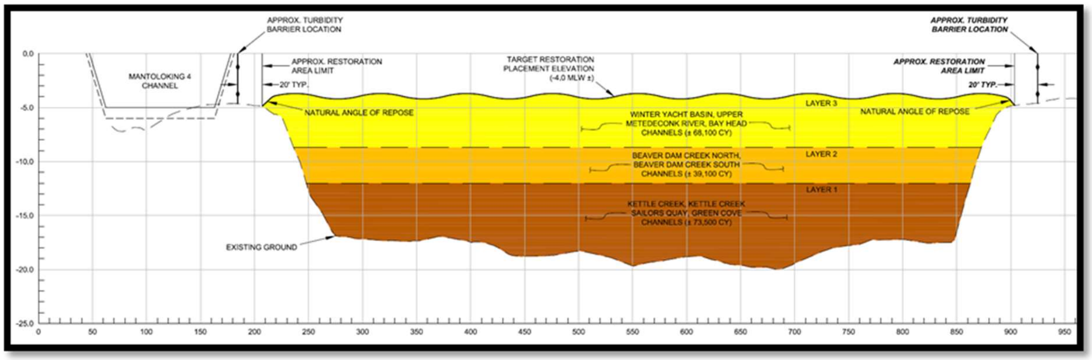

Figure 5. Filling plan for Dredged Hole 18

Adaptive management/monitoring plan

During construction, turbidity was monitored on each tide cycle at a point near the placement and at a control point outside of the turbidity control curtain (when utilized). While the turbidity curtain was deployed, turbidity readings were performed both 3’ inside and 50’ outside the curtain, in addition to the compliance points 200’ up current and 200’ down current of the turbidity barrier using a Global Water WQ770-B turbidity meter fitted with a WQ730 turbidity sensor.

Adaptive management techniques up to and including cessation of work were required by permit should turbidity measured in the compliance reading exceed 1.5 times the background reading. Should violations be observed, the first step was to ensure that there was a direct correlation between the observation and placement activities and a confirmatory reading. If the problem persisted, the following adaptive actions were to be taken:

- Review bucket decent rate;
- Open bucket closer to sediment interface;
- Tighten up turbidity barrier;
- Decrease the depth of each lift;
- Place in a “bowl” pattern to reduce disruption of previously placed sediment;
- Cease operations until the turbidity can be reduced to permissible levels.

RESULTS

Preconstruction evaluations

<u>Sediment Characteristics</u>

The sediment around Dredged Hole 18 was predominantly sand (95% or greater) with total organic carbon ranging from 1645 to 5225 mg/kg. Most of the chemical parameters were either at or below levels of regulatory concern, with the minor exception of the PAH benzo(a)pyrene in one sample, DDT in another sample, and some Arsenic, Copper and Lead (Table 1).

<u>Turbidity</u>

Background turbidity in and around Dredged Hole 18 was found to range from 9400 to 10,000 ug/L total suspended solids. According to the latest State of the Bay report, the background turbidity in upper Barnegat Bay averages 3-6 NTUs (Barnegat Bay Partnership, 2016). However, this part of the upper Bay is known to exceed water quality standards for turbidity on a regular basis.

Submerged Aquatic Vegetation (SAV)

Two beds of SAV were sampled, both containing *Ruppia maritima*. One of the beds was relatively sparse (approximately 2% coverage) and the other was more dense (approximately 46% coverage). It is assumed that these beds will provide enough seed source for natural recruitment in the restored area.

Table 1. Characteristics of dredged material proposed for placement in Dredged Hole 18.

Channel	Percent sand	Percent fines	TOC (mg/kg)	Criteria Exceedances
Green Cove	77.1	22.9	150,000	As in bulk sediment
Kettle Creek	15.0	85.0	74,966.7	None
Kettle Creek Sailor's Quay	48.1	51.9	77,116.7	As in bulk sediment, Pb in elutriate
Mantoloking 4	99.3	0.7	NM	None
Beaver Dam Creek North	57.7	42.3	106,271.4	As and B(a)pyrene in bulk sediment, Pb, Cu and chlordane in elutriate
Beaver Dam Creek South	35.6	64.4	106,300	None
Winter Yacht Basin	80.2	19.8	8,080	None
Bay Head	90.5	9.5	2,935	None
Upper Metedeconk River	89.0	11.0	21,160	None
Lavallette Beach Channel	73.2	26.8	9,560.8	DDT in bulk sediment
Lavallette Boat Ramp	>95	<5	NM	None

Table 2. Dredged and placed volumes of sediment in Dredged Hole 18.

Channel	Available Volume (CY)	Pay Volume (CY)	Placed Volume (CY)
Green Cove	3120	2,530	3,447
Kettle Creek	17770	15,565	22,544
Kettle Creek Sailor's Quay	41500	39,325	44,147
Mantoloking 4	2450	1,880	2,656
Beaver Dam Creek North	23100	16,650	17,147
Beaver Dam Creek South	16540	14,820	16,171
Winter Yacht Basin	1140	660	1,261
Bay Head	5700	4,130	4,255
Upper Metedeconk River	58090	47,360	52,863
Lavallette Beach Channel	80390	37,550	44,301
Lavallette Boat Ramp	560	560	560
Totals	250,360	181,030	209,352

Dredging and placement

Dredging was conducted between Nov 5 2018 and Dec 30, 2018 and between June 19, 2019 and January 22, 2020, for a total of 274 days. Weather, permit restrictions, plant relocation, shallow water draft restrictions and equipment repair account for down time. Thirty-seven thousand seven hundred (37,700) cubic yards were placed at Dredged Hole 18 in 2019 and 171,600 cubic yards were placed in 2019/2020 (Table 2). In most cases, work was done during daylight hours, but 24-hour operations were initiated in late 2019 in order to complete the project before the permit windows closed.

Turbidity monitoring

Turbidity readings over the course of the two seasons ranged from 1.4 to 68.8 NTU (Table 3). The average up current (background) reading was 8.6 NTU in season one, and 9.3 NTU in season two. The average down current (compliance) reading was 8.2 in season one, and 8.9 in season two. In both seasons, the upstream and downstream readings are not significantly different. Overall, during season one, only 3.5% of the initial readings were non-compliant (down current turbidity more than 150% of up current turbidity), and during season two 5.8 % of the initial readings were non-compliant. In no cases were sediment plumes observed coming from the placement operation and, when evaluated in aggregate, there is no correlation between distance from the restoration site and the amount of turbidity observed (Figure 6).

Table 3. Summary of Turbidity Results

		Up Current (Background)			Down Current (Compliance)			
	Obs.	Range	Mean	Stnd Dev	Range	Mean	Stnd Dev	t-test (p)
Season 1	88	1.85-39.82	8.6	5.56	1.45-23.0	8.2	4.57	0.62
Season 2	331	1.46-41.0	9.3	5.71	1.4-68.8	8.9	7.12	0.43

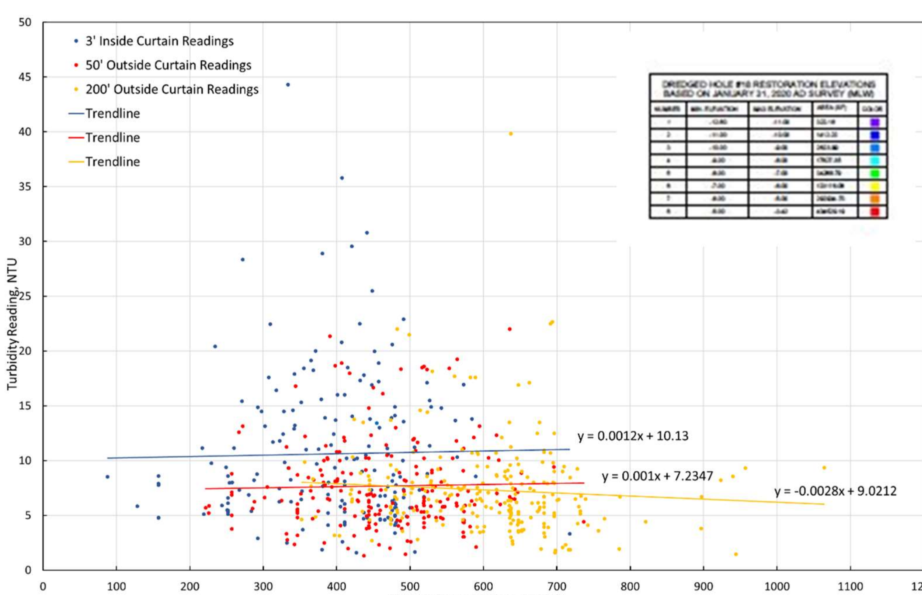

Figure 6. Turbidity Readings vs. Distance from Centroid of Dredged Hole

DISCUSSION

Turbidity monitoring

Wind and equipment moving activities at the site appeared to be the cause of most resuspension events. We observed a significant relationship between the average wind speed and turbidity (Figures 7 and 8). While other factors certainly play a role, it can be assumed that wind driven currents will influence turbidity in a shallow water embayment like Barnegat Bay, in which the current is otherwise minimal.

The NJDEP water quality standard in Barnegat Bay is a daily average of 10 NTU with a maximum of 30 NTU. The turbidity over the entire project averaged 8.8 NTU. Ninety percent of all readings were less than 20 NTU. Of the nine (9) readings that were greater than 30, three (3) were up current background samples and all were transitory and directly attributable to either wind or prop wash. This indicates that the placement operation at Dredged Hole 18 had little or no effect on the water quality of the Barnegat Bay.

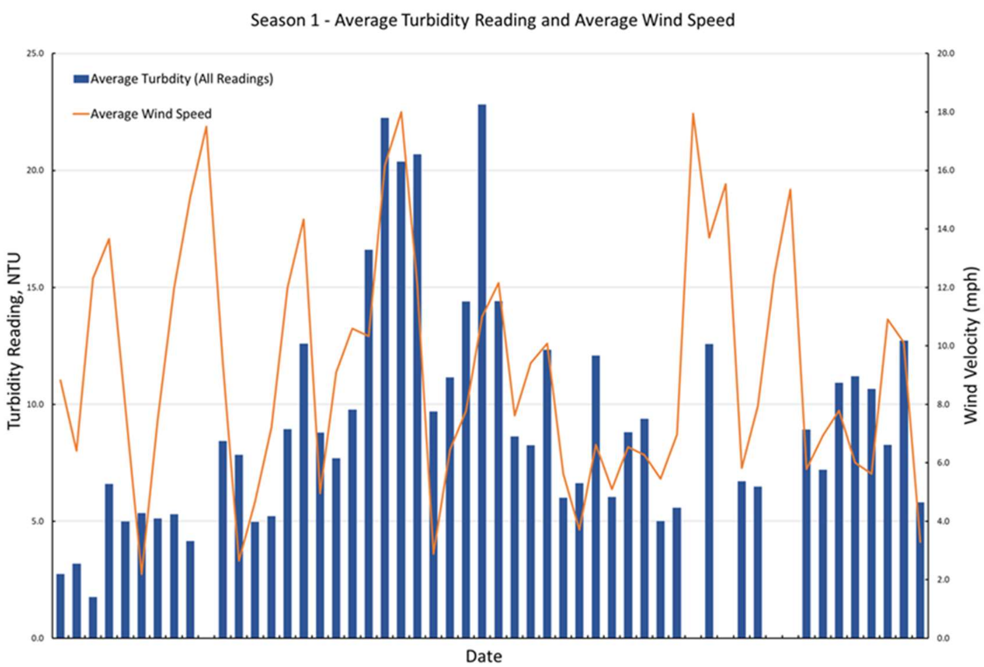

Figure 7. Average daily turbidity observed vs. average wind speed during Season 1.

Adaptive management

A paired comparison of background to compliance turbidity readings is illustrated in Figures 9 and 10. Only three (3) non-compliant readings were taken in Season 1, and all three were determined to be the result of high westerly winds. Of the 21 readings in Season 2 that were non-compliant initially, seven were associated with high winds causing high wave action that entrained material at a higher rate than normal, four were due to support vessels, and four were the result of abnormally low background turbidity readings. In two cases, asking the operator to lower the bucket further into the water before releasing the material corrected the problem. In the four other cases, a second reading failed to replicate the initial finding.

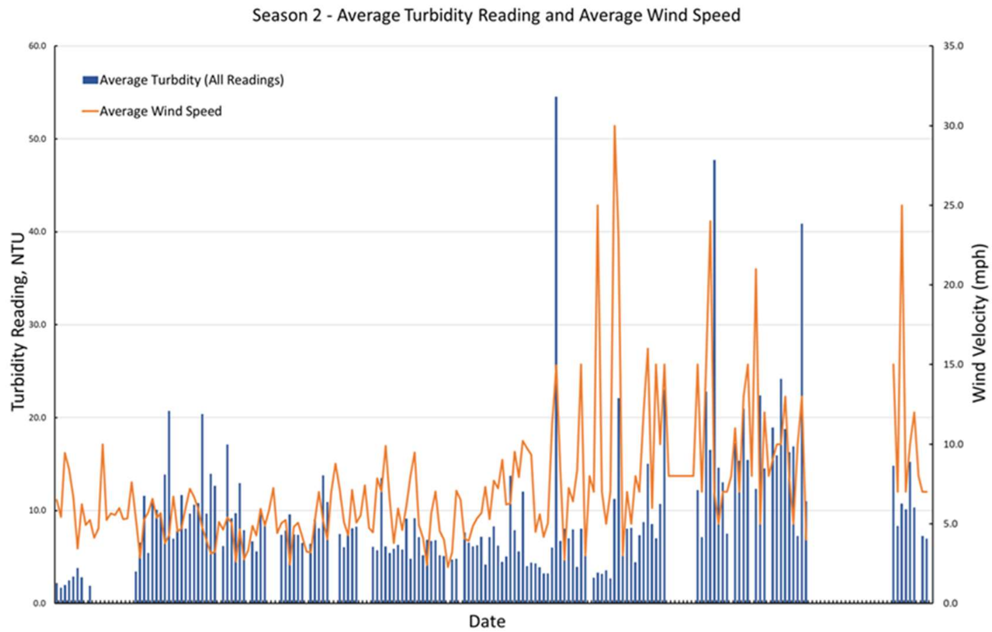

Figure 8. Average turbidity observed vs. average wind speed during Season 2.

Approximately 3,100 feet of turbidity curtain was deployed at Dredged Hole 18 during Season one. The high winds present during the operation made the curtain difficult to maintain and it presented a significant impediment to efficient operations. Given the lack of turbidity observed during the operation, the permitting agency allowed unloading to proceed without the installation of the curtain during Season two, provided that the low turbidity readings continued.

The relationship between up current and down current turbidity was similar both with and without the presence of the turbidity curtain (figures 9 and 10). In both cases, the noncompliance rate was less than 6% and was either explainable, transitory or easily remedied. In this situation, it appears that the turbidity curtain did not provide any measurable environmental benefit, however, removal of the curtain resulted in increased efficiency for the dredger and a significantly reduced timeline that allowed the project to be completed in two seasons, despite unexpected consolidation.

Consolidation

The volume of sediment needed to fill the dredged hole was initially estimated to be 180,000 cubic yards. This was a conservative estimate based on the volume of the dredged hole up to the surrounding bottom elevation and assumed no consolidation of material once placed. By the time the project neared completion, it was apparent that considerably more dredged material would be needed to fill the hole than initially estimated. At the end of season two, over 209,000 cubic yards had been dredged, filling most of the site to the target elevation of -4 to 5 ft MLW (figure 11). This corresponds to a consolidation rate of approximately 16%. Additional monitoring is scheduled over the next several years to monitor for further consolidation. With ongoing observation, if we suspect that consolidation is impeding SAV growth, additional material may be added to the site.

Dredging: weather/equipment/delays

Dredging in narrow shallow water channels can be challenging, especially when the placement site requires relatively long transport. Normal delays on the project were exacerbated by high westerly winds decreasing water depth, that occasionally made it difficult to get equipment up into channels at the lower ends of the tidal cycle. Winds also made it difficult to keep the turbidity curtain in place.

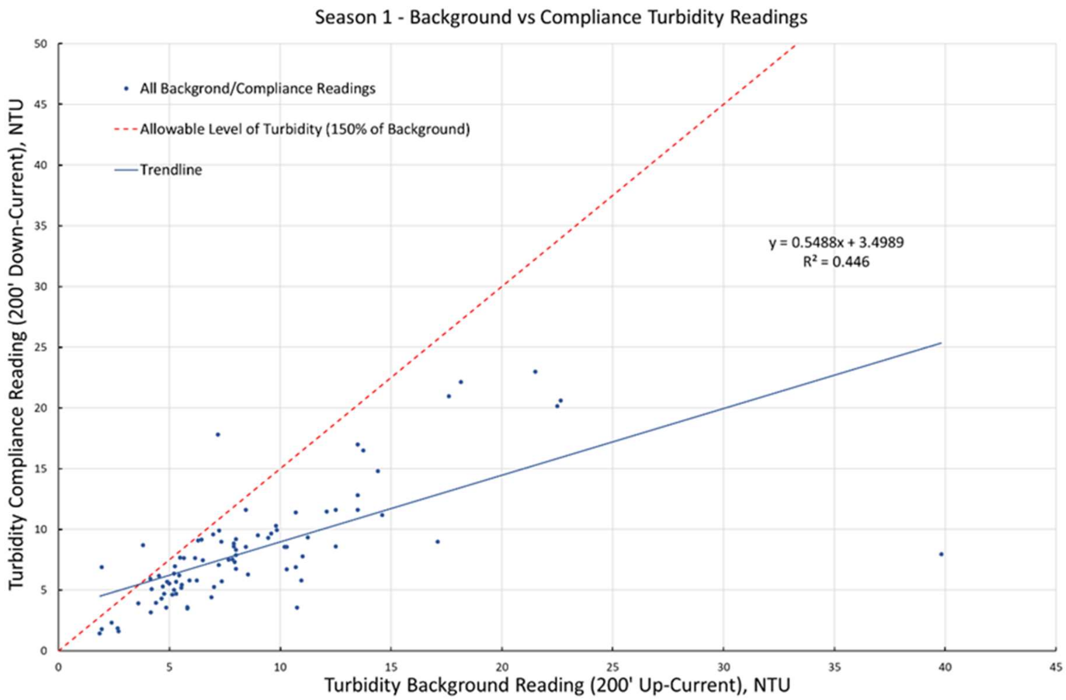

Figure 9. Comparison of Background to Compliance Turbidity Readings in Season One

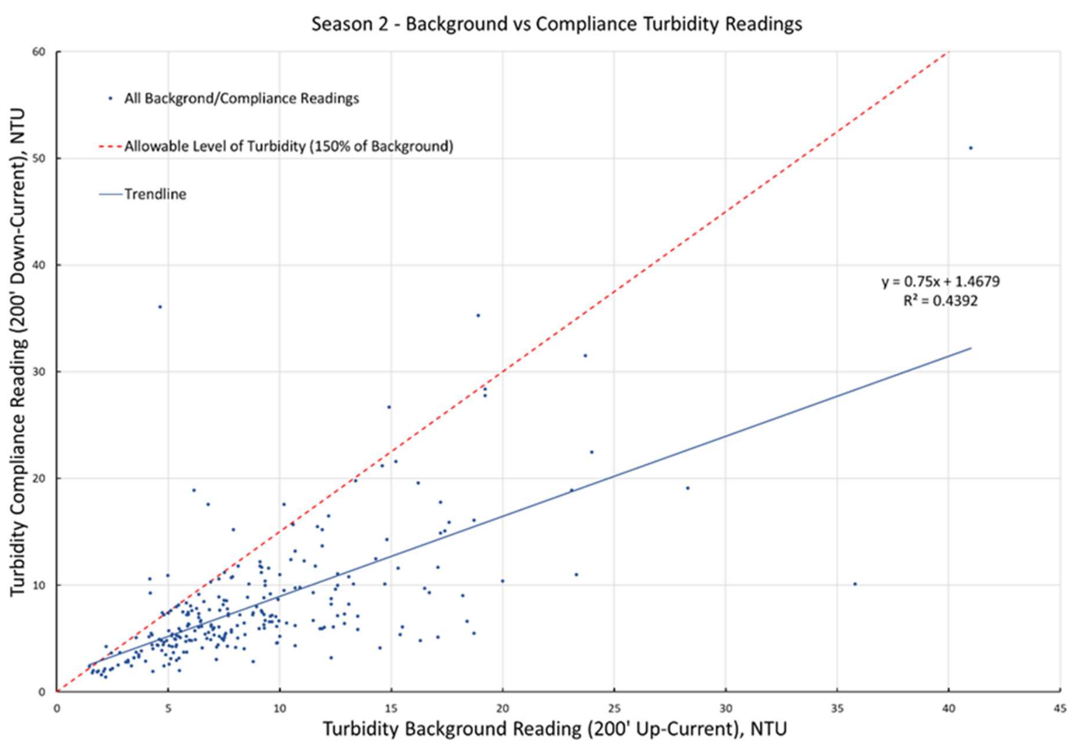

Figure 10. Comparison of Background to Compliance Turbidity Readings in Season Two

Cost

The long timeline of the project, use of small equipment, and the mechanical placement technique all drove up the cost of the project. If mobilization is not included, NJDOT paid the contractor $40.69 per cubic yard for dredging and placement. If we subtract out the cost of the turbidity curtain, the cost is reduced to $36.26. Engineering and oversight on the project cost an additional $4.25 per cubic yard.

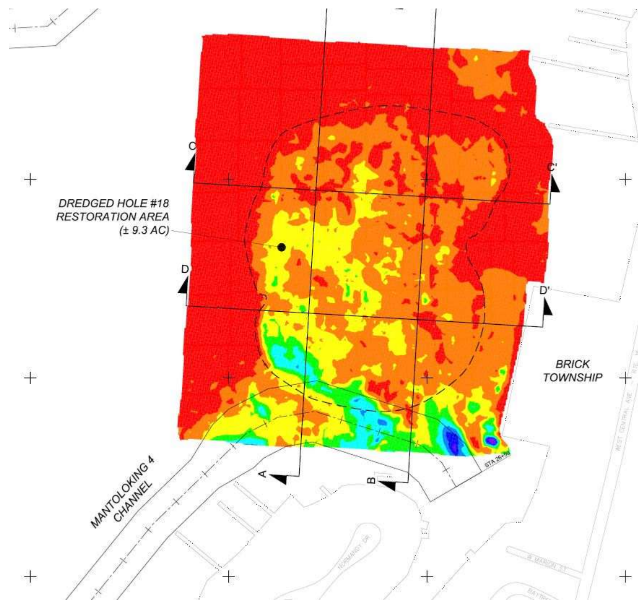

Figure 11. Final elevations of Dredged Hole 18.

Post construction monitoring

Post construction monitoring will be performed over the next four years both to evaluate cap integrity and SAV recruitment, and to monitor water quality and benthic community health as compared to nearby reference areas.

Cap integrity

Cap integrity will be evaluated at 18 locations (4 outside and 14 inside the restored area). Each sample will be examined visually and sand depth recorded. In addition, a total of nine composite samples will be evaluated for grain size and total organic carbon.

Water quality

Water quality will be assessed at each of three locations around the site by analyzing turbidity, dissolved oxygen, pH, salinity, and temperature using a YSI 6600 multi-parameter logger.

Submerged aquatic vegetation

Changes in the presence and abundance of submerged aquatic vegetation (SAV) will be evaluated at the four control locations outside of the site and one location inside the site. At the four control locations, 15 replicate 1m x 1m (3.28 ft x 3.28 ft) quadrat samples will be taken. An additional 30 quadrat samples will be conducted within the footprint of restored Dredged Hole 18 to evaluate the presence of SAV. Of the 30 quadrat samples, 15 will be spaced randomly across the entire footprint and 15 locations will be selected based on proximity to a potential SAV source bed. A total of 34 locations will be sampled annually for three years, starting in season two.

Benthic community

Benthic community analysis will also be performed at three locations outside and three locations inside the restored site area. Samples will be collected by Van Veen grab and preserved with ethanol. Organisms will be removed, counted and identified to the lowest practical taxonomic level. A multivariate analytical approach will be utilized to assess differences/similarities in community structure between the restoration and control sites.

CONCLUSIONS

The restoration of bottom contours was successfully implemented at Dredged Hole 18 resulting in 11 NJ channels being returned to a state of good repair. Monitoring over the next several years will determine if the restoration of SAV habitat was successful. The following conclusions can be drawn from evaluation of data collected during implementation:

- There is no evidence to suggest that placement activities at Dredged Hole 18 resulted in negative water quality impacts to Barnegat Bay.
- Wind events were a greater cause of water column turbidity than the placement operations.
- The use of a turbidity curtain did not result in a measurable difference in the frequency or magnitude of turbidity readings greater than background.
- The elimination of a turbidity curtain did result in increased dredging efficiency and reduced schedule.
- The use of mechanical dredging equipment is acceptable for this type of operation

REFERENCES

Barnegat Bay Partnership. (2016). State of the Bay Report. Ocean County College, Toms River, NJ. 80pp.

U.S. Army Corps of Engineers. (2001). New Jersey Intracoastal Waterway Final Site Selection Report. U.S. Army Corps of Engineers, Philadelphia District. Philadelphia, PA. Two Volumes.

CITATION

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DATA AVAILABILITY

All data used during the study are available from the corresponding author on request, subject to the data retention policies of the NJ Department of Transportation.

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OVERCOMING BARRIERS TO BENEFICIAL USE OF DREDGED MATERIAL IN THE US

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ABSTRACT

Thousands of projects have successfully used millions of cubic meters of dredged material for beneficial use applications since the concept was introduced in the 1970s. Most projects have been technical successes, though some were unable to achieve sufficient financial success to be sustainable. Despite those successes, currently less than 40% of dredged material in the US is used beneficially. Limited Federal budgets, as well as state and local sponsor budgets, discourage the use of more costly beneficial use alternatives, even if those alternatives are more environmentally sustainable. Incompatible project timing and volume inconsistencies between dredging projects and beneficial use projects also discourage increased beneficial use. These barriers must be overcome if beneficial use of dredged material is to become standard practice. A more holistic evaluation of beneficial use and disposal options is needed, considering both short-term and long-term benefits and costs. Cost differentials will narrow as disposal costs increase and conventional disposal capacities decrease. Furthermore, increasing the recognition of the sediment's *value* in the ecological health of our aquatic ecosystems with a desire to improve sustainability in view of sea level rise will generate creative opportunities and encourage innovative partnerships. Local and regional beneficial use advocacy groups can foster collaboration, communication, advanced planning, and coordination between stakeholders; these steps can bridge the gap between the timing of projects and volume differentials, and further support beneficial use projects in general. This paper discusses barriers to beneficial use of dredged material in the US and strategies to overcome them. Given that only a small fraction of dredged material is unsuitable for reuse without treatment, a logical goal is for all dredged material in the US to be used beneficially unless chemically unsuited to remain in the environment. While that laudable goal may not be achievable in the short term, identifying mechanisms to overcome economic and institutional barriers will facilitate expansion of beneficial use opportunities.

Keywords: sediment, sustainable infrastructure, resiliency, Engineering with Nature®, habitat development

INTRODUCTION

Dredged sediment has been used beneficially as long as dredging has occurred. The beneficial use of dredged material can be used for engineering or environmental purposes, including construction materials, beach nourishment, flood protection, or habitat creation. Dredged "spoils" were used historically to raise expansive areas of marshes and swamps adjacent to existing shorelines above the high-water tide to create new land (Kennish 2002; Wong 2019). The Tokyo Haneda Airport, where construction started in 1931, is just one example of many important infrastructure features resulting from such efforts (Watabe and Sassa 2016). Similar examples exist in virtually every major port city. Such projects resulted from a combination of convenience and cost. Landfill projects provided a nearby location to place dredged material and the resulting filled land had value

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where the swamps and marshes were assumed to have none. In addition, the proximity to shipping and nearshore industrial activities bolstered newly created land values.

The concept of dredged material beneficial use became more formalized during the 1970s and 1980s. Environmental regulations made sediment disposal more complicated and increased sediment disposal costs, particularly when associated with constructing new dredged material placement facilities. These societal and economic pressures made beneficial use more attractive. Construction of many successful beneficial use projects helped extend existing placement capacity of existing facilities while new solutions were pursued. This period culminated with the Engineer Manual 1110-2-5026 (USACE 1987) that summarized a host of successful strategies for dredged material beneficial use. Funded by the Dredging Operations and Environmental Research (DOER) program, the USACE recently revisited several USACE beneficial use projects constructed in the late 1970s to document their long-term successes and trajectories; these projects were initially documented by Newling and Landin (1985). The findings show that all projects produced ecological (e.g., habitat development) or engineering (e.g., shoreline resiliency) benefits. Drake Wilson Island is one successful example that continues to provide benefits, as summarized in the Engineering With Nature Atlas Volume 2 (https://ewn.el.erdc.dren.mil/atlas.html). The long-term success demonstrated by this project demonstrates that the technical capacity to successfully implement beneficial use has been available for decades.

With the successful application of beneficial use, dredged material drew increasing interest in the 1990s as a potential resource, especially in urban areas where soil sources are scarce. For example, the New Jersey Department of Transportation (NJDOT) conducted numerous demonstration projects related to the use of dredged sediment for mine reclamation, highway embankment construction, and other uses (Yozzo et al. 2004). They also evaluated a host of treatment technologies that could reduce chemical concentrations in dredged material to levels suitable for different beneficial uses.

Despite a long history of successful beneficial use projects (see for example Bridges et al. [2018] and https://budm.el.erdc.dren.mil/), beneficial use is not practiced on a widespread and consistent basis. Bridges (2018) asked, "What would it take to reach 100% beneficial use?" This paper investigates potential feasibility, cost, and institutional barriers that currently restrict achieving this goal and identifies potential solutions for overcoming these barriers and expanding beneficial use. Portions of this paper are excerpted from a forthcoming update on the PIANC (2009) international standard of practice on sediment beneficial use.

CATEGORIZING BENEFICIAL USES AND BENEFICIAL USE TRENDS

Dredged material consists primarily of super-saturated granular particles typical of most soils and sediment—gravel, sand, silt, and clay. Although some dredged material contains elevated concentrations of chemical contaminants, the vast majority of navigational dredged material does not. Thus, almost any need for additional soil or sediment provides a potential opportunity for using dredged material.

PIANC (2009) defines sediment beneficial use as *any use of dredged material rather than mere disposal is regarded as use.* This definition allows consideration of the widest range of options available to the port operator, contractor or other proposer seeking to use dredged material from dredging operations. The Central Dredging Association (CEDA 2019) defined sediment beneficial use as *the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development*. While also broad, this definition focuses on sediment uses that benefit society and the natural environment. It places a greater burden on decision makers to consider societal and ecological benefits of sediment use. USACE (1987), USEPA and USACE (2007a) and USACE (2015), and Childs (2015) identified multiple beneficial use categories in an attempt to better understand and expand beneficial use opportunities. Those uses are listed in Table 1. Here, we define beneficial use as *using dredged sediment to achieve additional benefits beyond the purposes related to its removal, including other economic, environmental, or social benefits*.

While these approaches categorize beneficial use by application or technology, the USACE Regional Sediment Management (RSM) Database (USACE 2020) uses a simplified version of Child's (2015) approach and categorizes beneficial use based on location where sediment is applied rather than type: i.e., beach, in-river, and

Table 1. Comparison of attempts to categorize beneficial use alternatives by previous efforts.

USACE (1987)	USEPA and USACE (2007a) and USACE (2015)	Childs (2015)
Habitat development	Habitat restoration and development	Upland placement for ecological habitat
Beach nourishment	Beach nourishment	Beach or nearshore placement for shoreline protection or beach nourishment
Parks and recreation	Parks and recreation	Placement for upland land development
Agriculture, forestry, and horticulture	Agriculture, forestry, horticulture, and aquaculture	Shallow water placement for wetland, marsh, or habitat
Strip mine reclamation and solid waste management	Strip-mine reclamation and solid waste management	Unconfined aquatic placement
Construction and industrial use	Construction/industrial development	Island placement for benefits
Multiple purpose	Multiple-purpose activities	Ocean placement for beneficial use
Material transfer		Upland placement for soil reuse
Shoreline stabilization and erosion control		Confined in-water placement for beneficial purpose
Aquaculture		

littoral; open water, upland, and wetland. Child's categories are used in the Great Lakes Beneficial Use manual (GLDT 2020).

USEPA and USACE (2007a) estimated that only 20-30% of the total volume dredged in the US is being used beneficially. Unfortunately, the data to differentiate beneficial use rates for channel maintenance as compared to channel deepening or other new work are not available. Since 1997, USACE has tracked dredge volumes and sediment beneficial use (USACE 2020). Figure 1 shows annual dredged volumes and beneficial use volumes from 1997 through 2017. The data show an average of 38% beneficial use for sediment removed from federal navigation channels between 1998 and 2017. For 2004-2006, beneficial use is closer to 30%, reasonably consistent with the conclusions drawn by USEPA and USACE (2007a). Other years are closer to 40% or 50% beneficial use.

While the volume of beneficial use in the US, 50 to 80 million cubic meters (MCM) annually, is impressive, Figure 1 also shows the potential for redirecting an additional 80 MCM annually to beneficial uses in lieu of disposal. The National Research Council (1994) estimated that only 5% of maintenance dredged material in the US is unsuitable for open water placement. More recent or specific citable data were not identified, but it is believed that only a very small portion would have restrictions on beneficial use or require treatment because of sediment contamination.

Encouraging the expansion of beneficial use will be especially important in upcoming decades, as dredged material placement options reach capacity in many areas and open water placement is under increasing scrutiny. Societal pressures, regulations, and space limitations make open water disposal and the permitting and construction of new placement facilities increasingly difficult and expensive. For example, the closure of the "Mud Dump" disposal site in New York / New Jersey Harbor in 1992 resulted in a dredging crisis for the State of New Jersey that spurred the region toward beneficial use (Maher et al. 2013). The closure of this open water disposal site put into jeopardy New Jersey's ability to conduct maintenance dredging and to implement new capital projects, like the planned deepening of entrance channels to the Port of New York and New Jersey. This eventually led to numerous policy changes, including regulatory overhaul and the establishment of policies that supported innovative techniques to manage dredged material, such as a greater investment in beneficial use. More recently, the State of Ohio banned open water disposal in Lake Erie starting July 2020, also leading to

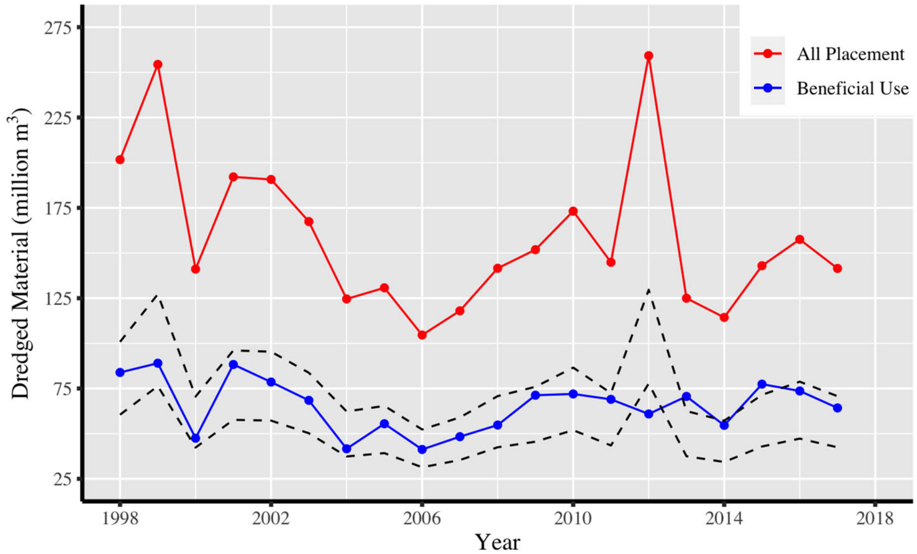

Figure 1. Dredging placement for USACE navigation dredging from 1998 to 2017. Dashed lines represent 50 and 30% thresholds of all dredged material placed and are shown to demonstrate what percentage beneficial use is of all placement. Data from the USACE RSM BU Database (https://rsm.usace.army.mil/BUDB).

increased focus on beneficial use alternatives, particularly as capacity in conventional disposal facilities (e.g., CDFs) is exhausted.

Beneficial use also has drawn recent interest thanks to two popular trends - increasing recognition of sediment as a valuable resource in a healthy aquatic ecosystem, and a push for increasing infrastructure sustainability (e.g., improved habitat and coastal resilience). Sediment loss or changes in natural sediment inputs can adversely affect riverine, estuarine, and coastal ecosystems and sea level rise can add to the effects in coastal ecosystems, such that an environmentally and ecologically motivated focus has been cast on beneficial use. Techniques that can accomplish resupply of sediment include sediment bypassing, thin-layer placement, and nearshore placement. Consistent with this observation, the RSM database shows that between 1998 and 2020 almost half (47.1%) of the sediment beneficial use (approximately 616 MCM) has been returned to river systems. An additional 16.8% (220 MCM) was used to restore or enhance wetland environments, 13.2% (173 MCM) was placed on beaches, 11.1% (145 MCM) was placed within the littoral zone, 10% (131 MCM) was used beneficially in upland locations, and 1.8% (24 MCM) was used beneficially in open water. "Strategic" unconfined placement (e.g., placing sediment within riverine or coastal environments) must consider long-term and system-wide watershed benefits and impacts. Benefits can include wetland nourishment and habitat maintenance, while negative impacts may include increased long-term sediment management needs (i.e., more dredging) and negative habitat impacts if areas are overwhelmed by increased sediment loads.

Over the last decade, progress in documenting sediment beneficial use also has been realized. CEDA (2021) and USACE (2021) both developed web sites dedicated to beneficial use, communicating recent advances and best practices. Highlights of technical progress include: using thin layer placement to restore coastal habitat; building dikes, foreshores, and marshland to decrease wave impact (i.e., improving resiliency), thus reducing the need for conventional dike construction; developing strategic and large-scale beach and dune nourishment to improve coastal resiliency; harvesting clean dredged material previously placed in confined disposal facilities (CDFs) to increase CDF storage capacity; and strategic and beneficial placement of dredged material distant from the original placement area.

PIANC (2009) summarized beneficial use experiences achieved since their 1992 report. Their primary objectives were to document the experiences gained, examine constraints on use, and make recommendations to increase beneficial use by providing a template to encourage sediment beneficial use as an alternative to disposal. In the decade since PIANC (2009) was published, many gains and advances have been realized, and documentation of beneficial use practices has increased. These advances have been influenced by key events and publications. Notably, in 2008, PIANC published a position paper on Working with Nature (WwN; PIANC 2008), followed by a Guide for Applying Working with Nature to Navigation Infrastructure Projects (PIANC 2018). Soon after the 2008 position paper, Building with Nature (BwN) and Engineering With Nature (EWN®) were launched, both of which are initiatives to implement WwN and are developing and demonstrating, through multiple dredging projects, the capabilities needed to achieve sustainable, triple-win project outcomes (see for example, De Vriend and Van Koningsveld 2012; Bridges et al. 2014, 2018). In 2018, the International Association of Dredging Contractors (IADC) and CEDA jointly published a guide on delivering dredging projects that enhance economic, social, and environmental values in a sustainable manner (Laboyrie et al. 2018). In 2015, the United Nations released its Sustainable Development Goals, a call for action to promote prosperity while protecting the environment, as part of its 2030 Agenda for Sustainable Development (United Nations 2019). Climate change impacts to waterborne transport infrastructure recently came to the forefront, prompting the need to develop adaptation measures (PIANC 2020). Collectively, these documents promote the advancement of beneficial use and the ongoing implementation of nature-based solutions to promote natural and increasingly resilient aquatic ecosystems.

BARRIERS TO EXPANDING BENEFICIAL USE

Creative sediment management alternatives are critical to support navigation dredging as further constraints on low-cost conventional management alternatives are imposed. Conventional disposal sites have finite capacity while open water placement continues to come under increasing scrutiny. These factors, combined with an increasing awareness of the importance of sediment in maintaining coastal resiliency, provide the impetus for creating additional opportunities for beneficial use. Identifying barriers and means to overcome them is necessary for expanding beneficial use opportunities.

Technical Barriers

Multiple technical barriers discourage beneficial use of dredged material. Example barriers include physical characteristics of dredged material incompatible with requirements for use, differences between dredged material volume available and sediment volumes required, the presence and potential need to remove contaminants, and the distance between dredging projects and beneficial use opportunities.

Physical Characteristics and Characterization

Physical characteristics of dredged materials vary widely, sometimes even within the same project area. For example, as energy associated with sediment suspension and transport changes geographically, seasonally, and over time, the segregation of particle sizes within an estuary or port facility can occur. Looking only at average particle size distributions may not give a sufficiently accurate characterization of dredged material and what portions of that material are suitable for various uses, particularly where particle size distributions are heterogeneous. Therefore, sufficient sediment sample collection and characterization needs to be conducted as part of the beneficial use project design. Complicating matters, dredging and dredged material handling can further segregate sediment particles as coarse sediment particles tend to settle more rapidly than fine particles.

Volume Incompatibility and Project Timing

Volume incompatibilities and unaligned project timing can also discourage beneficial use. If the volume of sediment required for a potential beneficial use is more than the volume of sediment available from dredging, the projects may be incompatible unless the beneficial use project is scalable. Many examples exist where a beneficial use project receives sediment from multiple dredging projects or over multiple dredging cycles. This spreads costs over multiple projects. Conversely, if the dredged material volume is in excess of that required for a beneficial use, the dredging project may need to bear the costs and risks associated with obtaining permits for and using multiple placement areas. To accommodate the potentially different timelines for beneficial use and dredging projects, alternative placement or staging options may be employed.

The US mined 80 to 120 million metric tons of sand and gravel annually from 2015 to 2019 (Statista 2020). Why is dredged material not used in lieu of mining, resulting in a financially beneficial partnership for all parties? The sporadic nature of dredging complicates commercial opportunities. Sand and gravel suppliers need inventory on-hand at all times to match demands. Dredging produces large volumes over short periods, and then may not produce additional sand for several years. Most sand and gravel suppliers do not have the capacity to hold material on site for an extended period. Thus, it is more prudent for them to generate their own inventory on a consistent basis even if it costs more to do so. CDFs also offer a potentially underused opportunity to reclaim sand, so long as the CDF material is uncontaminated and has properties of interest to the user. Harvesting clean sand from a CDF also can have the added benefit of increasing CDF capacity for sediment that does not have immediate or long-term use potential.

Inconsistent Sediment Quality

Inconsistent quality also limits dredged sediment beneficial use. Dredged material almost always contains some fines. Coarse materials are more valuable when segregated by size, so additional processing may be necessary. For some potential uses, the fines must be removed and, often, disposed of in an appropriate facility (CDF). Many suppliers have separation capabilities but may not be able to handle the large flow rates over short periods associated with dredging. Few suppliers have the capacity to manage large volumes and required processing and storage requirements, limiting commercial opportunities.

Sediment Contamination

Sediment known to have elevated contaminant levels pose additional concerns. Contaminants tend to bind preferentially to fine particles, making organically rich fines particularly challenging to beneficial use. If contamination is present, preprocessing may be required before dredged material can be used safely. Preprocessing comes in many forms, but separation and treatment are the most common. The goal of separation is usually to separate the lesser-contaminated sand particles for beneficial use whilst reducing the net volume of contaminated sediment that must be disposed.

Treatment of Dredged Material

The selected treatment process or degree of treatment required for beneficial use depends on the physical and chemical characteristics of the dredged material, the nature of the contaminants, and the purpose for which it is being used. Barriers lay in the capital and operational costs associated with the treatment, the level of treatment required, and storage capacity needed for the dredged materials. Contamination is a continuum and most dredged sediments are "suitable" for some kind of beneficial use without having to apply expensive remediation-like treatment technologies, although physical separation is often warranted. Categories of contaminant treatment technologies and associated considerations for each technology are provided below:

- **Solids Separation.** Separation of sand from fines is typically conducted to achieve a target grain size class of the dredged material or to isolate the fine fraction which typically contains a high fraction of the contaminants. Separation can be conducted via low-energy methods, which are typically much less expensive than other treatment methods described below.

- **Chemical Immobilization and Stabilization.** Contaminants can be immobilized and stabilized by adding pozzolanic materials, such as Portland cement, lime, fly ash, or slag. These materials react with the dredged material and bind particles and contaminants, which reduces contaminant leaching potential (Maher et al. 2013; PIANC 2009).

- **Thermal Treatment.** Thermal processes include desorption and capture at relatively low temperatures, and contaminant destruction at high temperatures. High-temperature products include bricks or lightweight aggregate. While technically feasible, thermal treatment costs are high, in part because the high-water content in sediment consumes substantial thermal energy.

- **Bioremediation.** Microorganisms can degrade some organic contaminants if provided sufficient time and proper conditions, typically by spreading the dredged material over large areas of land and stimulating the biodegradation via aeration. Bioremediation is contaminant- and site-specific and may not be suitable for heterogeneous material from routine navigational dredging. Bioremediation requires large areas of land, and associated costs include the need for aeration and potential amendments, including carbon sources.

Economic Barriers

For all types of dredging, costs have increased historically; according to the USACE, the cost per cubic meter increased two and a half fold between 1963 and 2018 (USACE Navigation Data Center 2021). Direct costs for beneficial use as compared to disposal vary greatly depending on site-specific conditions, including the characteristics and volume of dredged material, location and capacity of disposal facilities, transport of the dredged material, and production rate of treatment facilities (PIANC 2009). Direct costs associated with the beneficial use of dredged material are often higher than for conventional sediment disposal, thus resulting in a significant disadvantage for beneficial use. PIANC (2009) suggested that the following potential requirements be considered as part of a beneficial use project when developing project cost estimates:

- **Material Testing -** Testing of the chemical and physical properties of the dredged material is needed to determine the suitability of the material for beneficial use and any treatment requirements. Chemical and physical characterization requirements for beneficial use can be more comprehensive than the testing required for disposal.

- **Treatment -** For beneficial use of dredged material, physical processing, such as the separation of fines, or contaminant treatment may be required. The associated costs vary depending on the dredged material characteristics, type of treatment, scale, and either the ultimate disposal costs or the market value of an end product. Simple technologies such as natural sand separation and land-farming (bioremediation) are relatively inexpensive if the necessary land is available. Stabilization has relatively moderate costs and can be used to improve the geotechnical quality of the dredged material (PIANC 2009). Thermal immobilization treatment costs are much higher. The market value of potential end-products should be considered in determining net costs.

- **Permitting -** Existing placement areas typically have permits in place, having completed required environmental impact studies and assessments before opening. In contrast, beneficial use sites usually require new permits. Required environmental studies and assessments must be completed as part of the project. Not only can these studies be expensive, they can take significant time to complete. The permitting process adds additional time, especially when regulators have limited experience with beneficial use or a new use is proposed. Even for relatively simple projects, permitting can take one to two years and the outcome may be uncertain. Time, cost, and uncertainty associated with permitting discourage the development of new beneficial use sites.

- **Risk Assessment -** Many dredging projects operate on strict schedules and budgets. Such logistical constraints are especially true for maintenance dredging projects, which represent many opportunities for beneficial use. Beneficial uses often carry additional financial or schedule risks not associated with conventional sediment disposal. Many of those risks have been discussed above. Every project must balance the benefits of beneficial use with additional risks associated with using dredged sediment. The decisions to use dredged materials must be based on site-specific considerations and risk assessments and on possible mitigation measures.

- **Liaility -** Liability concerns can discourage beneficial use of dredged sediment, especially for uncontrolled uses. For example, sediment could be resourced from a placement site (e.g., from a CDF) for residential or commercial uses. However, some agencies and project owners fear potential liability for future impacts resulting from sediment-bound contaminants, even if they are not aware of them or were not involved in their generation. Without a widely accepted definition of "clean," many prefer to use quarried materials from a known source rather than dredged sediment or sediment from containment areas.

The vagaries of dredging and dredged material management costs complicate cost comparisons. Dredging and transportation costs vary with competition, fuel price fluctuations, and demand. Local regulations such as dredging windows can exacerbate these variations. Value assessments are even more difficult. Reliable navigation depths are crucial to sustain waterborne commerce, which has long economic tentacles. Quantifying benefits resulting from sediment reuse is even more challenging, especially when they will continue to accrue over decades. Yet, dredging project managers face the dilemma of integrating all three on a routine basis. Moreover, they must do so within constrained budgets that do not reflect anticipated values resulting from dredging projects (Wetta and Hanson 2011). It is not surprising that the most quantifiable of these short-term costs often drives decision-making. Nonetheless, dredging managers are often faced with balancing these values as part of project development, design, and execution. Pandal (1998), McLellan et al. (2001), Yozzo et al. (2014), and Maglio et al. (2020) are examples where cost was a primary factor in sediment management alternative selection.

Institutional Barriers to Expanding Beneficial Use

Institutional barriers to expanding beneficial use can be grouped into three categories: 1) lack of harmonized approaches between state and Federal agency regulations, 2) complex cost-sharing requirements, and 3) public and agency acceptance (GLDT 2020; PIANC 2009). These barriers are examined to identify potential opportunities to facilitate the expansion of beneficial use.

Need for Harmonized Regulatory Approaches

In the US, regulatory requirements for beneficial use differ among States and between State and federal agencies. Regulations must be considered for different regulated environments (e.g., upland, wetland, nearshore, aquatic) and for the products that may be generated using dredged material. Federal guidelines applicable to aquatic (defined as waters of the U.S., occurring below the ordinary high-water mark or marine) and upland placement are summarized in Table 2. Definitions of these environments vary among states, as do the exposure pathways and end-use environmental concerns (Kiel 2018).

Sediment chemical criteria for beneficial use are commonly assessed by bulk sediment chemical concentrations, although elutriate tests, toxicity tests, or modeling may be applied. Sediment quality evaluations may include but are not limited to risk-based evaluations (i.e., risk-based threshold criteria) or comparison to the ambient background sediment concentrations. Federal and regional guidance documents describe testing protocols and evaluation procedures (e.g., USACE 2003; USEPA and USACE 1998; USEPA 2016a and 2016b). USEPA guidance for performing beneficial use evaluations provides a step-wise or phased approach (USEPA 2016a and 2016b).

Table 2. Federal regulations for the placement of sediment (Kiel 2018; GLDT 2020; Illinois Marine Transportation System [IMTS 2020])

Aquatic placement	Upland Placement	Other Federal Regulations for Consideration
Sections 404/401 Clean Water Act (CWA) - suitability for aquatic placement water quality certification in coordination with permitting state; also addresses invasive species or contaminant migration across jurisdictions	Section 402 of CWA also applies for unconfined upland placement and discharge to a waterway with shared jurisdictional boundary can make permitting/testing more complex	Clean Air Act - fugitive dust and equipment emissions (Note that non-attainment may be a particular barrier for large reuse projects)
National Environmental Policy Act (NEPA) - addresses invasive species or contaminant migration across jurisdictions	NEPA	Surface Mining Control and Reclamation Act (SMCRA) -if used for mine land reclamation
Coastal Zone Management Act (CZMA)-where and what populations and activities exist where dredged material is placed or used	CZMA	Water Resources Development Act
Marine Protection, Research, and Sanctuaries Act (MPRSA) - prohibits the dumping of material into the ocean that would unreasonably degrade or endanger human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities	Endangered Species Act (ESA)- where and what populations and activities exist where dredged material is placed or used	Water Resources Reform and Development Act of 2014 (WRRDA)
	RCRA- solid waste management rules (depending on handling/permitting)	Rivers and Harbors Act
	Toxic Substances Control Act (TSCA) – polychlorinated biphenyls (PCBs) > 50 milligram per kilogram (mg/kg) confined disposal facility (CDF) or upland only (depending on handling/permitting)	National Historic Preservation Act

Some states regulate dredged sediment as soil or solid waste while others regulate it as sediment. Table 3 summarizes state approaches to beneficial use that was compiled from previously developed compendia (Kiel 2018, GLDT 2020, IMTS 2020) and state guidance (e.g., San Francisco Bay Regional Water Quality Control Board, SFWQCB 2000). The table includes states where criteria apply, if any, to aquatic or upland placement. Guidance and regulations for these same states are summarized in Table 4.

Many waterways also serve as state boundaries. Inconsistencies between neighboring states can impact coordination and the period of project execution. If chemical criteria for material beneficial use differ among states, there may be uncertainty regarding which laws prevail for a given project. Connecting waterways may also have differing environmental windows, or periods of the year when dredging and open water placement may occur due to ecological considerations. The Great Lakes Beneficial Use Testing Manual proposed a holistic, risk-based approach that dredged material be evaluated based on potentially impacted environments (aquatic or upland), jurisdictional authorities (federal or State), receptors at risk (human or ecological) and pathways of exposure (water, soil contact, food chain, air, etc.)," for environmental acceptability for beneficial use. This approach is consistent with USEPA guidance (2016a), which was developed to help states make beneficial use

Table 3. State guidelines for the placement of non-hazardous sediment (Maher et al. 2013; Kiel 2018; GLDT 2020; Illinois Marine Transportation System [IMTS 2020])

State	Aquatic Placement in Waters of the U.S.		Upland Placement	
	Sediment quality guidelines or water quality limits	Soil/waste limits	Sediment quality guidelines or water quality limits	Soil/waste limits
California[a]	•		•	
Illinois	•		•	
Iowa	N/A	N/A	N/A	N/A
Indiana	•			•
Kentucky	•			•
Ohio[a]	•		•	
Oregon	•		•	
Pennsylvania	N/A	N/A		•
Maryland	•		•	
Michigan	•		•	
Mississippi	•		•	
Missouri	•		•	
Minnesota	•			•
New Jersey	•		•	•
New York	•			•
Texas	•		•	
Washington	•			•
Wisconsin	N/A	N/A		•

[a] sediment and water quality limits include toxicity testing or bioassays
Notes: • = applicable; blank = unregulated/no framework; N/A = not applicable, no beneficial use allowed.

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

California	The Long-Term Management Strategy for the Placement of Dredged Material in the San Francisco Bay Region (USACE et. al 2001) presents long-term dredging, disposal and beneficial reuse strategy for the San Francisco Bay area. An objective of the plan was for LTMS agencies to apply their policies in a coordinated and comprehensive manner.
Illinois	For dredging projects with discharges to waters of the State or hydraulic dredging projects the Facility Evaluation Unit-Permit Section, Division of Water Pollution Control of Illinois EPA makes placement decisions. Testing procedures are contained within 35 Ill. Adm. Code 395. Either the Facility Evaluation Unit-Permit Section or the Permit Section of Illinois EPA's Bureau of Land make determinations for other dredging projects. No permit is required for upland beneficial use of mechanically dredged materials that are placed away from surface water and that do not discharge to waters of the State. (IMTS 2020)
Iowa	A joint federal-state dredging permit process requires physical and chemical characterization for water quality certification where projects will discharge dredged material to waterways. Most projects for habitat restoration and environmental cleanup manage dredged material in confined disposal facilities or upland landfills. Iowa Administrative Code 567-108 Beneficial Use Determinations (ITMS 2020) allows for sediment beneficial use as fill or alternative cover provided it is stabilized to meet criteria.
Indiana	Indiana Department of Natural Resources (IDNR) and Department of Environmental Management (IDEM) use the policy document, Remediation Closure Guide (WASTE-0046-R1-NPD), and statutory closure guide IC 13-12-3-2 and IC 13-25-5-8.5 are used to make beneficial use decisions. Site specific screening levels that incorporate institutional and engineering controls or generic screening levels may be used. (GLDT 2020; IMTS 2020)
Kentucky	Beneficial use is a permit-by-rule activity from the Kentucky Energy and Environment Cabinet Division of Water. (IMTS 2020).

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

Ohio	The Ohio Environmental Protection Agency Division of Material and Waste Management (DMWM), Beneficial Use Unit is the agency responsible for upland beneficial use. Placement for dredged material from harbor and navigation dredging activities is regulated under Ohio Administrative Code Chapter 3745- 599. Other beneficial use requests are considered on a project-specific basis. (GLDT 2020)
Oregon	Oregon Department of Environmental Quality has standing beneficial use determinations (BUD) for dredged sediment approved by the department's water quality program for unconfined in-water placement based on chemical screening. Dredged sediment that is not approved by the department's water quality program for in-water placement that are below risk-based screening levels or natural background managed in accordance with state requirements consistent with Chapter 340 Division 41. Other determinations are made on a case-by-case basis.[1]
Pennsylvania	Upland beneficial use evaluations use generic 10-5 risk-based soil screening concentrations, which follows USEPA toxicity criteria hierarchy for protection of human health. Pennsylvania Department of Environmental Protection: Administrative Code, 2011, Chapter 250, Administration of Land Recycling Program. (GLDT 2020)
Maryland	The Maryland Department of the Environment guidance document Innovative Reuse and Beneficial Use of Dredged Material (2019) includes regulations and permitting requirements for beach nourishment and marsh creation. The guidance also provides a risk-based framework that incorporates chemical concentrations, exposed populations, exposure duration and pathway(s) for other beneficial uses for which regulation and permitting requirements are less prescriptive.
Michigan	Michigan Department of Environment, Great Lakes, and Energy (EGLE) is the regulating agency for dredged material placement and evaluation. Uncontaminated dredged material (or greater than 90% sand) and dredged material that meets the Part 201, Environmental Remediation, generic residential criteria are not regulated solid wastes and can be used upland, without restriction from the solid waste regulations (Tittabawassee and Saginaw Rivers excepted). Otherwise, materials may be used upland under authorized restrictions or are required to be managed as solid waste.
Mississippi	Coastal Wetlands Protection Law Act, Title 49, Chapter 27, Mississippi Code § 49-27-61 requires beneficial use if greater than 2,500 cy will be removed, if BU sites are available, and materials are compatible. The guidance document, Master Plan for Beneficial Use of Dredged Material for Coastal Mississippi (CH2MHill 2011) identifies priority coastal zone BU areas, outlines permitting regulations, and provides testing guidance. In general, permits require upland confinement of dredged material unless otherwise permitted.
Missouri	Most dredged material is placed in-water; however, the Department of Natural Resources permits beneficial use for habitat restoration, mine reclamation, agriculture, and landfill generation. A state "MOG698" permit is required for placement of dredged material in a disposal facility. (IMTS 2020)
Minnesota	Dredged material is categorized by the Minnesota Pollution Control Agency into one of three management levels depending on sediment characterization results, including grain size and chemistry screened against Soil Reference Values. Dredged material may require a State Disposal System (SDS) permit for beneficial use, depending on sediment source and project volume. Other Projects in unspecified areas should follow the guidance, Managing dredge materials in the State of Minnesota (2014).
New Jersey	New Jersey gives priority to acceptable beneficial uses of dredged material over other dredged material management/disposal alternatives (Maher et al. 2013). Testing protocols for projects vary with dredge volume, sediment physical and chemical characteristics, and the type and nature of the beneficial use. Guidance is provided for the evaluation of raw dredged material and the creation and usage of processed dredged material (PDM).
New York	An upland BUD will be made for dredged material under New York State's Department of Environmental Conservation Solid Waste Management Facilities Regulations, 6 NYCRR Part 360. The BUD provides for a specified use at a location as fill, cover, topsoil, aggregate, or to allow its sale or distribution for these uses. The more protective of the soil cleanup objectives (SCOs) in 6 NYCRR Part 375, Environmental Remediation Programs Regulations, are used to evaluate dredged material. The Identification and Listing of Hazardous Wastes under 6 NYCRR Part 371 may also be relevant. (GLDT 2020)
Texas	The restoration of topsoil through placement of dredged solids is encouraged (TWDB 2005). Texas General Land Office issues leases, easements, and permits for projects on state-owned coastal lands. Additionally, Texas Parks and Wildlife Department is responsible for the management and protection of marl, sand, gravel, and shell located within the tidewater limits, with the exception of oil and gas lease activities, or navigation projects. Wetland loss is considered an opportunity for beneficial use.

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

Washington	Dredged Material Evaluation and Disposal Procedures User Manual (USACE et al. 2018) provides an interagency approach to the management of dredged material in Washington State. The manual is a framework for characterizing proposed dredged material for unconfined aquatic disposal suitability and characterizing proposed post-dredge surface material for compliance with state regulations. The Washington State Sediment Management Standards (SMS) and Model Toxics Control Act (MTCA) are used to evaluate sediment quality for non-navigation projects.[1]
Wisconsin	The Wisconsin Department of Natural Resources promotes the use of dredged material that minimizes harm to the environment and benefits municipal construction projects. Sampling protocols are provided in Wis. Admin. Code 347.01. Risk-based soil screening criteria are used to evaluate proposed beneficial use project. (GLDT 2020, IMTS 2020)
[1]In addition, the Sediment Evaluation Framework (SEF) for the Pacific Northwest describes procedures for the risk-based sediment assessment of potential contaminant-related environmental impacts of dredging and the aquatic placement of dredged material in inland waters and the disposal of dredged material in ocean waters. The SEF guidance was developed for the Pacific Northwest region, including the States of Washington, Oregon and Idaho.	

determinations. The USEPA guidance allows flexibility to integrate within existing evaluation frameworks and regulatory programs but acknowledges these factors, public perceptions, and market conditions may factor into the final determination.

Working with the Federal Standard to Select the Least-Costly Dredge Alternative

Local sponsors and stakeholders are common advocates for beneficial use. Cost sharing between the federal government and non-federal partners is common for most federally-funded dredging projects. Prior to revised wording in Section 125 of the *Water Resources Development Act of 2020 (WRDA2020)*, the Federal Standard prohibited USACE from paying for alternatives associated with maintenance dredging other than the least-cost acceptable option, unless another entity (e.g., a local sponsor, state, or other entity) paid the difference (USEPA 2021a). The Federal Standard defined the costs associated with maintenance dredging projects but did not dictate the disposal or placement option for a project (GLDT 2020). Historically, this standard imposed substantial cost constraints on beneficial use projects when beneficial use alternatives were more costly than conventional disposal methods. New-work dredging projects may be held to a different standard based on national economic development (NED) benefits. The differing approaches to regulation complicate the assessment of dredged material for a given use, which can result in an unwillingness on the part of project proponents to fully consider beneficial use. Regulatory factors that would need to be harmonized to expand beneficial use were summarized in GLDT (2020). It states that, to avoid unnecessary additional testing or duplication of testing, WRDA 2020 modified the Federal Standard verbiage, requiring that a water resources development project:

> *…fully identifies and analyzes national economic development benefits, regional economic development benefits, environmental quality benefits, and other societal effects*.

Essentially, WRDA 2020 requires new projects to consider the extent to which a project *produces benefits that are in excess of the estimated costs*. The new approach may be the byproduct of WRDA 2016 (Section 1122), which created a beneficial use pilot program, initially allowing ten maintenance dredging projects across the country that could reflect broader societal values while not having to be constrained by the Federal Standard. WRDA 2020 fosters the same consideration of natural and nature-based alternatives as structural alternatives and allows USACE to consider other environmental or economic benefits not directly related to the dredging project. Historically, without additional funding for channel maintenance to cover increased costs, USACE Districts have been reluctant to embrace higher cost alternatives even if the net benefits are greater. The impact of this new Federal Standard language has yet to be realized, though it is not difficult to imagine its transformational nature on sediment management decisions.

Maher et al. (2013) argues for upland disposal sites that "the reality of disposal options without beneficial use is that they are not sustainable; by definition any disposal site will eventually fill up." Maher et al. (2013) proposed a different standard of evaluation for the Federal Standard based on "sediment value" or the "value of a cubic yard." This value would factor in not only the navigational benefit, but the cost of sediment management and cost offsets realized by the beneficial use beneficiary as well. This approach leads to an evaluation of the sustainability of placement options that may be the most appropriate way to assess which alternative is "least costly" (i.e., not only least expensive, but also the least costly to the beneficiary and to the environment).

Public and Agency Acceptance

An important step in successfully implementing beneficial use on a wider scale is through educating the public and regulators on sediment management and beneficial use risks and benefits. There is a general perception that the public has a relatively poor understanding of environmental risks resulting from the dredged material use (PIANC 2009). Some jurisdictions classify dredged material as "waste," regardless of source, content, or quality. Consequently, waste management regulations and restrictions apply, which increases scrutiny and permitting requirements because the dredged material is assumed to be harmful. The perception that dredged material is a waste to be disposed, rather than a resource to be used purposefully, does not favor beneficial use. In contrast, other jurisdictions classify dredged material as a "mineral resource." While this puts dredged material in a more positive light, mineral resource regulations often require market prices for mineral uses, which may also inhibit beneficial use.

The perception of dredged material as waste also feeds into the "NIMBY" (not in my back yard) syndrome that sometimes pervades the permitting process. As long as the perceptions of regulators and communities are negative toward dredged material, it will be a challenge to grow the practice of beneficial use. Raising public awareness will improve the stakeholder commitment of resources (USEPA and USACE 2007b). Beneficial use diverts cleaner sediment from filling limited disposal (e.g., CDF, landfill) space, so that space can be conserved for material that is not able to be used beneficially, including contaminated material. Also, the appropriate beneficial use of dredged materials is consistent with USEPA's Sustainable Materials Management program (USEPA 2016b).

New Jersey Department of Transportation (NJDOT) and the New Jersey Department of Environmental Protection (NJDEP) have worked together since 1996 to implement a dredged material management plan inclusive of a beneficial use policy without compromising economic development or environmental protection (Maher et al. 2013). Economic advantages include turning sediment into feedstock to produce blended cement and a manufactured aggregate material by using processes that simultaneously remove contaminants to safe levels (Maher et al. 2013). Processed dredged material is more widely used than treated dredged material in NY/NJ Harbor. Millions of cubic yards have been processed and placed upland in the past two decades. This has resulted in the remediation and development of numerous contaminated sites. Since Superstorm Sandy in 2012, clean navigational dredged material has been used to improve coastal resiliency and to restore and enhance habitat.

Maryland Department of Environment (MDE) published guidance in 2019 on the innovative uses of dredged sediment such as soil amendments, engineered fill, or to create aquatic habitat. The guidance document arose out of the Dredged Material Management Act of 2001, which prioritized beneficial use and innovative reuse alternatives over other traditional dredged material placement methods.

Both New Jersey and Maryland are examples of the synergy between cultural acceptance of beneficial use, public and agency acceptance, and the role of legislation to support and even promote beneficial use. Wider implementation of policies to promote beneficial use could have a large impact on public acceptance and the proportion of sediment that can economically be dredged, beneficially used, and diverted from landfill placement (Figure 2).

EXPANDING BENEFICIAL USE OPPORTUNITES

Despite the successful history of beneficial use, the increasing constraints on disposal facilities, and the increased recognition of sediment value, disposal of dredged material continues to be the default approach. However,

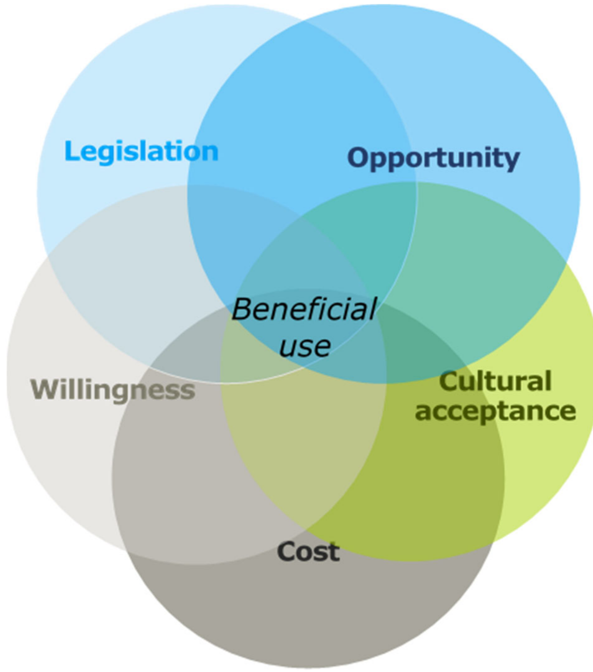

Figure 2. Overlap of critical dredged material components required to facilitate increased beneficial use.

identifying and implementing solutions to the existing economic, logistical, and institutional constraints will facilitate the transition from dredged material disposal to beneficial use. The viable solutions will need to be amendable to a variety of site-specific and project-specific conditions, such as maintenance dredging projects versus new work, uncontaminated material versus highly-contaminated material, and USACE-led projects versus non-USACE projects.

Overcoming Cost Barriers

For the beneficial use of dredged material to be competitive against disposal options, social, sustainability, and environmental factors should be considered in addition to cost, including cost offsets realized by the beneficial use customer. By conducting a more comprehensive and holistic assessment, the net benefits beyond direct and immediate monetary cost savings are evaluated. For example, the beneficial use option may result in increased business and employment within a location and provide long-term environmental benefits if the dredged material is used to improve habitats, such as shoreline restoration or wetland creation. This approach is also consistent with the EWN® principles. These are benefits and values that need to be considered in a long-term comprehensive evaluation and are often not realized in the upfront cost evaluation when comparing beneficial use against sediment disposal.

Many beneficial use projects today incorporate three success pillars of sustainability - economic value, social gain, and environmental benefit (CEDA 2019). The three pillars of sustainability are shaping how beneficial use projects are being implemented successfully. Examples of how the three pillars are being implemented in practice include: coupling dredged sediment supply and demand (e.g., Kleirijperij, Mud Motor in the Netherlands); making advancements in adaptive management (e.g., Markerwadden in the Netherlands); evaluating project value through quantification of ecosystem services (e.g., Prins Hendriks Dike, Horseshoe Bend in the US); acknowledging the role of dredgers, dredging, and dredged sediment to reduce CO_2 emissions and sequester carbon; and positioning dredging projects in ways that fit within a circular economy as prescribed in recent legislation driving sediment use (e.g., Netherlands) (Bridges et al. 2014; CEDA 2019; van Eekelen and Bouw 2020).

Beneficial use in the US is highest where economically advantageous partnerships exist, projects have strong local advocacy, and sediment characterization is consistent with available beneficial use options. Historically, successful beneficial use projects have typically been cost neutral for the dredging project while providing environmental benefits and/or increasing sustainability. Moving forward, increased focus on value (WRDA 2020) allows new projects to consider social and environmental benefits in addition to costs.

Overcoming Barriers through Policy

Policy established at the federal, state, and local levels can further support the establishment, coordination, and implementation of beneficial use projects. Historically, the Federal Standard had required USACE dredging projects to select the least costly dredged material disposal or placement alternative that meets all federal environmental requirements. This requirement has often discouraged sediment beneficial use projects due to cost constraints. For beneficial use to be applied more widely, policy needs to be developed or updated to support beneficial use application. Such policy changes are already being realized through WRDA 2020, which emphasizes project benefits by stating that the suitability of dredged material for a full range of environmental, economic, and societal beneficial uses should be considered.

At state and local levels, consistent and clear policy and the development of holistic sediment and dredged material management plans can foster a beneficial use mind-set and encourage the implementation of beneficial use projects. States could more actively recognize the additional benefits of dredging and dredged material, beyond navigation. For example, states could establish funding mechanisms to pay the additional costs of beneficial use of dredged materials in recognition of the broader economic gains by the state or local area, such as protection from coastal erosion/sea level rise or habitat and recreation enhancements. Such policy and long-term management plans need to be drafted with input of multiple stakeholders, established, and then implemented. These economic-related policies also facilitate overcoming the cost barriers previously discussed.

Overcoming Barriers through Partnerships

Consistent engagement among the various stakeholders has been demonstrated to be an effective tool in overcoming barriers to beneficial uses. Open communication and established relationships encourage stakeholders to ask questions, express their viewpoint, and understand other viewpoints. Generally speaking, beneficial use is more complicated than traditional placement options. Because beneficial use involves goals beyond just dredged material placement capacity, stakeholders want to suggest desired outcomes and share concerns with respect to their interests. A mechanism and venue for stakeholders to discuss their concerns and work collaboratively towards a consensus creates an opportunity to streamline beneficial use projects. Partnerships across multiple stakeholders can assist in upfront planning and coordination of project schedules. For example, reducing gaps in the timing between dredging projects and beneficial use projects ultimately reduces dredged material storage costs and overall project costs. Several outstanding examples of inter-agency, multi-stakeholder beneficial use partnerships exist; a few of these are provided below.

- At the USACE Portland District, the Portland Sediment Evaluation Team includes membership from USEPA Region 10, Oregon Department of Environmental Quality, Washington Department of Ecology, US Fish and Wildlife Service, and National Marine Fisheries Service and has a 15-year history of engagement that is crucial in moving projects forward (McMillan and Holm 2020).

- The San Francisco Bay Long Term Management Strategy includes USEPA, the USACE, the San Francisco Regional Water Quality Control Board, the San Francisco Bay Conservation and Development Commission and other stakeholders in the region. The goal of this group is to develop new approaches to dredging and dredged material management in the San Francisco Bay region through various objectives, such as conducting dredged material disposal in the most environmentally sound manner; maximizing the use of dredged material as a resource; and establishing a cooperative permitting framework for dredging and dredged material disposal (USEPA 2019).

- The USACE Mobile District participates in the Project Implementation Committee of the Mobile Bay National Estuary Program (http://www.mobilebaynep.com/). This interagency group assesses needs and resources, identifies and plans projects, seeks citizen input, and determines necessary tasks and roles for member agencies. The group's success is attributed to its ability to move such projects forward, the open communication focused on consensus, and a realization that the common goal is to implement successful beneficial use (Mroczko 2020).

- The New York/New Jersey Harbor Regional Dredging Team supports dredging projects in the region by developing comprehensive regional dredged material management plans that identify short-term and long-term disposal alternatives, consider methods to reduce dredging, and maximize beneficial use of dredged materials (USEPA 2021b). The team includes members from USEPA, USACE, New York Department of Environmental Conservation, New Jersey Department of Environmental Protection, the Port Authority of New York and New Jersey, and the New Jersey Department of Transportation.

- In the USACE New Orleans District, beneficial use is often the "least cost" option. Working groups previously focused on raising awareness and educating stakeholders on beneficial use practices and outcomes. Such working groups are no longer necessary to move beneficial use forward in the region. Economics, advocacy, and previous trust-building engagement has moved the practice from being unique to commonplace (Corbino 2020).

PROJECT CASE STUDIES

Case studies of successful beneficial use projects are presented below for the Seven Mile Island Innovation Laboratory and Drake Wilson Island.

Seven Mile Island Innovation Laboratory (SMIIL)

The USACE Philadelphia District, the State of New Jersey, and The Wetlands Institute implemented a collaboration framework by developing SMIIL along the New Jersey Coast (https://wetlandsinstitute.org/smiil/). The object of SMIIL is to transform the concept of dredged material as waste to dredged material as a resource, and to advance and improve dredging and marsh restoration techniques through innovative research, collaboration, knowledge sharing, and practical application consistent with RSM and EWN® principles.

Coastal New Jersey marshes are at risk due to sea level rise, sediment starvation, and marsh platform degradation. These influences contribute to reduced marsh habitat value, reduced coastal resilience, and increased coastal flooding risk. Sediment has become increasingly recognized as an essential resource for the continued health of marsh habitat and for maintaining/increasing coastal resiliency in the face of sea level rise. At issue was how best to advance the beneficial use practice to build on four marsh restoration and habitat creation projects using sediment from the New Jersey Intracoastal Waterway. The SMIIL approach was a marked departure from the traditional practice of dredging and placing the material in confined disposal facilities cut off from the natural sediment system.

The boundaries of the 24-square mile SMIIL were chosen due to the presence of existing and historic dredged material placement sites, confined disposal facilities, federal and state channels including the New Jersey Intracoastal Waterway, and extensive tidal marshes. The project goals focus on maintaining safe navigation channels while retaining dredged sediment in the system to benefit natural ecosystems and coastal communities. A working group was formed and continues to meet to identify and refine both short- and long-term objectives. Monitoring is ongoing and includes the collection of sediment, hydrodynamic, wetland vegetation, and local bird data to inform baseline conditions, initial designs, and beneficial use placement strategies that mimic natural processes and minimize unintended adverse impacts. Adaptive management strategies are in place to support long-term sustainability of dredging and coastal resilience in the region. Lessons learned from implementing this strategy are subsequently being applied in other areas of the SMIIL.

Drake Wilson Island

The USACE is making strides coordinating internally to improve communications across navigation and dredging programs. Such internal coordination enhances the ability of the USACE to align resources and coordinate across programs to improve efficiencies and communications about beneficial use projects. One effective way to promote beneficial use is to document and communicate how both present and past beneficial use projects have been implemented successfully. Drake Wilson Island is an example of a successful historic beneficial use project. The 5-ha marsh created on Drake Wilson Island in Apalachicola Bay (FL) was described by Newling and Landin (1985) then revisited in 2019 via funding by the USACE DOER program.

Prior to 1976, the island was an unmanaged dredged material placement area with low habitat value. In early 1976, sandy clay dredged material from Apalachicola Bay was used to construct dikes around the saline intertidal environment which was subject to long wind fetches and strong currents. Coarse-grained sandy dredged material from the adjacent Two-Mile Federal Channel was placed within the dikes to raise the elevation. Smooth cordgrass and saltmeadow cordgrass were planted between December 1976 and September 1977 to encourage native species establishment.

The marsh habitat creation project provided valuable habitat while preventing erosion into the adjacent navigation channel. Increased habitat diversity was observed relative to adjacent traditional dredged material placement locations. Ninety-seven plant species were observed in 1982 when monitoring was performed to assess the success of this beneficial use project. Newling and Landin (1985) observed various wildlife species using the island, the most notable being wading birds and a large clapper rail population. Figure 3 shows a thriving marsh habitat still in place on Drake Wilson Island as of 2019. Five distinct habitat types were observed on Drake Wilson Island as part of a retrospective monitoring study investigating long-term benefits of historical USACE beneficial use projects (Figure 4). Volume 2 of the Engineering With Nature Atlas provides additional information on the current status of the Drake Wilson Island beneficial use site (https://ewn.el.erdc.dren.mil/atlas.html).

Figure 3. Drake Wilson Island on the north shore of Apalachicola Bay, FL, ca. 2019 (photo credit Nathan Beane USACE ERDC)

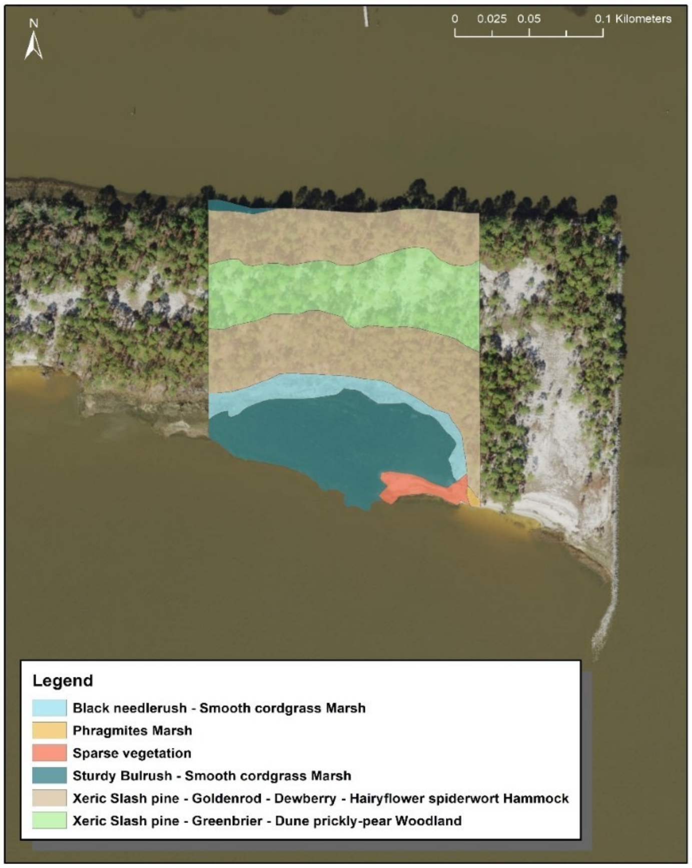

Figure 4. Five distinct habitat types on Drake Wilson Island identified in 2019 as part of a retrospective monitoring study investigating long-term benefits of historical USACE beneficial use projects.

CONCLUSIONS

Increased costs, schedule risks, permitting burdens, potential liability, logistical incompatibilities, and antiquated government policies result in disposal of large volumes of potentially valuable dredged sediments despite many beneficial use opportunities. Recently assembled data show 30 to 40% of dredged material from navigation dredging in the US is used beneficially. The consistency of this percentage over decades suggests the rate of beneficial use will not increase substantially without overt changes that address deterrents.

Historically, for USACE maintenance dredging projects, the Federal Standard is often cited as a rationale for choosing conventional disposal methods over beneficial use when costs for beneficial use exceed the cost of disposal. To increase beneficial use, a more holistic cost evaluation process that considers project value, including societal and ecological benefits, future cost avoidance, and a broader evaluation of cost impacts is needed to provide a more accurate comparison between disposal and beneficial use options. Cost estimates need to account for costs associated with reduced disposal volume capacity, and cost "off-sets" or "avoidance" when the purchase of raw materials is avoided by using dredged material. In addition, the environmental, recreational, and social benefits from habitat restoration/creation, coastal resiliency, and other such benefits afforded from beneficial use should be quantified. Tools like a net-environmental benefit analysis (Efroymson et al. 2003) or ecosystem services analysis (TEEB 2010) can be used to provide a more holistic quantification of value.

Large-scale, long-term beneficial use plans and policies are a potential tool to reduce schedule risks frequently associated with permitting requirements and the burden of obtaining additional permits. Beneficial use projects that provide quantifiable ecological improvements often address waterbody or watershed-wide concerns. These projects are likely candidates for programmatic permits that would reduce project-specific burdens and schedule risks. WRDA 2020 already prioritizes beneficial use over disposal. Additional federal legislation and policy that reduce liability concerns and remove dredged material from characterization as a waste could open additional beneficial use opportunities. Similar legislation at local, regional, and state levels would be even more effective, and could also be used to establish funding mechanisms to pay the additional costs of beneficial use in recognition of the overall, holistic economic advantages in the area.

In many cases, modest adjustments to navigation dredging schedules could significantly reduce sediment volume and project timing mismatches. Making these adjustments without impeding navigability will require up front planning and coordination. USACE and other project sponsors should actively pursue local and regional beneficial use opportunities as part of their local and regional dredged material management plans. These projects could significantly expand placement capacity, which increases the security of future dredging projects, but are often omitted from formal management plans because their timing and capacities are uncertain. Beneficial use working groups, regional dredging teams, and established regional sediment management plans and dredged material management plans have been instrumental in overcoming these schedule constraints or disparities in some areas.

Disposal of dredged material continues to be the standard practice in many areas of the country, such that significant advocacy, promotion, and support of beneficial use projects is needed to bring them to fruition. Local and regional beneficial use and other sediment management groups have increased the rate of beneficial use in some areas of the US, demonstrating how advocacy, collaboration and communication can result in the successful implementation of beneficial use projects. Active communication among stakeholders, including the private sector, non-government organizations, and local, regional, state, and federal regulators, effectively reduces impediments, and facilitates cost sharing often required to overcome increased costs associated with beneficial use. While USACE and their partners, as primary proponents of US navigation dredging, are in a strong position to foster these interdisciplinary groups and develop agency policies that support sustainable navigation infrastructure through increased beneficial use opportunities, this is not only USACE's burden.

Changes to federal and local policy, evaluating sediment disposal options based on environmental, economic and sustainability criteria, and the establishment of multi-stakeholder dredged material management teams at a local level are tools to increase the rate of beneficial use of dredged material. The development of location-specific dredge material management plans can be used to set expectations for the use of dredged material, which can in turn facilitate the coordination of dredge and beneficial use project schedules, establish funding sources to support dredging and beneficial use, and promote long-term societal and ecological benefits. Long-term monitoring of beneficial use projects with an environmental focus is necessary for understanding the changes in the health of coastal habitats that provide essential coastal defense, and for evaluating the overall success and effectiveness of the projects and the beneficial use paradigm.

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REFERENCES

Bridges, T.S. (2018). "Engineering with Nature: Toward Sustainable Systems," Western Dredging Association Gulf Coast Chapter Meeting, November 2018, New Orleans, LA. https://www.westerndredging.org/index.php/information/presentations-library/category/337-2018-in-new-orleans-louisiana?download=1773:national-project-perspectives-on-natural-nature-based-defenses

Bridges, T.S., Lillycrop, J., Wilson, J.R., Fredette, T.J., Suedel, B., Banks, C.J., and Russo, E.J. (2014). "Engineering with Nature Promotes Triple-Win Outcomes," Terra Et Aqua. 135:17-23.

Bridges, T.S., Bourne, E.M., King, J.K., Kuzminski, H.K., Moyniham, E.B., and Suedel, B.C. (2018). "Engineering with Nature®: An Atlas," ERDC/EL SR-18-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/27929.

Central Dredging Association (CEDA). (2019). "Sustainable Management of the Beneficial Use of Sediments," http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2019-05-BUS-ip.pdf.

CEDA (2021). https://www.dredging.org/ceda-working-group-on-beneficial-use-of-sediment-wgbu/203. Accessed January 2021.

CH2MHill. (2011). "Master Plan for Beneficial Use of Dredged Material for Coastal Mississippi," Gulf of Mexico Alliance/Habitat Conservation and Restoration Team, National Oceanic Atmospheric Administration Cooperative Award #NOAA GOMA 2003.

Childs, J. L. (2015). "Dredged Material Management Categories for Tracking Beneficial Use," DOER Technical Notes Collection. ERDC TN-DOER-R22, US Army Engineer Research and Development Center, Vicksburg, MS:. https://apps.dtic.mil/docs/citations/ADA619013.

Corbino, J. (2020). USACE New Orleans District. Personal communication. June 30, 2020.

De Vriend, H.J. and Van Koningsveld, M. (2012). "Building with Nature: Thinking, Acting and Interacting Differently," EcoShape, Building with Nature, Dordrecht, the Netherlands.

Efroymson, R.A., J.P. Nicolette, G.W. Suter II. (2003). "A Framework for Net Environmental Benefit Analysis for Remediation or Restoration of Petroleum-Contaminated Sites," Oak Ridge National Laboratory. ORNL/TM-2003/17.

Great Lakes Dredging Team (GLDT). (2020). "Environmental Evaluation and Management of Dredged Material for Beneficial Use: A Regional Manual for the Great Lakes," November.

Illinois Marine Transportation System (IMTS). (2020). "Neighbor State Dredging Review," Draft, February.

Kennish, M. (2002). "Environmental Threats and Environmental Future of Estuaries*,"* Environmental Conservation, 29(1), 78-107. doi:10.1017/S0376892902000061

Kiel, K.G. (2018). "*Beneficial Use of Dredge Material across the Great Lakes: Policies, Environmental Evaluations, and Projects*." Air and Waste Management Association Annual Seminar, January 2018, https://awmanfs.wildapricot.org/resources/Seminar/2018/Karen%20Keil.pdf.

Laboyrie, H.P., Van Koningsveld, M., Aarninkhof, S.G.J., Van Parys, M., Lee, M., Jensen, A., Csiti, A. and Kolman, R. (2018). "Dredging for Sustainable Infrastructure," CEDA/IADC, The Hague, The Netherlands.

Maglio, C., Das, H., & Fenner, F. (2020). "Modal Grain Size Evolution as it Relates to the Dredging and Placement Process - Galveston Island, Texas." Coastal Engineering Proceedings, (36v), papers.7. https://doi.org/10.9753/icce.v36v.papers.7

Maher, A., F. Jafari, W.S. Douglas, and J. Pecchioli. (2013). "The Processing and Beneficial Use of Fine-Grained Dredged Material- A Manual for Engineers," 146 p., New Jersey Departments of Transportation (NJDOT) and Environmental Protection (NJDEP).

Maryland Department of the Environment. (2019). "Innovative Reuse and Beneficial Use of Dredged Material Guidance Document," December 2019.

McLellan, T.N., Maurer, H., Fudge, B., and Heilman, D.J. (2001). "A Decade of Beneficial Use Brazos Island Harbor, Dredging," Proceedings of the WEDA XXI Technical Conference and Texas A&M University 32nd Annual Dredging Seminar, Houston, Texas, June 25-27, 2001.

McMillan, J. and J. Holm. (2020). USACE Portland District. Personal communication. April 13, 2020.

Minnesota Pollution Control Agency. (2014). "Managing dredge materials in the State of Minnesota," April 2014.

Mroczko, D. (2020). USACE Mobile District. Personal communication. May 7, 2020.

National Research Council. 1994. Restoring and Protecting Marine Habitat: The Role of Engineering and Technology. Washington, DC: The National Academies Press. https://doi.org/10.17226/2213.

Newling, C. J. and M. C. Landin. (1985). "Long-Term Monitoring of Habitat Development at Upland and Wetland Dredged Material Disposal Sites, 1974–1982." U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, U.S.A. TR D-85-5. NTIS No. AD-A159 106.

Pandal, A.P. (1998). "Beneficial Use of Dredged Material In Protecting the Eroding Coast - A Case Study," Proceedings of the 15th World Dredging Congress, Las Vegas, NV, July 1998.

PIANC. (1992). "Beneficial Uses of Dredged Material: A practical guide," Report of PIANC Working Group 19, PIANC, Brussels, Belgium.

PIANC. (2008). "Working with Nature," PIANC Position Paper. October 2008, Revised January 2011, Brussels, Belgium.

PIANC. (2009). *"Dredged Material as a Resource: Options and Constraints,"* EnviCom Working Group 104: PIANC, Brussels, Belgium.

PIANC. (2018). "A Guide for Applying Working with Nature to Navigation Infrastructure Projects, EnviCom," Working Group 176: PIANC, Brussels, Belgium.

PIANC. (2020). "Climate Change Adaptation Planning for Ports and Inland Waterways," EnviCom. Working Group 178: PIANC, Brussels, Belgium.

San Francisco Bay Regional Water Quality Control Board (SFBRWQCB). (2000). "Beneficial Reuse of Dredged Materials: Sediment Screening and Testing Guidelines," May, 2000.

Statista. (2020). https://www.statista.com/statistics/376643/industrial-sand-and-gravel-production-in-the-us. Accessed on September 23, 2020.

TEEB. (2010). The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis of the approach, conclusions, and recommendations of TEEB.

Texas Water Development Board (TWDB). (2005). Dredging vs. New Reservoirs Contract #2004-483-534

United Nations. (2019). *The Sustainable Development Goals Report*. New York. 60 pp. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

U.S. Army Corps of Engineers (USACE). (1987). *Beneficial Uses of Dredged Materia*l. EM 1110-2-5026. Washington, DC. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5026.pdf

USACE. (2003). "Evaluation of Dredged Material Proposed for Disposal at Island, Nearshore, or Upland Confined Disposal Facilities—Upland Testing Manual," Technical Report ERDC/EL TR-03-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

USACE. (2015). "Dredging and Dredged Material Management," Engineer Manual 1110-2-5025. U.S. Army Corps of Engineers, Washington, DC.

USACE. (2020). Regional Sediment Management Database, https://rsm.usace.army.mil/BUDB. Accessed 11 February 2021.

USACE (2021). https://budm.el.erdc.dren.mil. Accessed January 2021.

USACE, USEPA, San Francisco Bay Conservation and Development Commission, and SFBRWQCB (2001). "Long-Term Management Strategy for the Placement of Dredged Material in the San Francisco Bay Region." https://www.spn.usace.army.mil/Portals/68/docs/Dredging/LMTS/entire%20LMTF.pdf.

USACE Navigation Data Center (2021). "Actual Dredging Cost Data for 1963-2018." https://publibrary.planusace.us/#/document/6db4e2a5-20d7-4821-d598-8faf9cd66c6e; federal and industry cost corrected to 2018 dollars. Accessed January 2021.

U.S. Environmental Protection Agency (USEPA). (2016a). A methodology for evaluating beneficial uses of industrial-non-hazardous secondary materials. Office of Resource Conservation and Recovery. EPA 530-R-16-011.

USEPA. (2016b). Beneficial Use Compendium: A collection of resources and tools to support beneficial use evaluations. Office of Resource Conservation and Recovery. EPA 530-R-16-009.

USEPA. (2019). San Francisco Bay Long Term Management Strategy for Dredging. https://www.epa.gov/ocean-dumping/san-francisco-bay-long-term-management-strategy-dredging#:~:text=The%20San%20Francisco%20Bay%20Long,new%20approach%20to%20dredging%20and. Accessed January 2021.

USEPA. (2021a). "The Role of the Federal Standard in the Beneficial Use of Dredged Material," https://www.epa.gov/cwa-404/role-federal-standard-beneficial-use-dredged-material. Accessed January 2021.

USEPA. (2021b). Managing Ocean Dumping in EPA Region 2. https://www.epa.gov/ocean-dumping/managing-ocean-dumping-epa-region-2#rdt. Accessed January 2021.

USEPA and USACE. (1998). "Great Lakes Dredged Material Testing and Evaluation Manual," 1076 p.

USEPA and USACE. (2007a). "Identifying, Planning, and Financing Beneficial Use Projects Using Dredged Material, Beneficial Use Planning Manual," EPA842-B-07-001, October.

USEPA and USACE. (2007b). "Beneficial Uses of Dredged Materials Fact Sheet: Public Involvement and Outreach." EPA842-F-07-001E.

Van Eekelen, E, and Bouw, M. (Eds.). 2020. Building with Nature: Creating, Implementing, and Upscaling Nature-based Solutions. Ecoshape, nai010 Publishers, Rotterdam.

Watabe, Y.; Sassa, S. (2016). "History of land reclamation using dredged soils at Tokyo Haneda Airport," Japanese Geotechnical Society Special Publication, Volume 2, Issue 51, Pages 1784-1789, Released January 29, 2016, Online ISSN 2188-8027, https://doi.org/10.3208/jgssp.TC217-04.

Water Resources Development Act of 2016 (WRDA 2016), Pub L. No. 114-322, § 1, 130 Stat. 1645, https://www.congress.gov/114/plaws/publ322/PLAW-114publ322.pdf

Water Resources Development Act of 2020 (WRDA 2020), Pub L. No. 116-260, https://www.congress.gov/116/bills/s1811/BILLS-116s1811eah.pdf.

Wetta, R.B. and Hanson, W.H. "How does dredging effect the economy?," Proceedings of the WEDA XXXI Technical Conference and Texas A&M University 42nd Annual Dredging Seminar, Nashville, Tennessee, June 5-8, 2011.

Wong P.P. (2019). Reclamation. In: Finkl C.W., Makowski C. (eds) Encyclopedia of Coastal Science. Encyclopedia of Earth Sciences Series. Springer, Cham. doi: 10.1007/978-3-319-93806-6_254.

Yozzo, D.J., Wilber, P., Will, R.J. (2004). "Beneficial use of dredged material for habitat creation, enhancement, and restoration in New York–New Jersey Harbor," Journal of Environmental Management 73: 39–52.

RIVER REMEDIATION CASE STUDY: CAPTURING PCBS FROM IMPACTED SLURRY VIA SEPARATION AND WATER TREATMENT

S. Ponstein[1], C. McNeely[2] and A. Wilson[3]

ABSTRACT

Polychlorinated biphenyls (PCBs) are a group of chemicals often characterized by their high resistance to all forms of environmental degradation. The chemical stability of PCBs leads to their accumulation in soils and sediments in areas where transport is naturally facilitated, such as rivers and other waterways. As fish and other organisms interact with the impacted sediment, PCBs begin to bioaccumulate in the food chain. Remediation of PCBs-impacted sediment in waterways is therefore imperative to limiting PCBs exposure and associated health risks for humans and animals. This report presents a case study of a project in which approximately 21,000,000 gallons (80,000,000 L) of slurry collected from mechanically-dredged, PCBs-impacted sediment, were successfully treated while meeting stringent compliance limitations. Tactically implemented procedures and challenges faced by operations staff are discussed, and treatment data from the clarification and filtration systems, including geotextile tubes, is presented.

Keywords: Dredging, contaminated sediment, geotextile tube, polychlorinated biphenyl, remedial action

INTRODUCTION

The case study to be presented involves a river in the Northeast United States. Designated as a navigable waterway by the U.S. Army Corps of Engineers and regularly used by recreational vessels, this river was found to contain a 7.2 mile (11.4 km) stretch of PCBs-impacted sediment that required remediation. The impacted sediment at the bottom of the river was characterized as hard till and marine clays underlain by bedrock, allowing for mechanical dredging as a practical remediation option. Excavators were used to dredge the impacted material and place it in hopper barges for transport to the onshore operations site for processing. During transport, accumulated water and impacted sediment would mix, creating impacted slurry (a mixture of sediment and water). Once a hopper barge was docked, its contents were processed in one of two ways: first, a submersible pump attached to an excavator was used to pump impacted slurry from the hopper barge to a collection sump. From the collection sump, the impacted slurry was then pumped through a series of treatment steps before its eventual discharge as pretreated effluent. Second, remaining material would be excavated from the hopper barges and mixed with amendment to reduce free water in the material prior to its transport to a landfill. At times, this amendment process was found to be the most limiting factor to the project's efficiency; material was able to be dredged faster than it could realistically be dried and hauled away, thereby creating a bottleneck. Reducing the amount of water put through this drying process was therefore important to the project's success. As such, the submersible pump used to remove impacted slurry was placed as low as possible within the hopper barges. This operational change decreased the volume of water in the impacted sediment requiring solidification, but increased the volume of slurry requiring treatment through the water pretreatment system.

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Impacted slurry pumped from the hopper barges to the collection sump was sent through several steps of treatment before being discharged directly to a preexisting water treatment facility regulated under a State Pollutant Discharge Elimination System (SPDES) permit program. As such, treatment processes prior to this direct discharge were defined as being part of a pretreatment system. The water pretreatment system had known discharge limitations, and the increased flow of impacted slurry helped bring those to attention. Originally designed to manage maximum sustained flows of 150 gallons per minute (567 L/min) and slurry solids of approximately 2-4% by weight, the pretreatment system had to be modified after startup to accommodate the upswing in both flow and solids concentrations. These accommodations were made knowing that it was more cost-effective for the project to add additional treatment equipment that could be operated with the same staffing plan; only one operator and an assistant were utilized throughout the water pretreatment portion of the project. Through the strategic use of geotextile tubes, clarification processes, pressurized filtration equipment, and careful operational techniques, this project demonstrated that high concentrations of PCBs could be captured despite solids content and flow rates of the impacted slurry being significantly higher than anticipated.

SITE LAYOUT

Design of the site layout was a combined effort between the dredging contractor and the water treatment contractor. Efficiency was an objective of the design, and due to operational sequence, dredging operations were considered of higher priority relative to water pretreatment or dredged material solidification operations. As such, the onshore site layout was designed with intent to maximize dredging efficiency. Figure 1 shows an aerial view of the project site and how proximal separate operations were to one another.

Figure 1: Aerial View of the Project Site

As seen in the middle of Figure 1, the water pretreatment system is highlighted by eight holding tanks, three geotextile tubes, a settling sump, two semitrailers, and other treatment vessels. The pretreatment system is sided by haul roads to the left and bottom, dredged material solidification processes to the right, and on-water operations to the top. Along the nearside riverbank, three hopper barges are lined up from left to right. The first one, supporting two red containers full of impacted slurry that accrued during down river dredging operations, is currently being offloaded into the collection sump. This specific hopper barge was used for collection of impacted slurry ahead of shoreline processes. Next in line to the right, a yellow excavator is being used to pump any accumulated impacted slurry from the hopper barge to the collection sump (located behind the yellow excavator). Further right, a green excavator is being used to offload the remaining material from the third hopper barge.

Dredged material removed by the green excavator was sent through an apparatus in which amendment (contained in the two white silos) was added to improve solidification. Augers connected perpendicularly to the silos were used to mix the amendment with dredged material and discharge the mixture into a loading area directly in front of the silos. Front end loaders were then used to move the amended material to the correct mound location to allow for drying. In Figure 1, the mounds of amended material are relatively small, and the collection sump is overfilled, nearly reaching the amended material loading area. Relatively speaking, these observations suggest hopper barges unloaded prior to this photo being taken contained larger volumes of impacted slurry and smaller volumes of sediment. Though unpredictable and varying based on specific material being dredged at the time, this occurrence was not uncommon. Ultimately, it was a responsibility of the water pretreatment operator to maintain the collection sump level and minimize its impedance on the dredged material amendment process.

GEOTEXTILE TUBES FOR WATER TREATMENT

The first process of the pretreatment system began with maintaining the influx of impacted slurry within the collection sump. As the sump neared capacity, the operator would begin pumping the slurry from the collection sump into a geotextile tube using a dry prime pump with a floating suction line. This action was set up to be performed remotely from within the water pretreatment area to minimize convergence of personnel with heavy machine traffic. The timing of pumping the impacted slurry out of the collection sump became somewhat of an acquired proficiency as there were a few factors to consider when trying to optimize this process. It was determined that mechanically removing settled material from the collection sump on occasion and processing it similarly to dredged material was more effective than filling geotextile tubes with the settled material. With limited space available for the geotextile tubes, their ability to filter was considered more important, than say achieving the driest possible solids inside the tube. As such, an objective of the water pretreatment operator when pumping slurry into a geotextile tube was to minimize the concentration of solids entering the geotextile tube. This is not the normal operating procedure for a geotextile tube, however it was the best utilization for the geotextile tubes on this project. It was critical to allow suspended solids to settle for as long as possible in the collection sump. Not only did this prolong the lifespan of a geotextile tube from a filling standpoint, but it also reduced the volume of treatment chemicals used in the filling process. However, when a hopper barge came to shore for unloading, the pumping of its impacted slurry negated whatever settling had occurred in the collection sump. Therefore, allowing the sump to reach capacity at the end of the day was ideal, for example. Solids would be allowed to settle overnight, and much of the collection sump would be able to be pumped down at the beginning of the shift.

When pumping the impacted slurry from the collection sump, a coagulant and subsequently a flocculant were injected into the slurry pipeline upstream of the geotextile tube. These products were used to promote separation of the sediment and water that make up the slurry and enhance settling of the sediment inside the geotextile tube. A saddle tap in the pipeline located just upstream of the geotextile tube was used to collect slurry samples and check for flocculation. At the start of a fill cycle, the slurry was often lighter in solids and only required use of a coagulant for treatment. As pumping continued and the collection sump was drawn down, the solids content of the slurry would increase. By frequently observing the slurry samples for flocculation, the water pretreatment operator was able to determine how much coagulant was necessary.

There were a number of factors that determined the length of time of a geotextile tube fill cycle. Harm to the geotextile tube, whether it be a small tear, a rupture, or rolling, was of primary concern. Overfilling and instability of geotextile tubes are leading causes for such happenings, and it was up to the water pretreatment operator to ensure geotextile tubes were filled properly. Allowing geotextile tube pores to clog, either from lack of agitation or overdosing of polymer, was of concern when avoiding instability or overfilling. Limiting polymer usage was another factor when determining length of fill cycles. At times, the solids content of the slurry was found to be so high that the polymer pump could not adequately treat it. In this case, separation of sediment and water would not occur even with maximum polymer addition, and the efficiency of the geotextile tube would be greatly decreased. In this instance, extra settling in the collection sump would be required. Similarly, if it was determined that the collection sump had capacity and settling time available before more hopper barges were unloaded, pumping would be paused once treatment required more than a low polymer dose. Proper dosing in combination with selective pumping times were very important to effectively utilizing geotextile tubes for this project.

Figure 2: Geotextile Tubes Used to Capture Solids

As seen in Figure 2, filtrate water is released through pores in the geotextile tube fabric, while solids remain inside the geotextile tube. In this step of the pretreatment system, an overwhelming majority of solids, including sticks, rocks, and other debris, were captured within the geotextile tubes. Data collected and to be presented later in this paper suggests that removal of solids in the geotextile tubes heavily contributed to removal of PCBs by the overall pretreatment system. Not only did geotextile tubes capture a large majority of solids, but they did so while requiring relatively low maintenance from the operator. With appropriate attention, geotextile tubes provided equalization in the pretreatment system where influent flow was able to exceed effluent flow for some time without causing concern. With proper dosing, a geotextile tube was able to be filled and allowed to passively dewater while the operator tended to other matters such as backwashing media filters or collecting samples for process control monitoring. Up to three geotextile tubes were utilized concurrently during this project, allowing for extra dewatering time between fill cycles and providing extra capacity during times of high flow. Geotextile tubes were also used to recapture solids from underflow and backwashing of other pretreatment processes. Both forgiving and cost effective, the process of capturing solids ahead of more sensitive treatment equipment made geotextile tubes an integral part of the project's success.

CLARIFICATION PROCESSES AND PRESSURIZED FILTRATION EQUIPMENT

For the purpose of this paper, effluent from the geotextile tube filtration process is termed 'contact water' in order to differentiate from the heavy solids content of the impacted slurry pumped into the geotextile tube. Solids content that persisted in the contact water was typically very light and often undetectable to the human eye. From past experiences, it was found that PCBs tend to have an affinity for solids, and that capture of solids lowers PCBs concentrations in the water to be treated. Clarification and media filtration equipment used in this pretreatment system were found to work effectively for capturing colloidal solids and removing PCBs from the contact water. However, equipment sensitivity limited the capacity of the pretreatment system. The pretreatment system was originally designed for maximum sustained flows of 150 GPM (567 L/min), representing peak performance. As solids were captured, pressure across filtration equipment would gradually increase, and flow of contact water through the equipment would slow. Processes to remove captured solids from filtration equipment, such as backwashing and underflow sludge removal, required the pretreatment system flow to be significantly slowed, or stopped completely. It was therefore important to minimize the amount of solids entering the pressurized filter vessels in order to operate the pretreatment system most efficiently.

Like geotextile tubes, additional processes such as inclined plate lamella clarifiers and settling sumps allowed for equalization in the process flow where time could be used advantageously for capture of solids. Contact water from geotextile tubes was allowed to flow by gravity into a small depression at which point a sump pump transferred the contact water to a settling sump. Ferric chloride, an iron-salt coagulant, was added to the flow to aid in settling of suspended solids within the sump, which had a working capacity of approximately 60,000 gallons (227,124 L). A submersible pump was used to transfer contact water from the settling sump into a set of five 20,000 gallon (75,708 L) holding tanks prior to further treatment. Similar to the collection sump, in each instance that water was pumped into the settling sump, the existing settled solids would become resuspended. To combat this, the water pretreatment operator would often transfer a majority of the contact water from the settling sump to the holding tanks first thing in the morning, prior to starting a geotextile tube fill cycle. Utilizing selective pumping at equalization points in the flow plan proved to be a major factor in maximizing efficiency of the pretreatment system.

Contact water collected in the five holding tanks was pumped through the remainder of the pretreatment system equipment, which consisted of a lamella clarifier, multimedia filters, bag filters, and granular activated carbon (GAC) filters in that sequence. Though lamella clarification with use of ferric chloride was the first of the processes utilized, it was not found to be the most effective for solids removal. Ultimately, it was determined that clarification performance in the holding tanks was similar to that in the lamella. As such, the lamella clarifier, which acted as the bottleneck of the pretreatment system flow, was no longer needed for solids removal. In turn, multimedia filters were found to capture the largest portion of solids. Bag filters on the other hand, which were placed downstream of the multimedia filters, were not found to be very effective for most of the project. Bag filters were used with the intent of protecting the downstream GAC media from solids fouling. Absorption by GAC media was the final process of the pretreatment system and the only one specifically targeting organics removal. While it was found that PCBs were largely eliminated before this process, absorption by activated carbon did provide a firewall against effluent PCBs contamination.

PROCESS FLOW CHANGES

As previously mentioned, keeping up with the volume of impacted slurry generated was a challenge. Efforts were made to reduce the amount of solids sent to the pretreatment system, but ultimately the natural inconsistencies of mechanical dredging compounded by unpredictability of rain events led to changes being made. Bringing in extra manpower to operate the pretreatment system for 24 hours a day was explored, however it was decided extra equipment and process flow changes would work more effectively. While operations were ongoing, a second train of pretreatment equipment was mobilized and installed. This secondary system consisted of a sand filter, bag filters, and GAC filters. The two pretreatment trains were able to be operated independently and simultaneously, as needed. Plumbing of the five influent holding tanks was altered to provide an extra clarification step to both pretreatment trains. Ferric chloride was injected into the line prior to the holding tanks to enhance settling. Originally, holding tanks were plumbed in a manner that allowed for each to be filled and emptied individually. Under the new process flow, tanks were plumbed in series which allowed for extra solids settling as the contact water flowed by gravity within the series of five tanks. It was found, however, that the gradual flow within the tanks was not able to match flow from pumping into and out of the series of tanks. As such, contact water from the settling sump was pumped to the outside tanks and drawn from the middle tank for further treatment. This slight change allowed for doubling the flow into the middle tank and provided extra volume for intake from the settling sump. After the modifications, the pretreatment system was able to successfully treat impacted slurry with solids content in the range of 8-12% at sustained flow of 350 GPM (1,325 L/min).

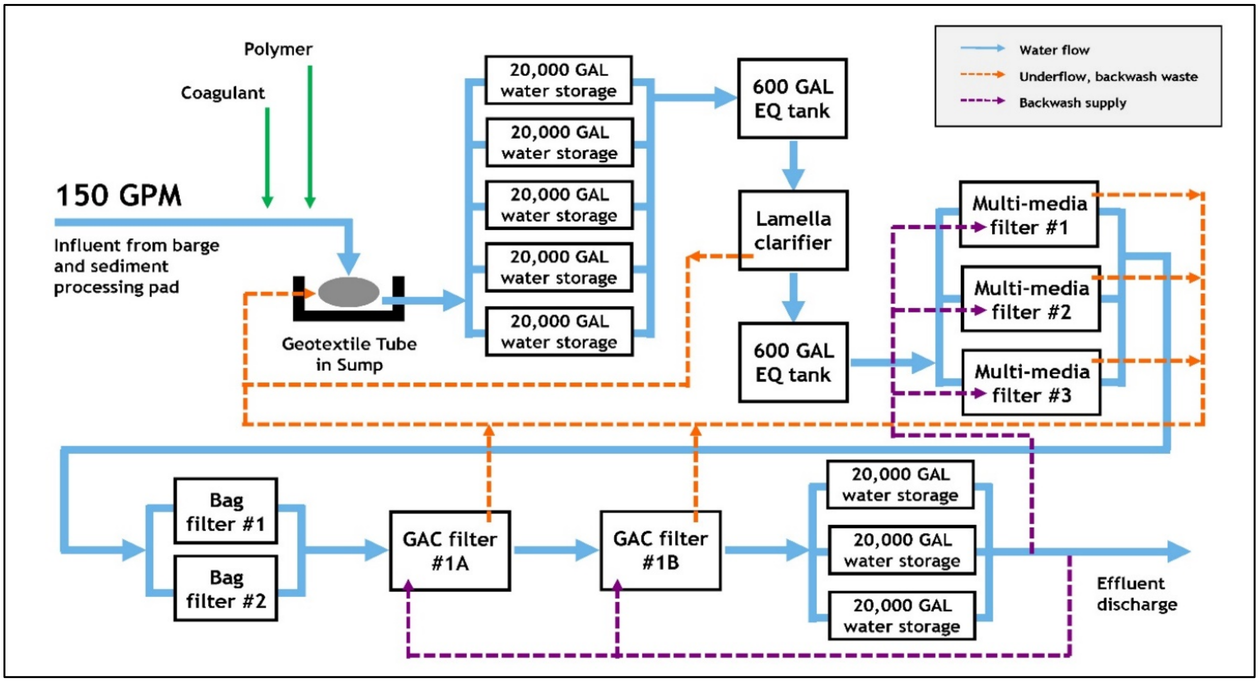

Figure 3: Original Process Flow Diagram

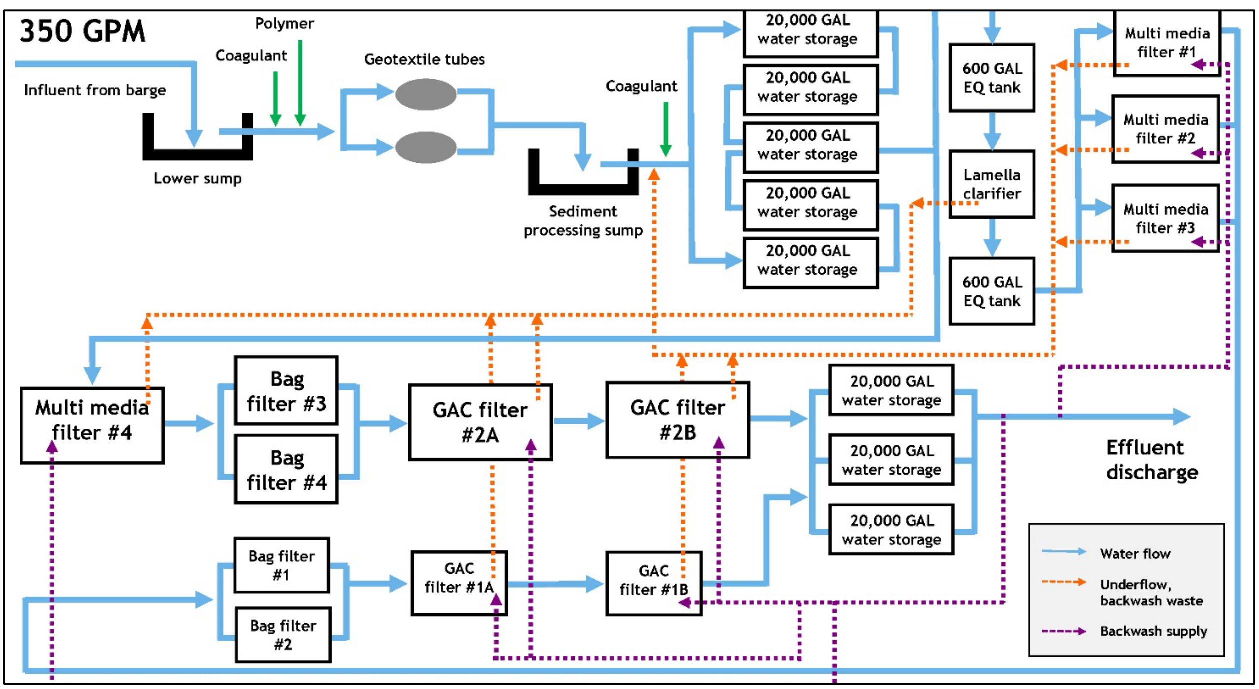

Figure 4: Final Process Flow Diagram

RATES OF CONTAMINATION REMOVAL

As previously mentioned, effluent water of the pretreatment system was discharged directly to a preexisting water treatment facility regulated under a SPDES permit program. On a weekly basis, samples of pretreatment system effluent were collected and sent to a laboratory for analysis of TSS and PCBs, to verify compliance with project specifications. Maximum allowable concentration limits of these analytes were set at 20 mg/L and 3 μg/L, respectively. Throughout the duration of the project, all samples submitted for compliance were found to be within the maximum allowable concentration limits. More importantly, none of the samples were found to have detectable concentrations of PCBs.

During the project, process control monitoring was used to determine how well each of the pretreatment processes was performing. Process control samples were collected bi-monthly and analyzed for TSS and PCBs concentrations for some processes, and TSS concentrations only, for other processes. Averages of the data can be seen below.

Table 1: Geotextile Tube Removal Rates of TSS and PCBs

	Geotextile Tube Influent	Geotextile Tube Effluent	Avg. Removal Rate
Avg. TSS conc. (mg/L)	71,000	23	99%
Avg. PCBs conc. (μg/L)	2.26	0.946	58%

Data from the first step in the pretreatment system, geotextile tube filtration, suggests that PCBs have a natural affinity to adhere to solids. Approximately 58% of PCBs were able to be captured by a process that filters material on a macroscopic level. Though the removal rate of PCBs is not as substantial as that of TSS, it is still impressive considering the consistent influx of impacted slurry, movement of material within the geotextile tube, and ensuing release of contact water. Clarification of the contact water in the settling sump and in the series of holding tanks was the next process monitored.

Table 2: Clarification Removal Rates of TSS

	Clarification Influent	Clarification Effluent	Avg. Removal Rate
Avg. TSS conc. (mg/L)	23	16	30%

Originally designed to simply be used as a means of flow equalization, clarification in the settling sump and holding tanks proved to be an adequate alternative to the lamella clarifier. Although a lamella clarifier has an integral solids removal system which is expected to be more effective at capturing and removing settled solids from the bottom of the clarifier, ultimately the portion of solids that were resuspended from pumping turbulence in the settling sump and holding tanks were able to be recaptured by multimedia filtration.

Table 3: Multimedia Filter Removal Rates of TSS

	Multimedia Filter Influent	Multimedia Filter Effluent	Avg. Removal Rate
Avg. TSS conc. (mg/L)	16	<1.0	~100%

Data shows that multimedia filters were able to capture a majority of the solids that were not captured by geotextile tubes. The next process in line, bag filtration, did not prove to be as effective.

Table 4: Bag Filter Removal Rates of TSS

	Bag Filter Influent	Bag Filter Effluent	Avg. Removal Rate
Avg. TSS conc. (mg/L)	<1.0	<1.0	Negligible

Though bag filters did not help much with the capture of solids throughout most of the project, they did provide protection from potential GAC fouling. However, at the very end of the project when geotextile tubes were offline and therefore unable to accept filter backwash, bag filters became much more useful.

Table 5: Pretreatment System PCBs Removal

	Influent	Effluent	Avg. Removal Rate
Avg. PCBs conc. (µg/L)	0.946	<0.023[4]	~100%

GAC vessels were arranged in a lead-lag formation. As such, the lead GAC vessel was utilized as the primary absorber of contaminants, while the lag GAC vessel largely acted as a safety measure. Data collected shows that average TSS concentration levels after the lead GAC were nearly below the method reporting limit of 1.0 mg/L, and that each sample was found to have non detectable concentrations of PCBs.

OPERATIONAL TECHNIQUES

When designing a treatment scheme, one of the first items contractors must address is the anticipated flow and quality of the water to be treated. On any dredging project, there are going to be unique site conditions, and occasionally, unexpected changes that affect the quality and quantity of water requiring treatment; therefore, it benefits a contractor to evaluate options to build flexibility and a range of performance into a treatment scheme. The ability to modify a water treatment system without shutting down dredge production or falling out of compliance can be the difference between project success or failure.

Process control monitoring is a critical practice for ensuring compliance is met throughout a project. During this project, process control monitoring was defined as any additional sample collection and analysis beyond that which is required for discharge permit compliance. Additions to discharge permit compliance such as extra sample points, higher sampling frequency, and testing of additional analytes were used to varying degrees during this project. Process control monitoring provides the operator with quantifiable data related to the performance and efficiency of each treatment process beyond what can be visually observed or measured with inline devices. Continuous discharge is the most efficient way to process water and support dredging operations, but it involves additional risk regarding discharge permit compliance. On this remediation project, the water treatment contractor elected to implement a process control monitoring schedule of bi-weekly TSS monitoring across each pretreatment process, as well as bi-weekly total PCBs monitoring after the lead GAC vessel. The water treatment operator also performed hourly measurements of turbidity and pH across each process using bench-top instruments. By consistently taking these measurements, the operator was able to identify trends and operate the equipment more efficiently.

[4] For this project, Total PCBs were calculated by adding the concentrations of the following congeners: Aroclor-1016, Aroclor-1221, Aroclor-1232, Aroclor-1242, Aroclor-1248, Aroclor-1254, and Aroclor-1260. Total PCBs was reported as a monthly average. The laboratory reported a different Method Detection Limit for each congener; the highest Method Detection Limit was 0.023 ug/L.

Figure 5: Water Pretreatment Operator Measuring Effluent Turbidity

In general, operations staff must thoroughly understand the design capabilities of the water treatment equipment in use to maximize efficiency and performance of the overall system. Characteristics such as power requirements, minimum/maximum operating flows, and operating pressure are important pieces of forming baseline knowledge for each treatment process. It is critical that the operator follow the manufacturer recommendations for maintaining equipment. A regular schedule of inspection, greasing, and oil changes must be developed and followed, for instance. Some maintenance, however, does not follow a schedule. For example, filter media must be changed when it becomes fouled as indicated by factors such as increased turbidity in filter effluent, increased pressure drop across the filter, or loss of media via the filter effluent. To achieve excellent operations, it takes more than performing regular equipment maintenance. The operations staff must also know and understand the intricacies of the project and the various factors that may affect the quality of water coming into the treatment system at any time. It is sound practice for operations staff to know how the treatment system sounds and looks when it is running properly. Staff must continuously observe water quality and take measurements of flow and pressure at various points throughout the system to know when a process is not functioning properly or when effluent characteristics are trending in a negative direction.

CONCLUSIONS

The authors define successful water treatment for dredging as a process that achieves compliance with discharge permit requirements without adversely impacting dredge production. This project demonstrated that PCBs can be effectively removed from impacted sediment by capturing solids ahead of sensitive equipment such as GAC vessels that are used to specifically target PCBs, but are unable to effectively capture organic contaminants in the presence of suspended solids. Through the use of geotextile tubes for filtration, over 99% of solids from the impacted slurry were able to be captured ahead of pressurized vessels. The process flow flexibility provided through the use of geotextile tube filtration played a very important role in being able to maintain efficient pace with the inconsistent flow and solids content of impacted slurry produced from dredging operations. While geotextile tubes offer it naturally, flexibility can also be designed into a treatment scheme with careful planning. If operations staff are provided equipment and space to adapt, only time and labor are needed to make adjustments to the treatment scheme. Ultimately it is the responsibility of the operations staff to be able to recognize issues before they become problematic and have the knowledge to identify a solution.

REFERENCES

Record of Decision, Grasse River Superfund Site (EPA, 2013)

CITATION

Ponstein, S., McNeely, C., and Wilson, A. "River Remediation Case Study: Capturing PCBs from Impacted Slurry via Separation and Water Treatment," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual Conference, June 15-18, 2021*.

DATA AVAILABILITY

Some data used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

ACKNOWLEDGEMENTS

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VOLUNTARY EARLY REMOVAL OF SEDIMENTS COMPLETED AT FORMER GREEN BAY MGP

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ABSTRACT

A Wisconsin Public Service Corp (WPSC) former manufactured gas plant (MGP) located in Green Bay, Wisconsin, enrolled in the United States Environmental Protection Agency (USEPA) Superfund Alternative Site (SAS) program, completed a voluntary early removal action of MGP-affected sediment in 2018-2019. The MGP project is in the Remedial Investigation (RI)/Feasibility Study (FS) phase. MGP-affected sediment was co-mingled with polychlorinated biphenyl (PCB)-affected sediment being remediated as a part of the Lower Fox River (LFR) PCB Project, completed by the LFR Remediation LLC (LFRR LLC).

An initial presence-absence sediment investigation was performed in 1995 and the 2017 RI defined two discrete areas of MGP-affected sediment, the South Focus Area (SFA) and North Focus Area (NFA) located at the confluence of the Lower Fox and East Rivers. MGP-affected sediment included visual observations of dense non-aqueous phase liquid (DNAPL) and elevated chemical concentrations. DNAPL mobility testing was performed in 2017 to inform the assessment of potential removal actions and fate of residuals. PCB material and MGP material were generally co-located in the soft sediment, while only DNAPL was present in the underlying clay fractures.

The LFRR PCB project had an early action in 2004 and has been ongoing since 2009. The project includes plans, procedures, equipment, and infrastructure to remove, dewater, process, and dispose of sediment. Leveraging the ongoing PCB remediation project equipment and infrastructure led to a more cost-effective and accelerated schedule to voluntarily address MGP-affected sediment and adjacent impacted shoreline soils. The SFA removal action was completed in 2018 with the removal of approximately 5,250 cubic yards (4,014 cubic meters) commingled polycyclic aromatic hydrocarbon (PAH) and PCB-containing soft-sediment. Additionally, excavated material was mixed with Calciment® or a Portland cement/Calciment® blend, and off-loaded for transportation to local landfill in Wisconsin including approximately 4,000 tons (3,629 metric tons) clay, and 2,740 tons (2,486 metric tons) shoreline soil. The NFA removal action was completed in 2019 with the removal of approximately 28,870 cubic yards (22,073 cubic meters)

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commingled soft-sediment and clay, construction of a 1.4-acre (5666 square meters) chemical isolation layer cap protected by an armored, grouted mattress cap.

This project demonstrates a collaborative and concerted effort between two independent Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) contaminated sediment projects. The construction portion of the project was performed under the existing regulatory oversight for the LFR PCB Project, with USEPA SAS and MGP group working closely with the PCB oversight team. Regular communication between all stakeholders was crucial to completing a successful project. Results will be incorporated into an RI/FS.

Keywords: CERCLA, NAPL mobility, chemical isolation layer cap, armored cap, contaminated sediment.

INTRODUCTION

The former WPSC Green Bay MGP (Site) is one of six former MGP sites addressed through the Administrative Order on Consent (AOC) and Statement of Work (SOW), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Docket No. V-W-06-C-847, dated May 5, 2006. The Site is currently enrolled in the United States Environmental Protection Agency (USEPA) Superfund Alternative Approach (SAA) program. Under the AOC/SOW, a generic approach to addressing the six sites is to be developed (the Multi-Site approach), describing the procedures and tasks to be followed to complete the Remedial Investigation/Feasibility Study (RI/FS) at the former MGP sites, including Green Bay MGP facility (Figure 1), which, in turn, may be modified to account for site-specific differences that may exist at a particular location. To facilitate project progress, the site has been divided into a sediment operable unit (OU) and an upland OU. The sediment OU (OU2) extends from the top slope of the East River riverbank, riverward and includes channel sediments, underlying clay, and surface water. The upland OU (OU1) extends from the top slope of the East River riverbank, landward and includes soil, groundwater, and potential vapor.

The USEPA-approved Site-Specific Work Plan (SSWP) Revision 1 (Natural Resource Technology [NRT] 2014) was implemented to characterize the extent of MGP residuals. An outcome of these characterization activities was a determination of the extent of MGP residuals in the East and Lower Fox Rivers that overlapped with the Lower Fox River (LFR) polychlorinated biphenyl (PCB) Project. MGP-affected sediment was co-mingled with PCB-affected sediment being remediated as a part of the LFR PCB Project, completed by the LFRR LLC. The LFR PCB project infrastructure and processes have been in place for a decade. Leveraging the ongoing PCB remediation project equipment and infrastructure lead to a more cost-effective and accelerated schedule to voluntarily address MGP-affected sediment and adjacent impacted shoreline soils.

The mutual interests of WPSC and USEPA in advancing the cleanup and the overlapping extent of the PCB and MGP residuals led WPSC to coordinate MGP sediment remediation activities with the LFR PCB project under a voluntary early removal action. Office of Land and Emergency Management (OLEM) Directive 9200.1-130 (2017) provides 11 recommendations for remediating contaminated sediment sites, including the performance of early removal actions (RA) during the RI/FS phase. Further, the August 23, 2019, OLEM Use of Early Actions at Superfund National Priorities List Sites and Sites with Superfund Alternative Approach Agreements Memorandum encourages consideration of early action as part of the overall strategy for site management. The memoranda state that actions should be taken at the point that sufficient information is available to support a response to mitigate risk or limit contaminant migration, which is consistent with Section 300.430(a)(l) of the National Contingency Plan. The objective of early actions is to achieve significant risk reduction, address immediate risks to human health and the environment, to control migration of contamination or in support of property reuse. The WPSC response action is considered an "early action" because it is taken before completion of the RI/FS phase for the site or OU is complete.

At the former WPSC Green Bay Site, MGP sediment removal activities were conducted in remedial footprints of the East River and LFR during 2018 and 2019 as voluntary early actions, leveraging the resources and infrastructure of the LFR PCB Project. Through agreements with the LFRR LLC, the MGP voluntary removal actions were conducted under the umbrella of the LFR PCB project.

Multiple working meetings with the USEPA, Wisconsin Department of Natural Resources (WDNR), WPSC, and the LFR Remediation LLC (LFRR LLC) led to the development of the Green Bay MGP Final Remedial Design Report (O'Brien and Gere [OBG] 2018a) for the South Focus Area (SFA), shown on Figure 1. USEPA provided WPSC an email/letter on November 28, 2018 (USEPA 2018), which stated:

"The U.S. Environmental Protection Agency (EPA) has reviewed the Final Remedial Design Report and Response to Comments (WPSC, July 13, 2018) for the shoreline soils and East River sediments in the South Focus Area of the Green Bay Former Manufactured Gas Plant Site. EPA has no further comments. As stated in previous comment letters, all data collected as part of this work will be carried into the Remedial Investigation/Feasibility Study for the Site. Additional action will be evaluated as part of the Remedial Investigation/Feasibility Study."

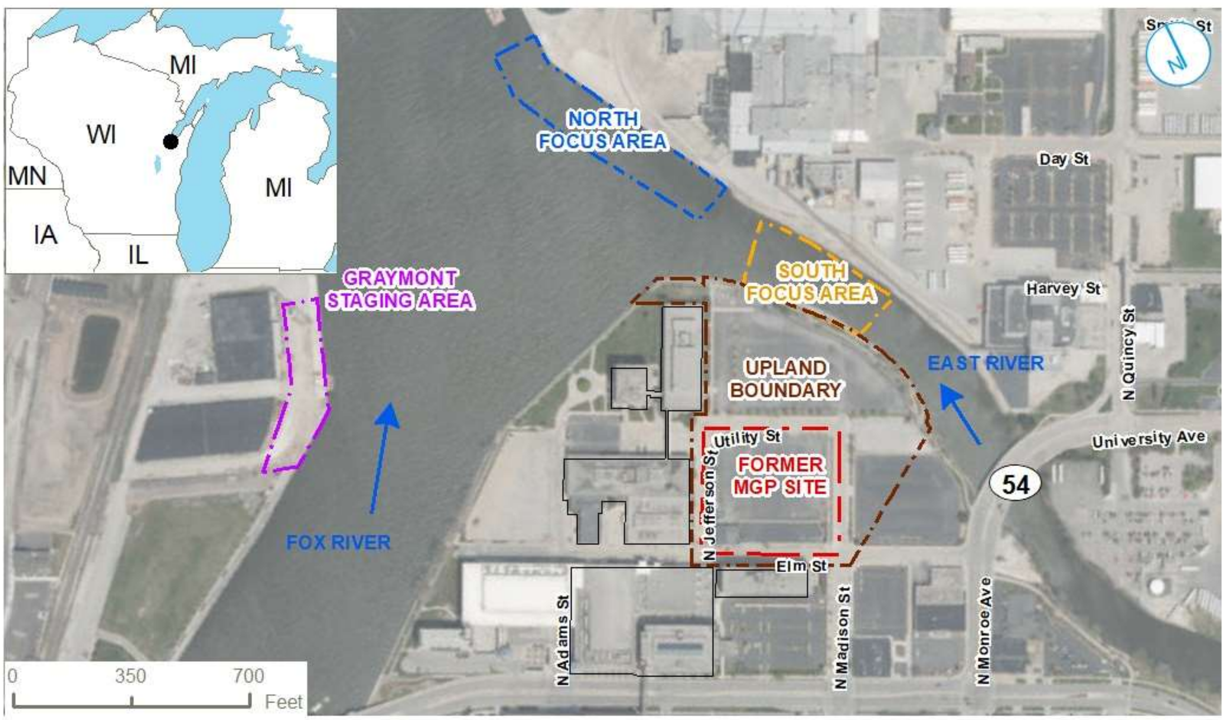

Figure 1. Former MGP Site, South Focus Area, and North Focus Area.

The SFA RA was completed in 2018 and the SFA Remedial Action Summary Report Revision 1 was accepted by the Agency Oversight Team (A/OT, including USEPA, WDNR, and their oversight contractor Boldt) in July 2019.

Working meetings continued during the execution of the SFA and subsequently for the development of the North Focus Area (NFA) design, which was submitted in the Addendum to the Final 2019 Update to Phase 2B Remedial Action Work Plan – Manufactured Gas Plant North Focus Area (RAWP Addendum), August 30, 2019 (Tetra Tech et al. 2019). USEPA provided the LFRR LLC a letter on September 4, 2019 (USEPA 2019) which stated:

"…the Response Agencies approve the "Manufactured Gas Plant (MGP) North Focus Area (NFA) Remedial Action Work Plan (RAWP), submitted August 30, 2019."

The NFA Remedial Action Summary Report Revision 2 (NFA RA Summary Report, Ramboll and AnchorQEA 2020) was accepted by the A/OT July 20, 2020.

SITE CHARACTERIZATION AND REMEDIAL ACTION

The timeline of sediment OU characterization activities are presented in Table 1. Sampling results from the 1995/1996 investigations were used to focus the grid-based approach for sampling locations collected from August 12 through August 26, 2014. The 2014 samples were analyzed for PAHs[6], benzene, toluene, ethylbenzene, xylene (BTEX), 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, and metals. The occurrence of PAHs above risk threshold screening levels (SLs) within the LFR PCB project footprint were correlated to visual observations of MGP residuals (i.e., oil-wetted or oil-coated sediment). Additional visual observation cores were collected by Tetra Tech in 2016-2017 to refine the MGP removal design (Figure 2). NAPL[7] mobility cores were collected by OBG in 2017 to inform the design of a cap for NFA sediment remaining following the implementation of dredging adjacent to a bulkhead wall as bulkhead structural stability limited the elevation of dredging (OBG 2018b). Cores were collected by OBG in 2018 and Ramboll in 2019 to characterize post-removal PAHs, BTEX, and metals (OBG 2019; Ramboll and AnchorQEA 2020). The results of characterization activities are presented in the Sediment Remedial Investigation Report, Revision 1 (Ramboll 2021), which is currently under agency review.

Table 1. Green Bay RI Characterization Timeline

Activity	**Date(s) Completed**
Presence-Absence Survey for MGP Residuals in the East and Lower Fox Rivers	July 1995
Additional Coring using vibracore	April 1996
LFR Superfund Project Sediment Investigation	August 2012
Focused Sediment Investigation and Surface Water Sampling	August 2014
Additional Borings advanced to support the design of the LFR Superfund Project	2016-2017
NAPL Mobility Investigation	November 2017

[6] The list of Total PAH (13) is as follows: acenaphthene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, fluoranthene, fluorene, naphthalene, phenanthrene and pyrene.

[7] The mobility testing laboratory uses the generic NAPL term and reports refer to "NAPL" mobility. At the Green Bay Site, NAPL is present as DNAPL.

SFA Post-Removal Verification Sampling	August 2018

Table 1. Green Bay RI Characterization Timeline (cont'd)

Activity	Date(s) Completed
NFA Post-Removal Verification Sampling	August 2019
SFA Year 1-Post Remediation Sampling	August 2019

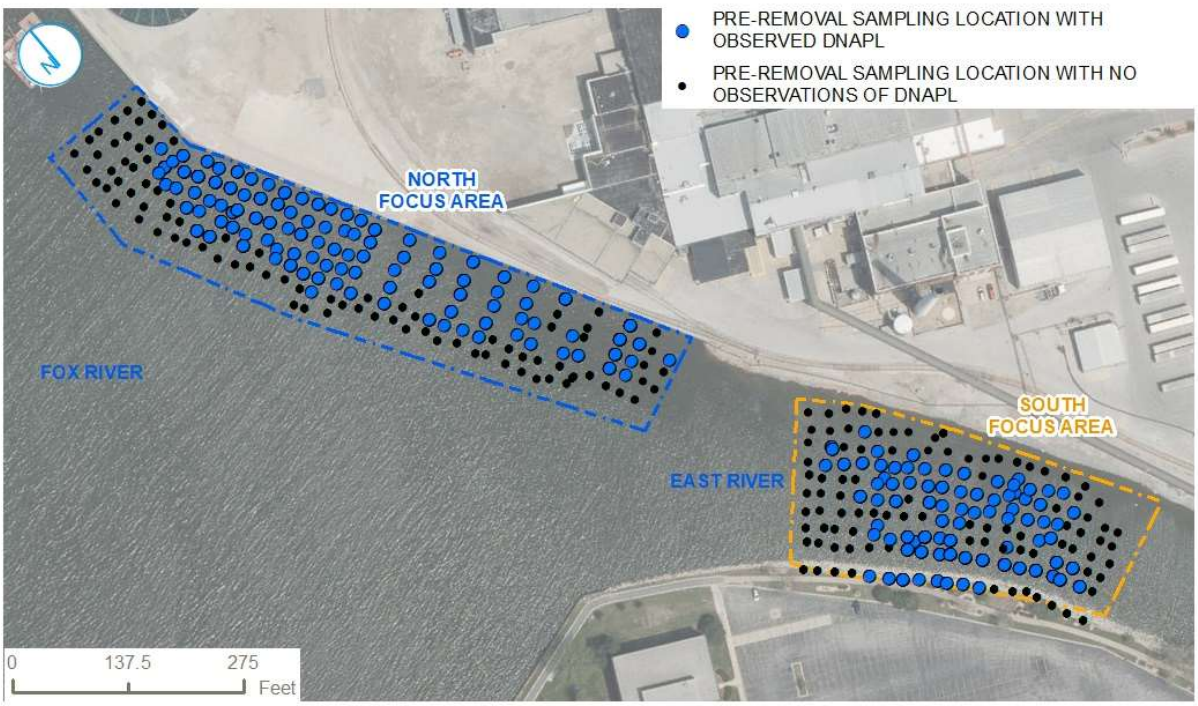

Figure 2. Pre-removal DNAPL observations in soft sediment or clay.

<u>*NAPL Mobility*</u>

A total of 27, approximately two-foot thick, undisturbed sediment cores were submitted to PTS Laboratories (PTS) for core photography (ASTM D5079) to identify sediment increments with visual indicators of potential DNAPL. Locations were selected based on the 2017 Tetra Tech visual observations of DNAPL. The observations of DNAPL were also considered (i.e., oil-wetted, oil-coated, or oil-stained) to evaluate a range of potential pore fluid saturation (PFS) values. DNAPL was not expelled in any of the 27 core segments analyzed by PTS, indicating that the DNAPL is immobile. DNAPL PFS values ranged from 1.4% to 9.3% of the total pore volume, which are below the PFS range typically associated with NAPL mobility of greater than 10%. Low hydraulic conductivity material, especially the clay, prohibits significant water volumes from passing through the matrix and indicates upward NAPL flux in this type of matrix is unlikely. However, a lack of measured NAPL mobility, PFS values less than 10%, and no discernable correlation between total PAH concentrations and PFS values may be reflective of the testing of low hydraulic conductivity material, notably the clay.

South Focus Area Removal Action

In 2018, adjacent riverbank shoreline soils and bedded soft sediment and clay were removed from the SFA in the East River. Remediation of the DNAPL and PAHs in sediment was performed within a temporary sheet pile turbidity containment area to meet the following remedial action objectives (RAO) and cleanup levels:

- Removal of soft sediment containing visually identified DNAPL and elevated PAHs to the extent practicable, with consideration given to stability of bulkheads and shorelines.
- Removal of visually identified DNAPL in clay, to the extent practicable, with consideration given to stability of bulkheads and shorelines.
- Removal of visually identified DNAPL in the south shore of the East River, in front of the sheet pile wall installed to support Upland Area 3 excavation.

Sand cover was placed inside containment following removal activities for residuals management. The SFA removal action (RA) was completed from July 9 to November 13, 2018 as documented in the SFA RA Summary Report Revision 2 (OBG 2019). Observations of dense non-aqueous phase liquid (DNAPL) and total polycyclic aromatic hydrocarbon Total PAH-13 concentrations in surficial sediments were documented as a part of SFA post-removal sampling.

South Focus Area Post-Removal Characterization

The SFA was sampled after the 2018 removal before placement of a residual sand cover and again one-year post-removal in 2019. A comparison of a spring 2019 hydrographic survey of the SFA to the fall 2018 post-removal clay survey illustrates that the dredged footprint filled in with natural sediment deposition during the winter season, with as much as 7-ft of sediment in some portions of the remedial footprint (Ramboll and AnchorQEA 2021). Sediment results were screened against MGP soil SLs and ecological SLs. A comparison of average surface sediment concentrations in 2019 compared to those of 2018 of parameters with SL exceedances indicates a surface sediment concentration reduction of nearly 90%, as presented on Table 2. The average Total PAH-13 was nearly an order of magnitude lower in 2019 than in 2018 and below the probable effects concentration (PEC) of 22.8 milligrams per kilogram (mg/kg). These reductions in concentrations indicate the remedy was successful and natural recovery is ongoing.

Table 2. Total PAH-13 Surface Sediment Post-Remedial Comparison

Post-Removal Sampling Event	Summary Statistic	Total PAH-13 (mg/kg)
2018	Minimum	0.042
	Maximum	227.07
	Average	35.49
2019	Minimum	0.006
	Maximum	11.84
	Average	3.93

North Focus Area Remedial Action

In 2019, remediation of the PCB and MGP residuals in soft sediment and clay was performed in the NFA. The RAWP Addendum (Tetra Tech 2019) identified target removal elevations to achieve the RAOs. The target removal elevations were based on sediment sampling completed in the NFA in 2017. Target removal elevations near the bulkhead wall were limited by wall stability, which determined safe dredge elevation (SDE) within about 30-ft of the bulkhead wall. Areas beyond the SDE footprint were sloped 3:1 to intersect the target elevations at which DNAPL was identified in native clay. Removal of soft sediment and clay to target elevations and cap construction were performed within a steel sheetpile containment system to prevent releases of suspended dredged residuals and to protect the RA from LFR flows.

Remediation of the PCB and MGP residuals in soft sediment and clay were performed, to the extent practicable and with consideration given to the stability of adjacent bulkheads and shorelines, to meet the following objectives and cleanup levels as stated in the RAWP Addendum (Tetra Tech 2019), which was approved by the Response Agencies in a letter from USEPA September 4, 2019 (USEPA 2019):

- Removal of all soft sediment in the NFA footprint
- Removal of all soft sediment between the containment system and the NFA footprint
- Removal of all soft sediment with PAH concentrations above 80 part per million (ppm)
- Removal of visually identified DNAPL in clay
- Isolation of remaining DNAPL and elevated PAHs in sediment or clay and PCBs in sediment, under an armored cap

The NFA RA was completed from March 25 to November 20, 2019. Observations of DNAPL and total PAH-13 concentrations in remaining surficial material were documented as a part of post removal sampling prior to cap construction.

North Focus Area Post-Removal Characterization

The NFA was sampled before placement of a residual sand cover, or where dredging elevation was limited by the bulkhead, before placement of a chemical isolation layer (CIL) and an armored cap. No oil-wetted or oil-coated material was observed in nine out of the ten borings advanced into the post-removal surface beyond the cap footprint. Trace (<5%) oil-wetted material was observed in silt in one boring. The total PAH PEC SL concentration of 22.8 mg/kg was not exceeded in any sample. This represents 0% of the NFA area outside the cap footprint with a PEC SL exceedance.

No oil-wetted or oil-coated material was observed in two out of the nine borings advanced into the post-removal surface where dredging elevation was limited, beneath the cap footprint prior to CIL and armored cap placement. The total PAH PEC SL concentration of 22.8 mg/kg was only exceed at four of nine locations, meaning for 55% of the NFA area within cap footprint, surface sediment did not exceed the PEC.

The presence of dredged residuals and exceedances of SLs beyond the cap footprint were mitigated by the placement of six inches of clean residual sand placed over the footprint beyond the capped area. Within the extent of the cap footprint, exceedances of SLs and the presence of residual DNAPL were mitigated by the placement of the CIL, armored cap layer, and a bulkhead buttress (including buttress sand layer) and benthic habitat layer. The contribution of latter two layers to attenuation were not considered in the cap design.

Response Action Summary

A summary of removed volumes and materials placed is provided in Table 3.

Table 3. Summary of Response Actions and Quantities

Remedial Action Area	Dredged Quantity[1] cubic yards | cubic meters		Placed Materials
South Focus Area			
WPSC Shoreline	1,245	952	0.1 AC (405 m^2) clean gravel
East River Soft sediment	5,246	4,011	1.07 AC (4,330 m^2) clean residual sand
East River Clay	1,637	1,252	
North Focus Area			
PCB Overburden Material	8,600	6,575	375 cy (287 m^3) clean sand backfill 1.02 AC (4,128 m^2) GAC sand area 1.45 AC (5,868 m^2) Organoclay 1.56 AC (6,313 m^2) residual sand 1.27 AC (5,140 m^2) of grouted mattress
MGP Soft sediment and clay	28,900	22,096	

[1] SFA sediment and clay were disposed under separate waste profiles. NFA sediment and clay were disposed under the same waste profiles and tracked together. PCB overburden in NFA was managed and disposed by the LFRR LLC.

ac = acre; cy = cubic yards; GAC = granular activated carbon; lf = lineal feet; m = meters

<u>*Site-Wide Post-Remedial Surface Weighted Area Concentration*</u>

Surface weighted average concentration (SWAC) methodology was used to derive an exposure point concentration over the approximately 15-acre (60,703 m^2) site. The SWAC methodology has been applied at other Wisconsin sediment sites including the LFR PCB project. A total PAH-13 SWAC was developed using Thiessen polygons and total PAH-13 concentrations from post-removal surface sediment concentrations normalized to 1% TOC (Figure 3). For areas falling outside the SFA or NFA remediation footprints, the remaining surface sediment Total PAH-13 concentrations from site investigation cores were used. If a polygon received the residual sand cover, a 90% dilution factor was applied, consistent with observed results from other Wisconsin sediment sites and as demonstrated within the South Focus Area 2019 post-remedy to 2018-pre-sand concentrations. Note that for the South Focus Area polygons, the 2019 post-remedy data were used in this evaluation, so no dilution was applied. A concentration of 0 mg/kg was assumed for the amended armored cap area. A site-wide SWAC of 1.13 mg/kg total PAH-13 results. The resulting sample frequency is just under one core per quarter acre (1,012 m^2). Table 4 categorizes the Theissen polygons by location, surface sediment type and summarizes how the sample types were managed in the SWAC calculation and how illustrated on Figure 3.

Table 4. Theissen Polygon and SWAC Approach Summary

Theissen Polygon Location	Surface Sediment Sample Type	Sand covered?	Dilution factor applied	Appearance on Figure 3
Outside NFA and SFA	Remaining site investigation	Yes	90%	Orange shading
	Remaining site investigation	No	None	No shading

Table 4. Theissen Polygon and SWAC Approach Summary (cont'd)

Theissen Polygon Location	Surface Sediment Sample Type	Sand covered?	Dilution factor applied	Appearance on Figure 3
Inside SFA	2019 post-remedy	No	None	No shading
Inside NFA-Amended Armored Cap	No post-cap sample, assume 0 mg/kg	No	Not applicable	Hatched
Inside NFA	2019 post-remedy	Yes	90%	Orange shading

CONCLUSIONS

The Former Green Bay MGP is undergoing the RI/FS process and results from the early action are being incorporated into that evaluation, including the development of remedial action objectives to support the Record of Decision. The long-term success of the remedy will depend on continued monitoring and maintenance of the NFA amended armored cap. The current conditions of the site are that surface sediment effects to benthos are a low probability because the site-wide SWAC is below the TEC of 1.6 mg/kg. These outcomes are viewed by WPSC as successes of the early removal action.

Performing an early removal action provided the following benefits to WPSC:

1. Cost savings
    a. A qualified contractor who was on-site for the LFR cleanup was leveraged, saving costs on contractor mobilization.
    b. Dredging project infrastructure (e.g. laydown areas, dewatering plant, trucking and traffic plans) was in-place and could be leveraged saving on the creation of certain work plans, scheduling, and contracting.
    c. A regulatory communication structure was in-place and frequent, regular project communication with agency and community stakeholders was seamless.
2. Programmatic efficiencies
    a. The collaboration between the two CERCLA projects allowed streamlining of field characterization activities before design and during/after remedial implementation.
    b. The participation in an early removal action streamlined the RI/FS process for the sediment OU of the former MGP by focusing the RI evaluation.
3. Contractor work quality
    a. Because there was oversight of construction contractors by LFRR LLC consultants, WPSC consultants, and agency personnel, the quality of the work delivered by the contractor had little room for error.

The successful construction of an early removal action and the realized benefits of the project are the direct outcome of collaboration between the two CERCLA projects, a robust and frequent communication program with the agencies, and significant planning efforts by all involved in the project.

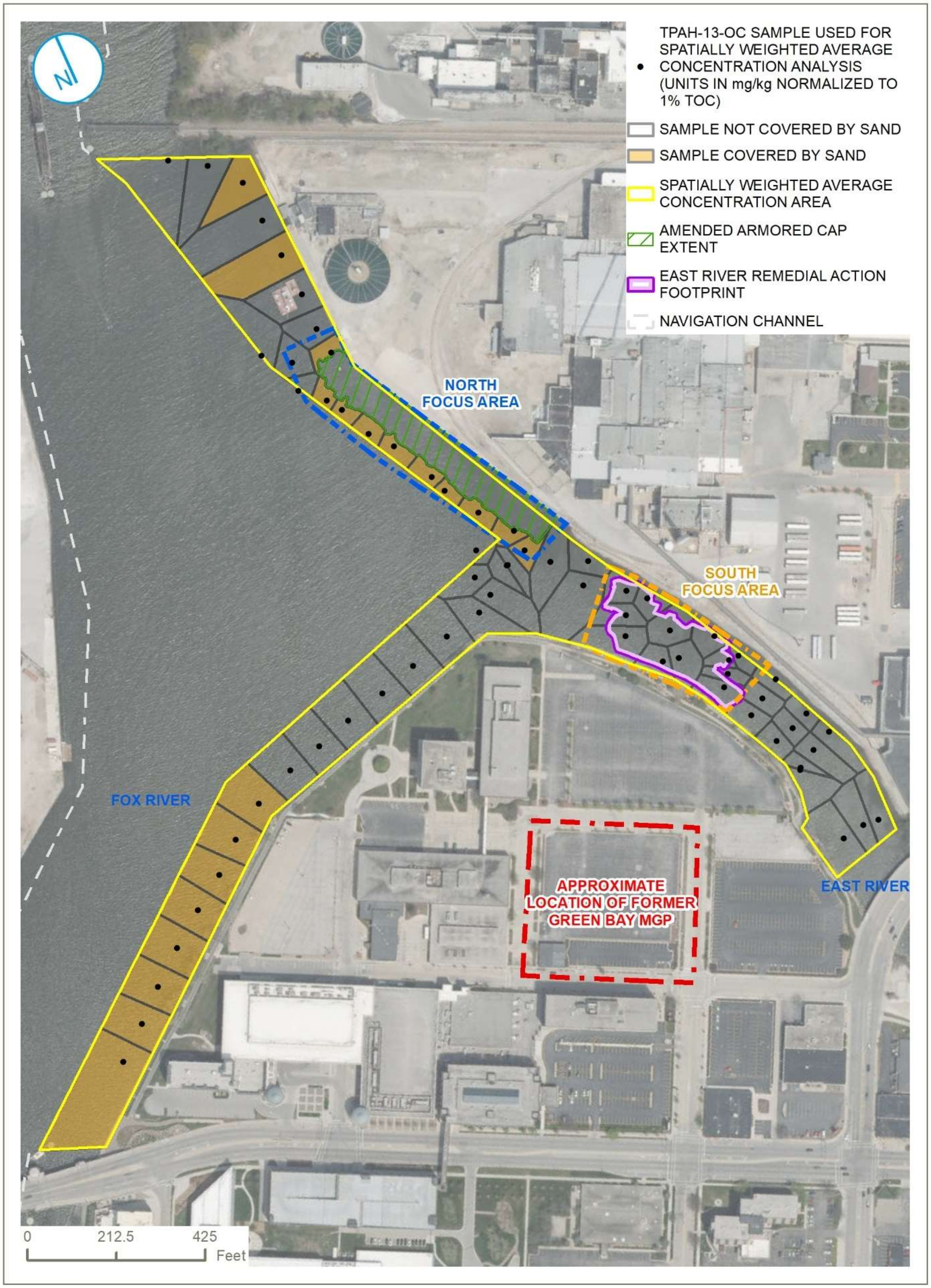

Figure 3. SWAC polygons and total PAH-13 organic carbon normalized concentrations.

REFERENCES

NRT 2014. Site Specific Work Plan (Revision 1), Former Green Bay MGP, Green Bay, Wisconsin. December 22.

OBG 2018a. Green Bay MGP Remedial Design Report, Green Bay, Wisconsin WIN000509948. July 12.

OBG 2018b. Former Green Bay MGP Site Mobility Sampling Data Summary Report. April 10.

OBG 2019. Former Green Bay MGP Site South Focus Area Remedial Action Summary Report, Revision 2. August 23.

Ramboll and Anchor QEA 2020. North Focus Area Remedial Action Summary Report, Revision 2. June 26.

Tetra Tech et al 2019. Addendum to the Final 2019 Update to Phase 2B Remedial Action Work Plan – Manufactured Gas Plant North Focus Area Lower Fox River and Green Bay Site Operable Units 2-5; Brown and Outagamie Counties, Wisconsin. Document Control Number: LFRR-19-031. August.

USEPA, United States Environmental Protection Agency 2018. Review of the South Focus Area Final Design Report and Response to Comments, Green Bay Former Manufactured Gas Plant Site, Green Bay, Wisconsin. November 28.

USEPA, United States Environmental Protection Agency 2019. Approval of the Addendum to the Final 2019 Update to Phase 2B Remedial Action Work Plan – Manufactured Gas Plant North Focus Area (RAWP Addendum), submitted August 30, 2019. September 4.

CITATION

Goetz, S., Paulson, R., Hagen, J. and Simmons, C. "Voluntary Early Removal of Sediments Completed at Former Green Bay MGP," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual Conference, June 15-17, 2021*.

DATA AVAILABILITY

All data, models, or code generated or used during the study are available in a repository or online in accordance with data retention policies of Unites States Environmental Protection Agency.

ACKNOWLEDGEMENTS

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INNOVATIVE TREATMENT OF WOOD-WASTE-IMPACTED SEDIMENTS USING REACTIVE AMENDMENTS AND DIFFUSIVE-GRADIENT-IN-THIN-FILMS PASSIVE POREWATER SULPHIDE TESTING TECHNIQUES

D. Berlin[1], D. Vlassopoulos[2], M. Kanematsu[3], T. Wang[4], M. Waters[5], K. Ritchot[6]

ABSTRACT

Esquimalt Harbour, British Columbia, has historically been used for log rafting, log storage, and wood mill operations over the last 70 years, resulting in the accumulation of over 200 hectares of wood waste deposits. As wood waste decomposes, it creates biological oxygen demand in sediments that can reduce or eliminate oxygenated zones. This can lead to a buildup of compounds such as sulphides and ammonia, which are toxic to benthic organisms at higher concentrations.

Public Services and Procurement Canada, on behalf of the Department of National Defence, has completed studies of wood waste sediments and is currently implementing a pilot project to address high sulphide levels in Esquimalt Harbour sediments. The studies include use of an innovative passive porewater sampling technique to quantify dissolved sulphides using the diffusive-gradient-in-thin-films (DGT) method to quickly and accurately measure porewater sulphide concentrations. These concentrations ranged from less than 1 milligram per liter to over 200 milligrams per liter in harbour sediments. The DGT method, which is based on the reaction of sulphide with silver iodide, is becoming increasingly common as a reliable in situ technique for quantifying a range of sediment porewater constituents.

Cleanup of sediments with wood waste has historically involved dredging, capping, or monitored natural recovery. However, in situ treatment amendments have the potential to immobilize porewater sulphide. An innovative bench-scale testing program was conducted to assess the effectiveness of sand cover mixed with a range of treatment amendments to reduce bioavailable porewater sulphide concentrations in wood waste sediments. The results were used to design and implement a pilot project in Esquimalt Harbour to test the effectiveness of sand amended with iron carbonate to control sulphide concentrations and support a healthy benthic community. This paper describes design and construction of the pilot project that consisted of placement of amended cover in early 2020 in two different types of soft wood-waste sediments. Observations on placement method effectiveness, mixing, and 1 year of pilot project monitoring are also presented.

Keywords: In situ treatment, diffusive-gradient-in-thin-film (DGT), wood waste, pilot project, siderite, bioavailability

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INTRODUCTION

Background

Since the mid-1800s, Esquimalt Harbour, Esquimalt, British Columbia, has been home to numerous industrial activities, including civilian and military shipbuilding and repair, commercial and military ship operations, and private logging and milling. These historical activities have generated a wide variety of organic and inorganic pollutants, which have made their way into the harbour and have become part of the underlying sediments. In particular, log booming, log storage, and wood mill operations during the last 70 years have led to the accumulation of wood and wood waste in the subtidal area of the harbour (Figure 1). Wood waste deposits can negatively affect marine benthic communities through physical alteration of sediments and toxicity from the by-products of anaerobic decomposition.

Contaminated sediment locations within Esquimalt Harbour are being remediated in a phased approach as part of the Federal Contaminated Sites Action Plan (site ESQ-1). As part of this effort, sediments in the northern portion of Esquimalt Harbour were evaluated for potential adverse effects of wood waste on the aquatic environment. Previous studies have described widespread areas of surface and subsurface sediments containing wood waste and wood waste decomposition by-products. Subsequent studies have refined the extents of wood waste and decomposition by-products, including porewater sulphides. The purpose of the Esquimalt Harbour Wood Waste Remediation Project is to develop and implement a risk management and remediation strategy that effectively reduces the ecological risks associated with sediments affected by wood waste.

Figure 1. Vicinity Map

Site Setting

Esquimalt Harbour is located at the south end of Vancouver Island, as shown in Figure 1. The harbour is governed by the Canada Marine Act and Transport Canada's Natural and Man-made Harbour Regulations, and it is under the control of the Department of National Defence. The harbour authority is the Canadian Forces Base Esquimalt Queen's Harbour Master.

The harbour has a long history of urban and industrial development dating back to the 1850s. This development has resulted in shoreline and drainage characteristics that are unique relative to other waterbodies but characteristic of working harbors. Harbor shorelines in southern Esquimalt Harbour are located within highly engineered systems that include large structures (e.g., naval jetties, drydocks, graving docks), bulkheads, and navigation channels developed to enhance the Royal Canadian Navy's operations throughout the harbour. Much of the northern harbour is residential; shorelines in this area are less developed and include several small residential piers and floats. The mouth of Millstream Creek, located at the northern end of the harbour, is a gently sloping mudflat. Shorelines largely consist of undeveloped sandy beaches and rocky shorelines.

Esquimalt Harbour encompasses 50 hectares of intertidal area and 304 hectares of subtidal area. The deepest location in the harbour is 16 meters (m) at the entrance. Hydrographically, under most conditions, the harbour behaves as a tidal estuary, with flows and currents driven by tidal exchange with the Strait of Juan de Fuca. The study area is in the northern portion of Esquimalt Harbour, where logging activities have historically taken place and sediment containing wood waste may be present. The study area contains bathymetric elevations as deep as -11 m Chart Datum (CD). Tidal exchange in the northern part of the harbour is less than in the southern part because it is farther from the Strait of Juan de Fuca. The freshwater inputs and incoming sedimentation are higher in the northern part of Esquimalt Harbour due to the proximity to Millstream Creek. The study area has higher total organic carbon (TOC) than other areas of the harbour due to the presence of wood waste. Like the southern part of the harbour, the grain size distribution in the study area is mostly fine-grained, with some sands, gravels, and bedrock.

OVERVIEW OF EFFECTS OF WOOD WASTE ON THE MARINE ENVIRONMENT

The effects of wood waste on the marine environment have been well documented. Breems and Goodman (2009), Kendall and Michelsen (1997), and the Washington State Department of Ecology (Ecology; 2013) summarize the impacts of wood waste on sediments in the region that includes Esquimalt Harbour (focusing primarily in Puget Sound) and discuss relevant considerations for the remediation of sediments containing wood waste. The following sections summarize the physical, chemical, and biological and ecosystem impacts on the benthic environment that can occur when large quantities of wood waste are deposited on the sea floor.

Physical Effects

Wood waste includes logs, bark, wood chips, and processed wood (e.g., sawdust), as well as the partially decomposed wood fibers that result as these materials degrade over time. Wood waste can physically affect sediment quality and benthic communities. Wood waste accumulations as shallow as 1 centimeter (cm) can lead to a decline in the abundance of suspension feeders, while deposits up to 15 cm can greatly reduce invertebrate biomass and diversity (Conlan and Ellis 1979). Surficial deposits of wood waste can physically isolate benthic organisms from native sediments, prevent access to suitable habitat, and prevent colonization of the sediment. Large accumulations of wood waste are slow to decay and may persist in the aquatic environment for decades (Ecology 2013). The persistence of wood waste in surface sediment depends on the degradation rate of wood, the deposition rate of new sediment, sediment transport mechanisms (e.g., vessel scour, wind/wave forces, tidal currents), and biological mixing within the biologically active zone. All of these factors are considered when assessing the persistence of wood waste impacts in sediment.

Chemical Effects

Sediment chemical conditions change with depth below the sediment surface (i.e., the sediment-water interface). The upper layer of sediment is the aerobic zone, where sediment tends to be mixed by biological activity and aerobic respiration dominates. Below the aerobic zone is the redox potential discontinuity (RPD) layer, which represents the transition from the oxidized zone to the reducing environment with depth. Below the RPD layer is the anaerobic zone, where oxygen has been completely utilized and anaerobic respiration dominates (Ecology 2013). The chemical impacts of wood waste are mostly related to a thinner aerobic zone and the generation of toxic degradation by-products within the anaerobic zone.

Wood waste, like other organic material, creates increased biochemical oxygen demand in sediment as it decays. Excessive biochemical oxygen demand can reduce or eliminate the aerobic zone in surface sediments. As wood waste decays and creates anoxic sediment, sulphides and ammonia production can increase to levels that are toxic to the benthic community. For marine sediments, when oxygen is absent and nitrates and nitrites have already been reduced to produce ammonia (NH_3), sulphate is then reduced, leading to the formation of sulphides (including hydrogen sulphide). Wood waste also decays, leaches, and degrades into other compounds that can be toxic to aquatic life. Decaying wood can also generate methane and release tannic and fulvic acids, phenols and methylated phenols, resin acid, benzoic acid, benzyl alcohol, as well as terpenes and tropolones.

Biological Effects

Wood waste in sediment can reduce abundance and diversity of the benthic community, reduce fitness and survival of bivalves, and reduce fecundity and increased egg mortality of Dungeness crab (Ecology 2013). Sulphides are known phytotoxins and high concentrations can negatively affect seagrass growth and survival and have been linked to seagrass die-offs (Elliott et al. 2006). Literature review suggests sulphide toxicity values for numerous marine species can be as low as 1 to 2 milligrams per liter (mg/L) for highly sensitive species.

Wood-waste-impacted sediment conditions also encourage bacterial mats, such as *Beggiatoa* spp. (a group of bacteria that use sulphur as an energy source), that are often characterized by a high oxygen demand and a thin or nonexistent RPD depth within the sediment column (Ecology 2013). Dense white bacterial mats (between 0.5 and 3.0 cm thick) form when the oxygen-sulphide transition zone exists at the sediment-water interface (Jørgensen 1977; Muβmann et al. 2003). The presence of the dense white mats is typically dependent at the oxygen-sulphide transition zone at the sediment-water interface.

DISTRIBUTION OF WOOD WASTE

Diver surveys in northern Esquimalt Harbour found widespread areas with moderate wood waste presence (more than a third of observations exceeded 10% wood waste coverage, and more than a sixth of observations exceeded 50% wood waste coverage). Several areas contain 100% wood waste coverage. Diver probes and cores were used to evaluate the thickness of sediment containing wood waste in 192 locations in the study area. Similar to surface sediment, moderate deposits were widespread, with 40% of locations containing sediment with wood waste that exceed 0.4 m in thickness.

The types of wood waste vary by location and include logs, bark, chips, and fibers (e.g., sawdust). Sunken logs, wood fragments, and bark can be found throughout the study area, due to historical log rafting. At present, log rafting is infrequently performed but represents a potential ongoing source of wood waste. TOC can be elevated in sediments containing wood waste. Most of the surface sediments exceed a TOC concentration of 3%, with samples from the site ranging from 0.04% to 35% with a median of 4.3% in 202 samples. Based on these observations, 640,000 m^2 of the study area contains surficial or buried wood waste.

DISTRIBUTION OF WOOD-WASTE DECOMPOSITION BY-PRODUCTS

Porewater Sulphides Using DGT Method

Porewater sulphide testing was conducted in the Esquimalt Harbour areas containing wood waste to provide information on the potential toxicity, for use in considering remediation and/or risk management options. Additional sampling in 2018 through 2021 was conducted to quantify dissolved sulphide using a passive porewater sampling technique using the DGT method to provide more accurate measurements of porewater sulphide concentrations. The DGT method has been developed over the last two decades (Rearick et al. 2005) and is becoming increasingly common as a reliable in situ technique for quantifying sediment porewater sulphide levels. The method is based on the reaction of sulphide with silver iodide, a white powder impregnated in a gel to produce silver sulphide, a black solid. The intensity of the color developed is proportional to the amount of sulphide accumulated in the gel.

DGTs accumulate more sulphides with longer exposure times but can become saturated at high concentrations. Shorter exposure periods were used for sampling locations with anticipated high porewater sulphide concentrations and longer exposures were used for sampling locations with anticipated low porewater sulphide concentrations. Exposure periods were 0.5 hours, 2.5 hours, or 24 hours, depending on the anticipated porewater concentration from previous investigations. Ex situ DGTs were analyzed at Anchor QEA's Environmental Geochemistry Laboratory via optical densitometry. Porewater sulphides can be measured by DGT in sediment collected in surface sediment grab samples using a piston or by directly inserting a spear into sediment, which measures the upper 15 cm porewater sulphide profile (Figure 2).

Porewater sulphides were found at elevated levels throughout most of the study area (Figure 3). Porewater sulphide concentrations were measured in 65 samples ranged from 0.27 to 105 mg/L. The median concentration is 25 mg/L, and more than 80% of samples exceeded 2 mg/L, which has been shown to cause toxicity in highly sensitive species. In general, elevated porewater sulphide was co-located with sediment containing wood waste.

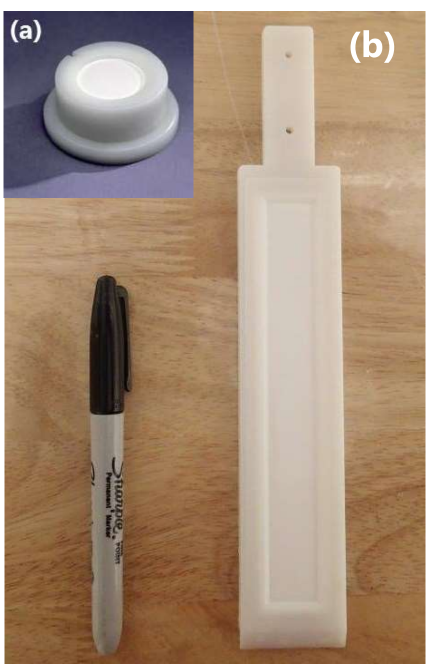

Figure 2. Example DGT Devices: (a) Piston and (b) Flat-Probe

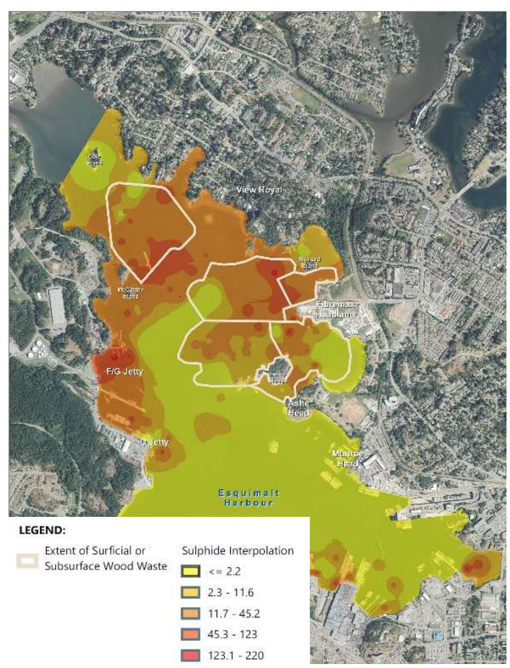

Figure 3. Wood Waste Areas and Porewater Sulphide Concentrations

POTENTIAL REMEDIATION OPTIONS

Potential remediation options for sediments containing wood waste include monitored natural recovery, enhanced natural recovery (ENR), in situ treatment, capping, and dredging. Monitored natural recovery is not considered effective for most parts of the management areas but could be effective where burial of wood waste and low propwash disturbance has been observed. Dredging is the most expensive remedy due to the need for a suitable disposal site, and may not be required as other most cost effective solutions may be appropriate. ENR, in situ treatment, and capping are potential solutions, which were evaluated as part of bench scale testing (Berlin et al. 2019) and as part of a pilot project described in the next section.

ENR refers to placing a layer of clean material (usually sand) on top of sediments to speed up (or enhance) the natural recovery process. ENR immediately replaces the surface sediments with clean sediment. In the case of sediment containing wood waste, the ENR layer would replace the high-TOC and largely anaerobic surface sediments with a clean sediment layer that allows recolonization of a healthy benthic community. Capping is similar to ENR, but is intended to isolate in situ contaminants from the marine environment to prevent direct contact with aquatic biota or humans. Engineered caps are usually greater than 1 m to account for potential erosive forces, contaminant mobility, and bioturbation. However, build-up of wood waste by-products beneath the cap may diffuse upwards towards the cap surface.

In situ treatment of sediment refers to biological, chemical, and/or physical treatment to immobilize, transform, or destroy deleterious substances while leaving the sediment in place. In situ treatment for porewater sulphides involves the placement of reactive material, such as siderite (iron carbonate [$FeCO_3$]), pyrolusite (manganese oxide [(MnO_2]), and mixed metal oxide (MMO) on site sediments, mixed with sand and placed in a thin layer over sediment (similar to ENR). Bench scale testing using these Esquimalt Harbour wood waste sediments and these three amendments showed each to be effective at binding or oxidizing sulphides, which results in reduced bioavailability and/or toxicity (Berlin et al. 2019).

Bench Scale Testing Conclusions

Siderite ($FeCO_3$) was selected as the preferred amendment for the pilot project based on the results of the bench-scale study, geochemical modeling, and experience at other cleanup sites (Berlin et al. 2019). Siderite dissolves in water and produces carbonate and ferrous (Fe+2) ions, the latter of which can combine with sulphide to precipitate iron sulphides, including mackinawite or pyrite (Lennie et al. 1997). Over time, mackinawite can transform to thermodynamically more stable pyrite. Fe+2 released from siderite may also be oxidized to ferric iron (Fe+3) and precipitated in the form of iron oxides and oxyhydroxides, which can abiotically oxidize dissolved sulphide.

A homogeneous mixture of approximately 5% granular siderite and 95% sand was recommended for use in the pilot project, placed to a nominal thickness of approximately 30 cm. While bench scale testing was conducted with powder reactive amendments because their reaction kinetics are faster than those in granular form, granular forms of these amendments are expected to be just as effective as the powder forms in the long term and are also expected to be better suited for in situ application, particularly for mixing and placement effectiveness.

The dosage of the amendment (5% on a dry-weight basis) was shown to be effective at reducing dissolved porewater sulphide concentrations for both bench-scale testing and modeled predictions. Kinetic modeling conducted indicated that siderite is expected to be a more effective amendment in the long-term.

PILOT PROJECT DESIGN

A field pilot project was constructed in early 2020 in Esquimalt Harbour to: 1) evaluate the site-specific effectiveness of ENR (clean sand cover) and in situ treatment (clean sand cover amended with siderite) for remediating sediments containing wood waste and 2) test the constructability of blending and placing the amended sand material in two different wood waste areas with unique physical and geotechnical characteristics. The pilot project has included 1 year of monitoring to assess the effectiveness at addressing adverse surface sediment conditions associated with the presence of wood waste. The pilot project consisted of design, construction, and monitoring of no action, constructed ENR, and in situ treatment areas within Esquimalt Harbour for assessment and comparison. The results of the pilot project will be used to inform selection of the preferred remedial actions for sediments containing wood waste in Esquimalt Harbour and the implementation of in situ treatment should it be selected.

To address the specific impacts of wood waste present in the aquatic environment, two remedial action objectives (RAOs) were identified to develop and evaluate wood waste remedial options in Esquimalt Harbour:

- RAO 1 (primary): Reduce the presence of wood waste in the biologically active zone (upper 10 cm) to levels typical of unaffected areas of Esquimalt Harbour. The presence of wood waste has resulted in a change in physical condition of the sediments that has negatively affected the diversity and abundance of the benthic community present in the sediment biologically active zone.
- RAO 2 (secondary): Reduce the concentration of wood waste degradation by-products in the biologically active zone to levels present in other areas of Esquimalt Harbour that do not contain wood waste. Levels of porewater sulphides in wood waste areas are above literature-derived reference levels that have been shown to cause adverse effects to benthic invertebrates.

Site Selection

The pilot project work areas were sited based on thickness of wood waste estimated from surface grab samples and sediment cores, geotechnical properties of surface sediments, and surface sediment conditions (i.e., images) identified from diver surveys. Specific selection criteria for the pilot project work areas included areas with significant thickness and visual evidence of wood waste, one area that has firm surface sediments and one area that has soft surface sediments based on geotechnical information. Each area was located in areas without significant propwash scour, such as the Jones Marine Services lease area. Based on these criteria, two general areas were selected for use in the pilot project. Work Area 1 is in the northern part of Esquimalt Harbour and Work Area 2 is located west of Inskip Island (Figure 4).

Work Area 1

Work Area 1 is in the northern part of Esquimalt Harbour with water depths ranging from -4 to -6 m CD. The historical source of wood waste is log rafting, with wood fragments and bark primarily present and sunken logs scattered throughout the work area. This area is generally characterized by relatively thin deposits of wood waste (average thickness is 0.4 m) compared to other areas, but high levels of porewater sulphides (75 percent of samples exceeded 30 mg/L). Besides the presence of wood waste in Work Area 1, this area has a very soft layer of fine grained, flocculent suspended sediments that appears to have a high fraction of organics, including algae, and accumulates just above the more competent sediment surface. This sediment was hard to sample using traditional sediment sampling equipment, but was noted by divers as a layer similar to fluidized mud.

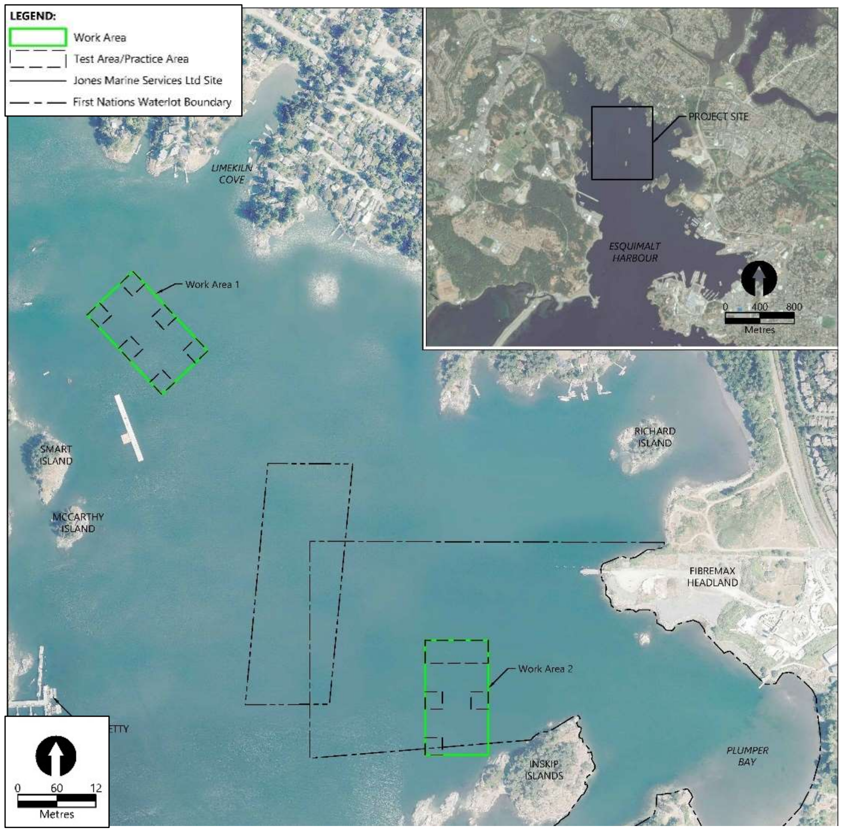

Figure 4. Pilot Project Work Areas

The pilot project objectives in this work area are to evaluate performance of ENR and in situ treatment for remediation of wood-waste-impacted sediments and to examine the implementability of three different placement methods on the softer surface sediments in this area. Placed materials in Work Area 1 may be more likely to mix with the softer surface sediments, which could make the placement of a well defined layer of ENR or in situ treatment cover material more difficult. Six 30-m by 30-m Test Areas (TA) were identified in Work Area 1, one of which was a control plot. Each TA was separated by 50 m to allow for spreading of placed material and migration of soft sediments during material placement, without impacting an adjacent TA. The size of Work Area 1 is 190 by 110 m.

Work Area 2

Work Area 2 is located west of Inskip Island with water depth ranging from -5 to -8.5 m CD. Historical sources of wood waste are from log rafting, with bark and wood fragments primarily observed. No layer of soft fine-grained, flocculent sediment with high organics was observed in Work Area 2. However, relatively deep wood waste deposits (up to 2 m) with coarse wood and a high density of sunken logs are present.

Successful methods for placing material on firm surface sediments are well documented; therefore, the pilot project will not evaluate different placement methods in Work Area 2. However, a 40-m by 110-m Practice Area is included in Work Area 2 for the contractor to conduct Practice Placement and demonstrate that their means and methods for each of three placement methods are adequate to meet specifications, prior to work in either Work Area. The pilot project objectives in Work Area 2 will focus only on the performance of ENR and in situ treatment for remediation of sediments containing wood waste in Work Area 2. Three 30-m by 30-m TAs have been identified in Work Area 2, one of which was a control plot. Each TA was separated by 50 m; the size of Work Area 2 is 110 by 200 m.

Remedial Technologies and Materials Selection

The goals of the pilot project are to evaluate effectiveness and implementability of ENR and in situ treatment for remediation of wood-waste-impacted sediments. The control plot will represent the "no action" remedial option, where no material will be placed.

Control (No Action). The control (no action) remedial option is a standard baseline comparison where no material will be placed. TA 6 in Work Area 1 and TA 9 in Work Area 2 (Figure 5) will be used primarily to compare against ENR and in situ treatment TAs constructed as part of the pilot project.

Enhanced Natural Recovery. ENR was implemented in the pilot project through placement of clean sand on sediments containing wood waste. Clean, fine-grained river sand dredged from the Fraser River were selected for use. The contractor washed the material to meet the gradation requirements and to remove excess highly suspendable fines prior to placement to help meet required gradations and achieve water quality monitoring requirements. ENR areas in the pilot project consisted of 30 cm sand plots placed in TA 4 in Work Area 1 and TA 8 in Work Area 2, with a vertical placement tolerance of plus or minus 15 cm. The targeted placement thickness of 30 cm was selected to provide enough fill material to prevent sulphide diffusion and advection to the surface of the fill material based on results of the laboratory bench-scale testing (Berlin et al. 2019).

Capping. Clean sand was also placed in a consistent layer with a targeted placement thickness of 60 cm in TA 5 in Work Area 1, with a vertical placement tolerance of plus or minus 15 cm. This targeted placement thickness was selected to account for potential mixing of fill material into soft surface sediments present in Work Area 1 and to evaluate the feasibility of capping as a potential remedial technology over soft sediment.

In Situ Treatment. A blend of clean sand and granular siderite was selected for use as in situ treatment in this pilot project based on the results of the laboratory bench-scale testing, geochemical transport modeling, and literature review (Berlin et al. 2019). Kinetic modeling indicated that siderite is expected to be a more

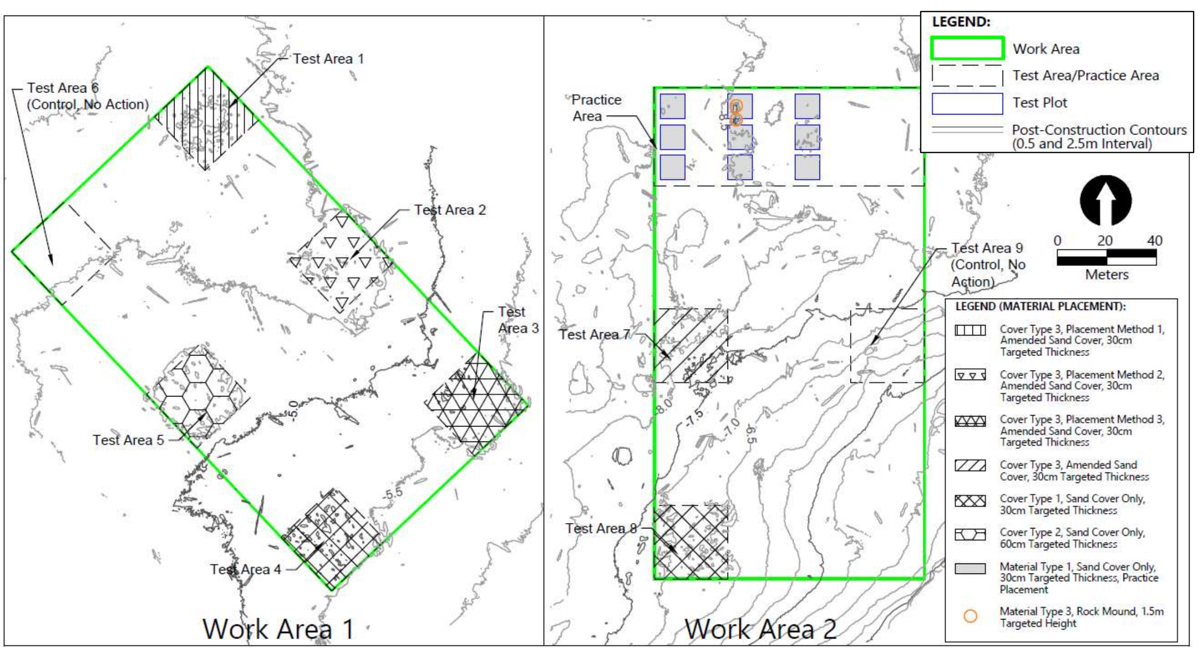

Figure 5. Material Placement Test Areas

effective amendment than other metal oxides in the long-term, suggesting that siderite is expected to be effective at suppressing porewater sulphide concentrations in the long term (i.e., greater than 30 years). Granular siderite was mixed at a 5% dosage of the blend by dry weight with the same clean sand used for ENR areas. The mixture was placed in a consistent layer with a targeted placement thickness of 30 cm and a vertical tolerance of plus or minus 15 cm. Amended sand was placed in TAs 1, 2, and 3 using three different placement methods selected by the Contractor, which included environmental clamshell bucket above water, skip box above water, and skip box near the seabed. Amended sand was also placed in TA 7 using the Contractor's preferred method (skip box above water). Uniformly blended amended sand was verified by quality control samples provided by the Contractor prior to placement.

Pilot Project Construction

Pacific Pile Marine Civil Constructors (PPMCC) completed the pilot project construction. PPMCC successfully placed clean sand within required tolerances using all three placement methods, including an environmental clamshell style bucket from above water and a custom designed and manufactured "skip box" style bucket with a rectangular trap door bottom from both above water and below water, from just above the seabed. The contractor's third-party surveyor performed the bathymetric pre-and post-construction surveys, as well as daily progress surveys. Daily dive surveys were also conducted to verify placement thickness. Construction occurred from January 30 to February 17, 2020.

The Contractor's preferred method for placement was using the skip box released from above the water surface. This method was the fastest rate of production (approximately 138 cubic meters [m^3] per hour), with approximately 6 m^3 per load, with an average load cycle time of 2 minutes and 36 seconds over the course of the project. The environmental clamshell bucket from above water held an estimated 2 to 4 m^3 per load and had an average cycle time of 1 minute and 52 seconds for the project (64 to 128 m^3 per hour). The method using skip box released near the seabed was the slowest method with an average cycle time of 3 minutes and production rate of approximately 120 m^3 per hour, which resulted in the most mounding. A single placement pass was sufficient to achieve thickness targets for each method.

Based on the observations from the post-placement bathymetric and dive surveys, the environmental clamshell bucket above the water appeared to result in the most uniform surface coverage throughout the TA boundaries, likely as a result of the smaller material volume placed with each load, but all methods met the acceptability requirements for placement tolerance over coarse wood waste (Practice Area) and fine-grained softer wood waste areas (Work Area 1).

Two rock mounds were also placed within the Practice Area on top of clean sand to evaluate the potential for future habitat enhancements, considering the potential for settlement.

Observed Bed Consolidation

During the initial placement of clean sand in the Practice Area, the thicknesses measured by the difference between the pre- and post-placement bathymetric surveys showed only very thin thicknesses of sand (approximately between 5 and 15 cm) compared to the expected thickness of slightly greater than 30 cm based on volume placed. This difference was attributed to consolidation of the existing seabed (silty sediments and wood waste) under the excess loading from the placed material, resulting in underestimated placement thicknesses using bathymetric survey comparisons. The dive surveys using sediment cores and hand excavation methods typically measured the cover layer in Work Area 2 to be between 5 to 20 cm thicker than the computed thickness from the bathymetric surveys. The Practice Area Test Plots showed the most consolidation, with slightly less consolidation in TAs 7 and 8, and very little consolidation in Work Area 1.

Observed Gas Bubbles and Sea Foam Formation

During the work, gas bubbles, or ebullition, were observed at the water surface after placement of each load. Gas bubbles were often observed rising from areas adjacent to, but not directly below, the placed load.

No odors were observed from the bubbles. Bubbles continued for several minutes, suggesting gas was released from the seabed as it was squeezed from the wood waste material that was being consolidated.

Construction Conclusions

All placement methods were effective at placing the targeted placement thickness of material within the required vertical placement tolerances. Overall, the project successfully demonstrated that a thin layer of material can be reliably and consistently placed within the specified vertical placement tolerances without substantial mixing of underlying wood waste. Each placement method was able to effectively deliver the sand/siderite amendment on top of the wood waste sediments without any indication of differential settling that would have resulted in a layer of siderite below the sand (due to its higher density).

YEAR 1 PILOT PROJECT MONITORING

Post-construction monitoring activities occurred between March 2020 and March 2021. Monitoring included the following elements:

- Bathymetric surveys to document long-term elevation changes.
- In-situ DGT sampling to monitor dissolved sulphide concentration profiles.
- Divers collected core samples and provided observations to assess sediment conditions.
- Surface water data to understand conditions that may affect sulphide production.
- Benthic macroinvertebrate monitoring to assess recolonization post-cover.
- Sediment Profile Imaging (SPI) to assess the surface sediment conditions post-cover.

Bathymetry Monitoring

The bathymetry analysis indicates that sand and siderite-amended sand covers have generally remained stable. Consolidation of the cover material is occurring, as observed by divers from the increasing difficulty associated with core penetration of the cover with each sampling event. Consolidation was also noted during the SPI work as the SPI equipment was only able to penetrate 10 to 15 cm into the cover surface.

The 11-month post-construction bathymetric survey indicated that TA 8 (30 cm sand cover) is continuing to settle. TA 8 is located west of Inskip Island (Work Area 2), where highly porous coarse wood waste is prevalent. The high porosity of underlying wood may also have contributed to uneven settling in this area.

TA 3 (amended sand cover) and TA 4 (sand cover) each showed isolated locations with deeper areas (up to 25- to 30-cm decrease in seabed elevations) after 6 months. Spudding holes were repaired as part of the Pilot Project construction, but continued consolidation of the material placed in these locations is likely the result of continued consolidation over the 6-month time period. No further consolidation was evident at 11 months. No obvious signs of exposed wood were observed by divers or SPI plan view images in these areas, suggesting the cover remains intact.

No major disturbances to the covers were noted during any of the monitoring events. No signs of mixing during or after placement, from propwash or currents, was observed during diver observations, photos of the cover surface, or SPI observations of cover TAs. Additionally, bathymetry monitoring indicates no movement of logs in or around the TAs. Some logs do penetrate up through the cover, but sand or siderite-amended sand was present on and around the logs, suggesting placement provided some degree of protection and remains stable.

The two rock mounds located within the Practice Area exhibited 15 to 20 cm settlement after 6 months and another 10 cm settlement between 6 and 11 months, suggesting the rocks continue to be stable on top of the sand cover that overlays coarse wood waste.

SPI and Diver Observations

SPI photos indicate the presence of finer-grained sand particles present in the upper few cm of most sand and siderite-amended sand covers (Figure 6). This suggests some differential settling occurred during placement, with coarser sand and granular siderite settling first, and finer-grained particles settling last. No evidence of layering or a layer of siderite was observed in diver cores or SPI photos. No significant mixing between the sand and underlying sediments was observed at the bottom of diver cores that achieved full penetration through the cover. The apparent redox potential discontinuity (aRPD) surface was observed in most plots a few cm below the surface, indicating a few cm of oxidized surface sediments. Black staining was observed a varying depths, indicating reaction of dissolved sulphides with iron dissolved from siderite to form iron sulphide precipitates (FeS) such as mackinawite or pyrite.

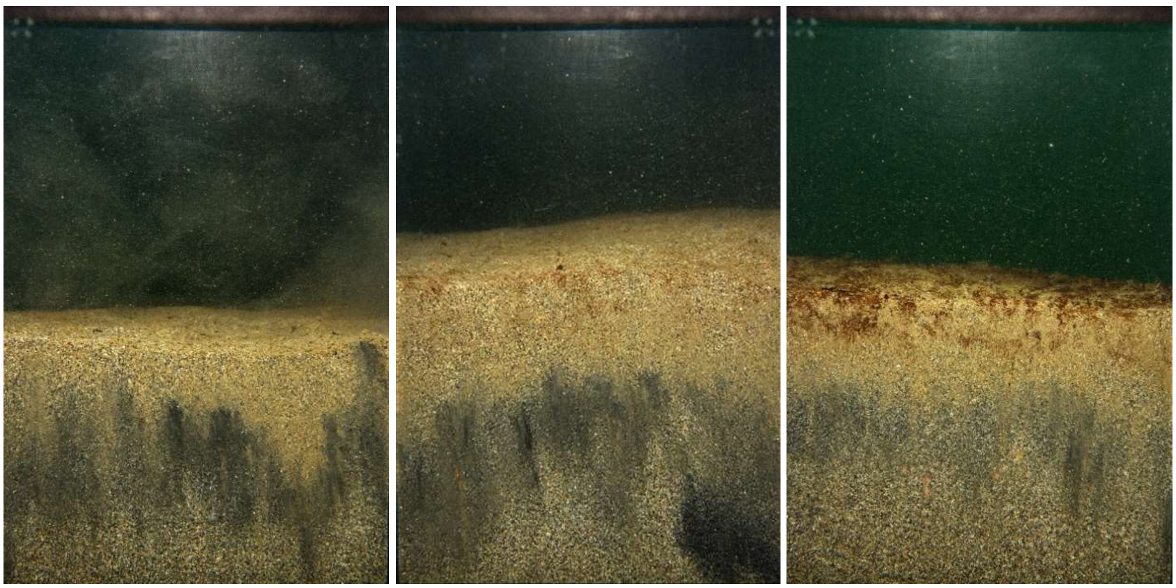

Figure 6. Sediment Profile Imaging of Test Area 7 (Amended Sand Cover) after 12 months

Cover Effectiveness for Sulphide Management

Results from 12 months of monitoring indicate similar effectiveness of siderite-amended sand cover and sand-only cover to control dissolved porewater sulphide concentrations, with very low to no sulphide detections in nearly every TA for each event. However, one monitoring event each contained slight elevations of porewater sulphide for the siderite-amended sand cover and the sand cover TAs in Work Area 2. TA 8 (sand only) contained elevated sulphides below 13 cm in October 2020 (8-month). TA 7 (siderite-amended sand cover) contained a slightly elevated sulphide concentration below 11 cm in March 2021 after 12 months (Figure 7).

TA 8 also had significant black FeS(s)-like precipitate observed in SPI photos as well as presence of Beggiatoa, indicating presence of sulphides at the cover surface (Figure 8). Overall, the performance of siderite-amended sand cover in the in situ pilot project was consistent with the results of the bench-scale treatability study. Additional monitoring may be necessary to determine the longer-term effectiveness of each cover type at controlling porewater sulphide concentrations.

In the control areas, sulphide concentrations in sediment porewater were extremely high in almost all monitoring events, indicating sulphate-reducing conditions were maintained in surface sediment (0 to 15 cm) throughout the year. TA 6 in Work Area 1 contained higher sulphides (20 to 60 mg/L) than TA 9 in Work Area 2 for each monitoring event (10 to 30 mg/L). Sulphide concentrations were greater for both control TAs in August and October, likely due to more active sulphide production by sulphate-reducing bacteria under warmer temperature and from less mixing of the water column, potentially resulting in a thinner layer of oxidized sediment.

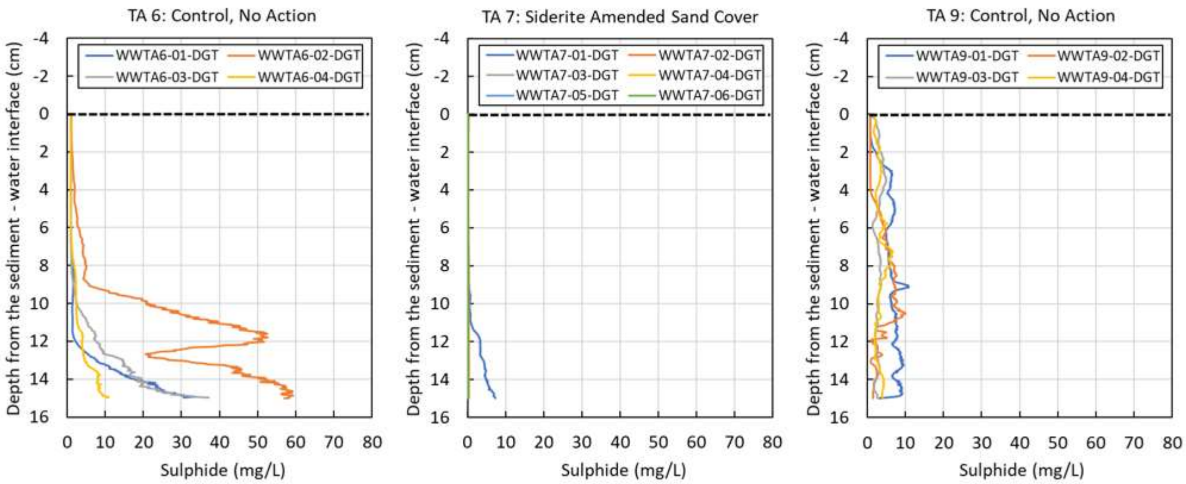

Figure 7. Dissolved Sulphide Concentration Profiles after 12 months (March 2021)

The DGT monitoring demonstrated that sand cover is effective at reducing the transport of dissolved sulphide from the underlying sediment. The naturally occurring iron content of sand sourced from the Frasier River could reduce hydrogen sulphide concentrations by abiotic oxidation of sulphide by iron oxides and/or redox manipulation by iron oxides, but this effect is not expected to last in the long term, and higher porewater sulphides measured in TA 8 may suggest porewater diffusion from below may exceed sequestration capacity of the naturally occurring iron.

In October 2020 (8 months post-construction), dissolved sulphide was detected by two DGT samplers in the sand cover in TA 8 at 13 to 15 cm below the surface (up to 7.3 mg/L). It is possible that sand cover is not effective at controlling the upward diffusion of dissolved sulphide in the long term. However, bathymetry monitoring suggests TA 8 is decreasing in elevation more than other TAs. Bathymetry and SPI observations also suggest uneven settling is occurring in TA 8, which can result in compression of underlying wood and force porewater upwards into the cover. It is also possible that DGT monitoring locations were in an area with less sand cover thickness, which can be variable and may not have been adequate to control dissolved sulphide concentrations in the top 15 cm. However, no other DGT monitoring from sand (TA 4 – 30 cm; TA 5 – 60 cm) measured porewater sulphides at this level, which also likely contained variable cover thickness inherent to any construction placement activity.

Dissolved sulphide concentrations were detected in one of the siderite-amended sand cover areas in March 2021 (12 month; TA 7). All other siderite-amended sand cover areas were effective, likely as a result of siderite dissolving into Fe(II) ion and reacting with dissolved sulphide to precipitate FeS(s) in the sediment layer. SPI indicated black staining from iron sulphide precipitates observed several cm below the cover surface, suggesting siderite is effectively sequestering any porewater sulphide migrating up through the cover from below. FeS is far less likely to be toxic to benthic organisms than freely dissolved sulphide.

Low concentrations of sulphide near the sediment surface were observed in some DGT samples for both sand and siderite-amended sand TAs. These concentrations are likely due to the deposition of sediment and algae from the surrounding area onto the TA, which may be providing conditions that result in sulphide generation at the top of the cover. SPI photos indicate the presence of reducing conditions at the cover surface in some photos, especially at TA 8, where the entire sediment column appears to be reduced with

FeS(s)-like precipitate (Figure 8). TA 8 also contains Beggiatoa on the cover and in some places 1 to 2 cm within the cover, which suggests the presence of sulphides on and near the cover surface. Similarly, diver cores indicated dark sediments both near the sand cover surface and at the bottom of the cover in TA 4, indicating reducing conditions and possibly FeS(s)-like precipitate at the top and bottom of the cover.

Water quality measurements indicate some stratification occurs during the summer and fall, with lower dissolved oxygen and redox levels near the bottom of the water column. These measurements were not low enough to support sulphide production in the water column (all results were above 4 mg/L dissolved oxygen), but measurements were collected just above the sediment and not directly at the sediment-water interface, where anoxic conditions could be present.

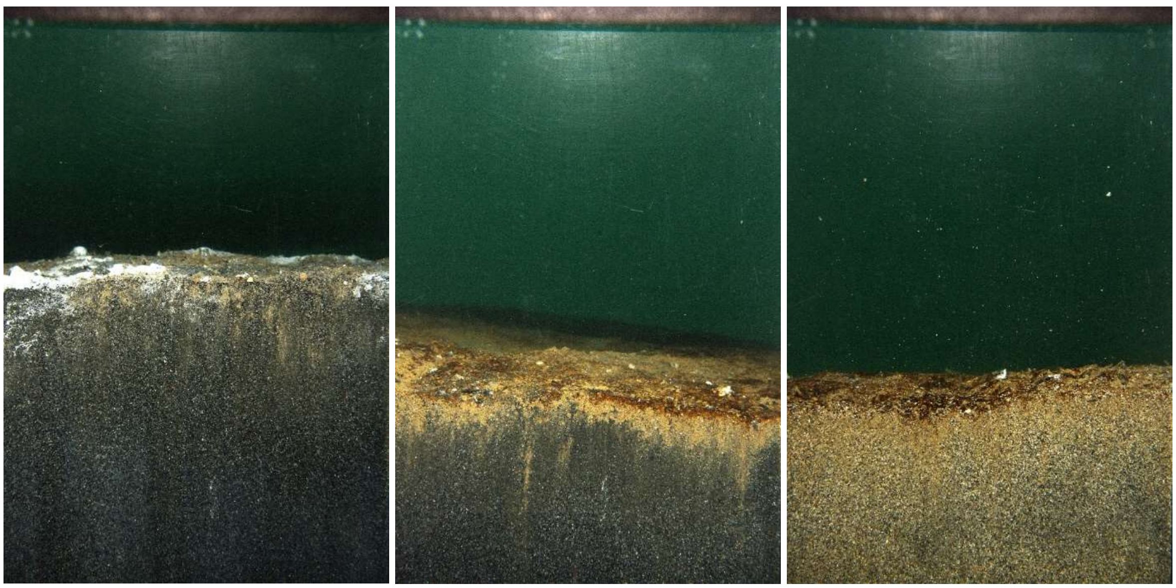

Figure 8. Sediment Profile Image of Test Area 8 (Sand Cover Only) after 12 months

Recolonization of Covered Test Areas and Rock Mounds

Benthic and epibenthic recolonization is occurring in the covered TAs, and epibenthic recolonization is occurring on the rock mounds placed in the practice area. Stage 1 recolonization (early colonizers) with some evidence of Stage 2 was observed in many TAs. Sand and amended sand TAs contained higher abundance, more taxa, and greater diversity than the control plot (TA 6) in Work Area 1, but not in Work Area 2. However, the Work Area 1 control (TA 6) contained lower richness and diversity than the Work Area 2 control (TA 9). The observed rate of recolonization is consistent with the expected rate of recolonization in the time period evaluated. More mobile benthic invertebrates would colonize first followed by less mobile organisms and those with different dietary requirements than the early colonizers. Reddish-brown algae are present on the sediment surface of the covered TAs and control TAs. Beggiatoa was observed in sediment profile and plan view images for TA 8, suggesting elevated dissolved sulphide concentrations in this TA.

Next Steps

Additional monitoring is planned for 2021 to assess performance of the pilot project, including to assess further consolidation and the effectiveness of sand compared to siderite-amended sand at controlling porewater sulphide concentrations. The conclusions of the pilot project will inform both the effectiveness and the implementability of the technologies and will help to determine the final selection of remedial technologies or restoration actions for sediments containing wood waste.

REFERENCES

Berlin, D., D. Vlassopoulos, M. Kanematsu, J. Dunay, E. Malczyk, and T. Wang. "Innovative Treatment of Wood-Waste-Impacted Sediments Using Reactive Amendments and DGT Passive Porewater Sulphide Testing Techniques." *Proceedings of the Western Dredging Association Dredging Summit & Expo '19, Chicago, IL, USA*, June 4-7, 2019.

Breems, J., and T. Goodman, 2009. Wood Waste Assessment and Remediation in Puget Sound. Prepared for Estuary and Salmon Restoration Program of the Puget Sound Nearshore Ecosystem Restoration Project.

Conlan, K.E., and D.V. Ellis, 1979. "Effects of Wood Waste on Sand-Bed Benthos." *Marine Pollution Bulletin* 10.

Ecology (Washington State Department of Ecology), 2013. Wood Waste Cleanup, Identifying, Assessing, and Remediating Wood Waste in Marine and Freshwater Environments. Publication No. 09-09-044. September 2013.

Elliott, J.K., E. Spear, and S. Wyllie-Echeverria, 2006. "Mats of *Beggiatoa* Bacteria Reveal That Organic Pollution from Lumber Mills Inhibits Growth of *Zostera Marina*." *Marine Ecology* 27(4):372–380.

Jørgensen, B.B., 1977. "Distribution of Colorless Sulfur Bacteria (*Beggiatoa* Species) in Coastal Marine Sediment." *Marine Biology* 4:19–28.

Kendall, D. and T. Michelsen, 1997. Management of Wood Waste Under Dredged Material Management Programs (DMMP) and the Sediment Management Standards (SMS) Cleanup Program DMMP Clarification Paper SMS Technical Information Memorandum. Publication number 07-09-096. September 1997.

Lennie, A.R., Redfern, A.T.R., Champness, P.E., Stoddart, C.P., Schofield, P.F. and D.J. Vaughn, 1997. Transformation of mackinawite to greigite: An *in situ* X-ray powder diffraction and transmission electron microscope study. *American Mineralogist* 82:203-309.

Muβmann, M., H.N. Sculz, B. Strotmann, T. Kjær, L.P. Nielsen, R.A. Rossello'-Mora, R.I. Amann, and B.B. Jørgensen, 2003. "Phylogeny and Distribution of Nitrate-Storing *Beggiatoa* spp. in Coastal Marine Sediments." *Environmental Microbiology* 5:523–533.

Rearick, M.S., Gilmour, C.C., Heyes, A., R.P. Mason, 2005. Measuring sulphide accumulation in diffusive gradients in thin films by means of purge and trap followed by ion-selective electrode. *Environmental Chemistry & Toxicology* 24:3043-3047.

CITATION

Berlin, D., D. Vlassopoulos, M. Kanematsu, T. Wang, M. Waters, and K. Ritchot. "Innovative Treatment of Wood-Waste-Impacted Sediments Using Reactive Amendments and DGT Passive Porewater Sulphide Testing Techniques." *Proceedings of the Western Dredging Association Dredging Summit & Expo '21,* June 15-17, 2021.

DATA AVAILABILITY

All data generated or used during the study are available from the corresponding author by request.

DESIGN AND DREDGING OF THE SAN ELIJO LAGOON RESTORATION PROJECT

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ABSTRACT

San Elijo Lagoon in San Diego County provides vital salt water and freshwater habitat for resident and migratory wildlife and sensitive, threatened, and endangered plants. The lagoon is nearly l,000 acres and offers recreational opportunities to the surrounding community. Economic development of the 20th century has negatively impacted the environmental quality of the lagoon habitat through urbanization of the lagoon's watershed and the addition of transportation infrastructure. The construction of U.S. Highway 101, Interstate 5, and a railroad line over the lagoon has resulted in constricted tidal and storm flows. Over time these infrastructure projects, along with urbanization upstream, has led to degraded habitat and impaired water quality inside the lagoon. Resource agencies, land and infrastructure owners, and local agencies collaborated to return the site to more stable tidal conditions through a large-scale restoration effort. The Nature Collective with funding from the State Coastal Conservancy and San Diego Association of Governments commissioned restoration alternatives development and analyses. Alternatives were analyzed for hydraulic and hydrologic function, habitat area, quality and function, water quality, sediment quality, sustainability, and maintenance needs of each. Numerical modeling addressed concerns of hydrology, flood protection, water quality, inlet stability, shoaling, and shoreline effects during sea level rise. The selected lagoon restoration alternative was designed to be sustainable through the 2065 time horizon. Lagoon restoration was required to occur concurrent with two other major infrastructure projects as part of the North Coast Corridor Improvement Program. All three projects occur within the lagoon and are coordinated. Sea level rise and climate change were addressed by inclusion of three higher-elevation fill areas to act as transitional habitat in the short-term and wetland habitat in the long-term as sea level rises. Also, the lagoon valley to the east extends inland several miles and rises in elevation to provide a suitable ramp for wetland habitat transgression during sea level rise. It was estimated that wetland habitat areas can be maintained over time with such transgression. Lagoon restoration began in 2017 and continued through mid-2020. This paper focuses on challenges associated with coordinating a complex coastal dredging operation with two other major projects, lessons learned regarding coordination, engineering, permitting, construction, and monitoring, beneficial material re-use and disposal options, and construction methods in a very soft and wet environment.

Keywords: Wetland Restoration, Inlet Stability, Flood Conveyance, Sea Level Rise, Beneficial Reuse

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INTRODUCTION

The San Elijo Lagoon Restoration Project (SELRP or Project) encompasses restoration of the existing San Elijo Lagoon to improve the physical conditions of hydrology, hydraulics, and elevations for increased habitat function and value. The Project was developed to restore and maintain the lagoon ecosystem through hydrologic augmentation for the benefit of native estuarine and brackish marsh wildlife and vegetation. San Elijo Lagoon (SEL) is located in the City of Encinitas, San Diego County, California. It is at the downstream end of the Escondido Creek Watershed and is the terminus of Escondido Creek and La Orilla Creek. Tidal water flows into the lagoon from the Pacific Ocean, adjacent to Cardiff State Beach (Figure 1).

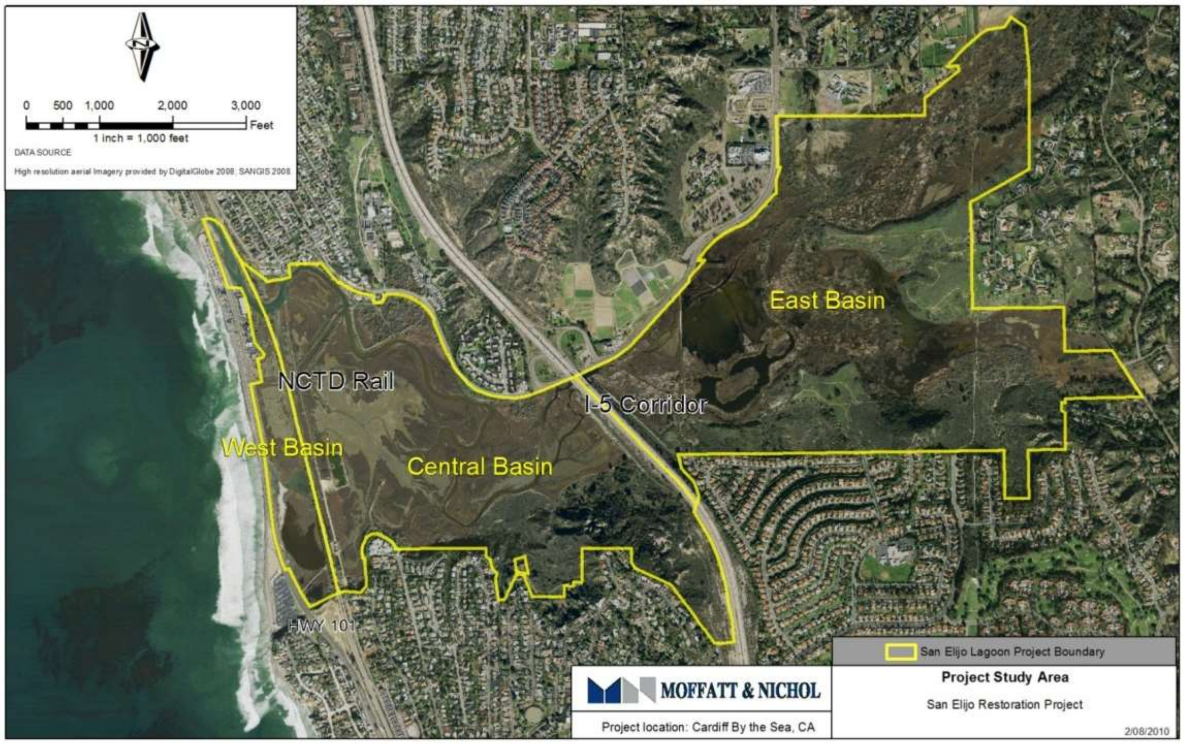

Figure 1. Project Area within the City of Encinitas, San Diego County, CA

Dredging and excavation was relied upon heavily to modify the lagoon geometry, improve tidal hydraulics and hydrology, and adjust lagoon elevations to become suitable for certain habitat types. This Project was one of five within the surrounding lagoon area that were constructed simultaneously. The other four projects were: the North Coast Corridor (NCC) Improvement Project that replaced the Interstate 5 Freeway (I-5) Bridge over the lagoon; the Los Angeles-San Diego (LOSSAN) Railroad Double Track Project that replaced the old trestle bridge with a new rail bridge over the lagoon and added a second rail line; the construction of the San Elijo Joint Powers Authority sewage outfall pipe; and the construction of the Cardiff Beach Living Shoreline project. The SELRP, NCC, and LOSSAN projects were coordinated by the San Diego Association of Governments (SANDAG) and Caltrans together.

The lagoon project area consisted of approximately 960 acres (~4 km^2), primarily within the San Elijo Lagoon Ecological Reserve (Reserve), and separated into three (3) basins, or restoration areas: West Basin, Central Basin, and East Basin. The West and Central Basin has estuarine and associated salt marsh wetlands, and the East Basin has extensive freshwater wetlands. The estuary at San Elijo is connected to the ocean through an inlet at South Coast Highway 101. The Reserve is jointly owned and managed by the

California Department of Fish and Wildlife (CDFW); County of San Diego Parks and Recreation Department (County DPR); and the Nature Collective (formerly San Elijo Lagoon Conservancy).

This paper highlights the lessons learned throughout the lagoon restoration process and across the diverse areas of action. Those actions included identifying the Project need and objectives, permitting, design and engineering, and construction. Throughout all tasks, multi-agency coordination guided the Project features and successfully led to implementation.

PROJECT NEED AND OBJECTIVES

The lagoon is a regionally important coastal wetland with substantial environmental resources. It provides habitat for federally listed threatened and endangered species, as well as other sensitive plants and wildlife, and offers recreational opportunities within the Reserve. Lagoon functions have become compromised over time, largely due to urban development and infrastructure, which have placed constraints on the lagoon ecosystem and altered the ratio of vegetated to unvegetated intertidal habitats (AECOM 2016). The lagoon has exhibited symptoms of eutrophication, as documented by episodes of low dissolved oxygen (McLaughlin et al. 2010). The loss of mudflat habitat in particular has caused concern among natural resource managers and stakeholders. Mudflat habitat is located too high for a full tidal lagoon because it formed when the inlet mouth was closed to the ocean and lagoon water levels were higher from impoundment. Today the mouth is managed to be open, and mudflat is converting to vegetated marsh because hydrologic conditions are favorable for salt marsh plant growth.

Over recent history, the lagoon system degraded due to expansion of urban development within the watershed of the lagoon. Human development altered the hydrology and, subsequently, the physical and biological functions of the lagoon system. Significant changes to San Elijo Lagoon began with the construction of the Santa Fe Railroad bridge in 1887, which constricted tidal flow into the lagoon through a narrow and fixed channel. Other changes that caused tidal and fluvial “choke points” in the lagoon include: the construction of Coast Highway 101 in 1891; berms and shallow ponds constructed for duck hunting in the lagoon in 1937; and the construction of Interstate 5 in 1965. The construction of the Lake Dixon Dam upstream of the lagoon limited the flow of freshwater from Escondido Creek in 1971 and in the 1980s a dike was constructed in the East Basin. All of these projects required construction of supporting berms that further constricted the natural circulation and tidal influx within the lagoon. These upstream fluvial restrictions combined with the tendency for sediment shoaling at the inlet led to a muted tidal prism. The muted tidal prism was not sufficient in maintaining a stable inlet and consistent tidal flux. As a result, inlet closures recurred periodically, often for years at a time if no intervention was made.

Mechanical breaching of the ocean inlet is performed regularly to maintain a predominantly open inlet and to allow tidal flushing within the lagoon. Since the mid 1990’s, the tidal inlet has been actively managed, and the mouth of the lagoon has remained open over 80 percent of the time. Though opening the inlet allowed freshwater to exit the lagoon and saltwater exchange to occur more frequently, severe tidal muting persisted.

Human population growth and watershed development increased storm water flows and urban runoff into the lagoon. This has increased the nutrient load and affected habitat distribution within the lagoon. The combined effects from development within the watershed and the restriction of, and periodic obstruction of, tidal flow from the Pacific Ocean into the lagoon has led to adverse effects on salt marsh habitat distribution and quality. Tidal flushing was restricted, and water quality conditions were impaired for nutrients, bacteria, and sediment. Habitats within the lagoon have been rapidly converting to habitats with less heterogeneity and to habitats with greater freshwater influence than saltwater influence. Habitat was distributed at elevations and locations that were related to relic closed mouth conditions and were progressively transitioning to distributions more reflective of managed mouth conditions.

In addition to the impacts described above, sea level is anticipated to rise over the coming decades (OPC 2018). As mean sea level and high tides increase over time, the existing salt marsh will gradually become submerged if no action is taken. Consequently, the existing conditions and predicted sea level rise at the Reserve created the necessity for restoration efforts.

The overarching purpose of the SELRP is to protect and restore, then maintain via adaptive management, the ecosystem and the adjacent uplands to perpetuate native flora and fauna characteristics of southern California. These goals are distilled into four categories:

1. Physical restoration of lagoon estuarine hydrologic functions;

2. Biological restoration of habitat and species within the lagoon;

3. Management and maintenance to ensure long-term viability of the restoration efforts; and

4. Maintenance of recreational opportunities within and adjacent to the lagoon.

AGENCY AND PROJECT MANAGEMENT

The Project site contains an amalgamation of several landowners and stakeholders. Leadership and stakeholder involvement was coordinated through the creation of a large Stakeholder Advisory Committee (SAC) which played a critical role in the early development of the Project until the completion of construction in the year 2020.

Initially, the academic studies that documented the environmental importance of the site resulted in incrementally leading the site towards the consideration of wetland restoration. The Nature Collective, a non-profit and part-owner of the site, organized the SAC with groups including the City of Solana Beach, City of Encinitas, County of San Diego, SANDAG, Caltrans, California Coastal Commission (CCC), U.S. Army Corps of Engineers (USACE), Environmental Protection Agency (EPA), Regional Water Quality Control Board (RWQCB), State Lands Commission (SLC), North County Transit District (NCTD), U.S. Fish & Wildlife Service, California Department of Fish & Wildlife, and more. The SAC did not have a preconceived idea of what the Project may become. Instead, they took the step to initiate a feasibility study in the early 2000's. This was followed by a USACE investigation of the Project's potential incorporation into the greater Encinitas-Solana Beach Coastal Storm Damage Reduction Project. However, USACE ultimately chose not to pursue this Project.

By 2008, one SAC member, SANDAG, focused on SELRP as a potential mitigation site in support of the Interstate-5 widening project. They tasked AECOM to prepare a data gap analysis to reveal the necessary steps forward to implementing the mitigation project. The gap analysis identified an array of necessary future studies. Funding for the studies were awarded by the CA State Coastal Conservancy to The Nature Collective, who tasked Moffatt & Nichol (M&N), AECOM, Nordby Consulting, and others to prepare studies pertaining to hydrology, water quality, sea level rise, habitat, sediment characterization, and more.

Additionally, the Nature Collective increased the frequency and involvement of the SAC in the Project development. SAC meetings were held every other month from 2008 to 2011. The meeting's attendees and topics were exhaustive. Through this process it was learned that the Project would be best planned alongside resource agencies. The agencies helped conceive of alternatives and gained a sense of ownership over the Project and its success. Their involvement helped determine restoration design habitat distributions, design sea level rise scenarios, channel geometry, public improvements, and more.

As studies continued, resource agency enthusiasm grew and lead towards further funding and implementation of preliminary engineering, environmental review and permit applications. SAC involvement continued through this process, and resource agencies were able to provide guidance and make tweaks to suit each groups' goals. This ultimately helped smooth the way for the permitting and design phases through the year 2017. The resource agencies continued to be involved through the construction phase, which began in 2018 and was completed by August 2020.

WETLAND RESTORATION DESIGN

The SELRP was initiated to create a more resilient lagoon ecosystem that can accommodate future climate change scenarios, including sea level rise. The Project was designed to enhance and restore the physical and biological functions of the lagoon system by improving freshwater flood conveyance, decreasing tidal muting, and increasing the tidal prism and tidal circulation within the Reserve. The following section documents how such goals were achieved through engineering design.

The tidal hydraulics of the lagoon are constricted at the mouth by the Highway 101 bridge and constricted in the Central and East Basins by the I-5 bridge. The tidal inlet is narrow, long, and depth-limited by a bedrock and cobble sill at the mouth. High and low tides are muted, with low tides muted by more than 2 feet in the Central Basin. Project objectives and constraints led to the development of design alternatives proposing various channel geometries. The alternatives are summarized below in order of increasing intervention:

1. Existing conditions are maintained (i.e., no project) (Figure 2).

2. Restrict channel design to enlarging the main feeder channel throughout the site, extending the main tidal channel farther inland, and clearing and enlarging existing constricted channel connections. Existing habitat areas would essentially remain intact.

3. Design a more substantial deepening and widening of channels, an enlargement of subtidal area inland, and a greater diversity of habitats than currently exists. Significantly increase the tidal prism compared to the enlargement of the main channel (Figure 3).

4. Propose new tidal inlet and subtidal basin located south of the existing inlet, a deepening and widening of channels inland, and a greater diversity of habitats. Significantly increase the tidal prism compared to channel deepening and widening alternatives.

Hydrologic modeling was performed to assess the influence of design alternatives on the Project site. Under existing conditions (i.e., No Project alternative prior to 2017 construction), tidal flows were restricted due to the narrow and meandering channel between Highway 101 and the Railroad, and the presence of a sill at the bed. Tidal ranges were significantly muted for both high and low tides, and muting increased progressively from the West Basin through the East Basin. The two lower intervention alternatives were found to significantly reduce tidal muting and improve circulation in the wetland basins. This was due to expansion of the cross-sections under all bridges as well as creation of a shorter, more direct main channel path from watershed to ocean. For the alternative which proposed a new inlet, tidal muting was further reduced, and circulation was improved in the wetland basins. Grading under all alternatives would create a greater range of habitat diversity. Ultimately, the third alternative above was selected as the preferred concept in the environmental review process and its design was further developed, as discussed in the following hydrology, sea level rise, and beneficial reuse sections.

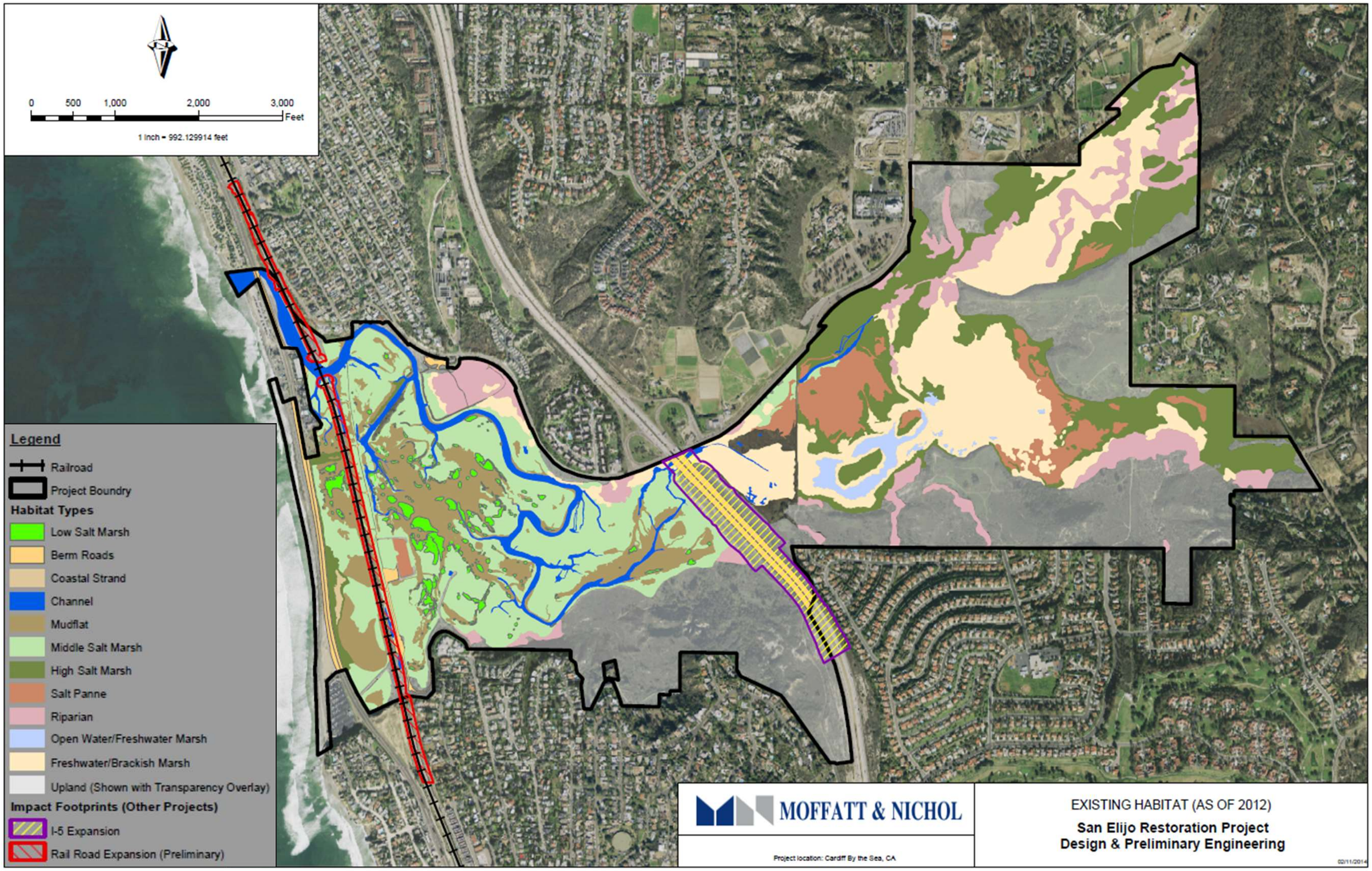

Figure 2. Pre-Restoration Habitat Conditions

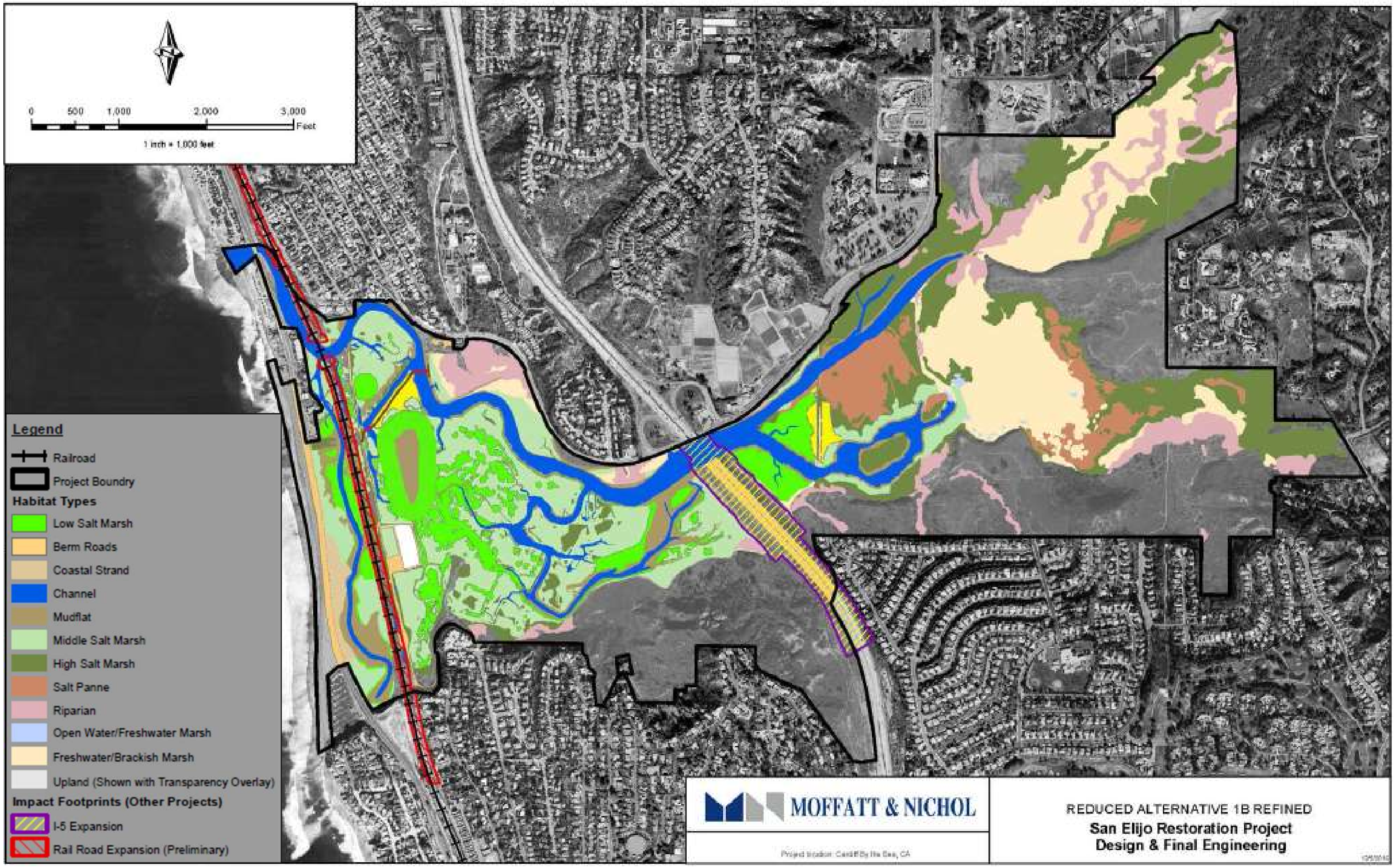

Figure 3. Preferred Concept Habitat Conditions

HYDROLOGY DESIGN

Inlet Stability

One goal of the project was to design the tidal inlet so that it remained open with minimal maintenance. The existing inlet was unstable and subject to siltation and possibly closure if not dredged on a regular basis. The inlet itself was not to be modified, however. Instead, the main tidal channels connecting to it were deepened to improve hydraulics.

The magnitude and duration of tidal flow velocities at the inlet are important to inlet stability. The peak ebb tidal velocity at the inlet is higher than the peak flood tidal velocity, and the duration of ebb flows is longer than the duration of flood flows. This indicates that the inlet is ebb-dominant. A minimum tidal flow velocity of 3 feet per second (fps) is typically required to suspend and erode sand (i.e., scour velocity) to help maintain a stable inlet. For the preferred concept, modeling showed peak ebb flow velocity exceeded 6 fps and scoured sand, and therefore net sediment flow is predicted to be out of the lagoon rather than into the lagoon (Table 1). However, ebb flow velocity potentially would not scour cobble which can be found in the inlet (Moffatt & Nichol 2011a). Sediment may accumulate in the lagoon over time but will be flushed out from the main channel during stormflows prior to occurrence of the peak lagoon water level, so sufficient stormflow drainage will still occur to prevent flooding of adjacent areas. It is anticipated that continued management of the inlet will still be required. Additionally, due to the increase is flow velocities at the inlet, rock rip-rap was required along the slope of the primary channel segment adjacent to the Highway 101 bridge. The size of rock (size 1/2 ton over quarry run) is based on the fluvial storm and tidal velocities predicted by the model.

Under sea level rise, inlet flow velocities were found to increase for the preferred concept. The Tidal Inlet Stability Study (Moffatt & Nichol 2012b) found the inlet to be relatively more stable under the sea level rise condition. These effects are due to the increased depth of the tidal inlet from sea level rise, while the tidal prism remains constant. The inlet depth may increase to a point at which tidal flow velocities slow and shoaling occurs. Shoaling in the inlet could fill a portion the channel cross-section and cause tidal flow velocities to increase once again and lead to a new form of equilibrium.

Table 1: Summary of Tidal Inlet Hydraulic Results in 2015

Alternative	Year	Maximum Velocity at Inlet (fps)		Overall Duration at the Inlet (% of Time)		Ratio of Overall Duration of Ebb versus Flood at Inlet (%)	Duration of Velocity over 3 fps at Inlet (%)	
		Ebb	Flood	Ebb	Flood		Ebb	Flood
No Project	2015	5.1	3.2	60	40	1.48	14	1.0
Preferred Concept	2015	6.9	2.1	52	48	1.09	8.3	0.0

Tidal Prism and Flood Conveyance

Increased tidal prism and conveyance was another primary Project objective. In a study of these processes, the limiting factor for this Project was found to be the long and narrow inlet channel between Hwy 101 and the railroad bridge. The main channel through the I-5 bridge and Central Basin is also narrow, shallow, and sinuous in planform resulting in additional energy losses during normal tidal fluctuations and extreme flood events (Moffatt & Nichol 2011b). Stormflows of 100-year return period were coupled with the highest measured high tide and showed that the No Project alternative resulted in flooding of adjacent roadways.

The preferred concept design was refined using model results optimize channel geometry to determine the extent to which tidal flows may enter the lagoon, and extent to which stormwater may exit the lagoon. Channel geometry was designed to enhance flushing and storm drainage within the stream canyon. The channel depths and widths were increased throughout the Project area. Primary channels were designed with 5:1 (H:V) slopes, except where adequate area for larger channel footprints did not exist. In these instances a 3:1 (H:V) or 2:1 (H:V) was used depending on existing constraints. The primary channels were designed to an invert elevation of -4 feet NAVD88 and a width of 75 feet. This ensured main tidal channels have an average of 2 feet of water in them for tidal conveyance and subtidal habitat at the lowest low tide in the lagoon. Secondary channels were designed with 5:1 (H:V) slopes, except where adequate footprints did not exist. Secondary channels were designed to an elevation of -3 feet NAVD88. This design depth is a foot shallower than the main channels and allows for tidal conveyance and subtidal habitat. The inlet channel of the West Basin and main channel of the Central Basin were thus designed for increased flow capacity.

Bridge optimization modeling found that increasing the I-5 Bridge channel width to 261 feet would relieve some flooding of the adjacent roadway (Moffatt & Nichol 2012a). Through the coordination of SELRP and the I-5 Widening projects, Caltrans was able to take the recommended channel width into consideration of bridge design. The channel network was generally widened and deepened at each bridge but the I-5 is still under construction so that channel is not yet opened up. The channel under Highway (Hwy) 101 was not expanded but natural forces have caused it to increase in cross-section from increased tidal flushing. These improvements provide the more favorable conditions for tidal range, flood conveyance and other environmental benefits throughout the lagoon than pre-construction conditions.

The design was found to improve the tide range within the internal basins of the lagoon (West Basin, Central Basin, and East Basin) (Table 2). Measurements of tides are ongoing and predictions are being evaluated for confirmation, The tide range in the Central Basin was predicted to increase by 1.5 feet. The East Basin tidal range was to become similar to that in the Central Basin, which indicates that the proposed channel cross-section under the I-5 Bridge would be sufficient to not cause further muting in the East Basin. The increased tidal range would improve the tidal inundation frequency characteristics within the lagoon to benefit habitat by increasing the vertical zonation of habitat colonization.

Table 2. Tidal Range and Muting under Pre- and Predicted Post-Construction Conditions

Project	Tidal Range (ft)				
	Open Ocean	Inlet	West Basin	Central Basin	East Basin
Pre-Construction	7.97	4.56	3.99	3.85	3.76
Post-Construction	7.97	6.97	5.77	5.30	5.30

Residence Time

A third goal of the Project was to decrease the residence time of seawater. Through the above channel design and bridge optimization, the preferred concept was predicted to increase tidal flushing frequency and shorten residence times of the lagoon which provides water quality benefits. Model results show that under existing conditions, the lagoon can contain freshwater and nutrients for several days that may stress salt marsh habitat. Improved tidal flushing reduces nutrient concentrations assuming inputs remain constant. Additionally, the Project results in slightly more rapid recovery of salinity levels. Under existing conditions, residence times can range from 1 day near the tidal inlet to 15 days near I-5, to no flushing in the East Basin. The preferred concept should change residence times to less than 1 day near the inlet, 6 days near I-5, and 8 days in the East Basin. The Project should require up to approximately 10 days for marsh salinity to return to dry season values. Residence time analyses are still ongoing are being confirmed from predictions.

Dredging measures were taken to improve lagoon water quality and hydrology, muted tidal exchange, and the restricted water circulation. Had these measures not been taken the lagoon would have continued to degrade the physical and biological functions of the lagoon. Freshwater marsh and higher elevation saltmarsh habitats would have likely continued to expand and dominate the system, at the expense of more rare intertidal habitats. Threatened, endangered, and sensitive species dependent on the aquatic intertidal habitats of the lagoon would have been adversely affected by these conditions (AECOM 2016).

Design for Sea Level Rise

Restoration of San Elijo Lagoon required planning and engineering with projected sea level rise (SLR) to safeguard the success of restoration efforts in the long-term (Moffatt & Nichol 2010a). Tidal water levels determine the elevations and distribution of habitats within the lagoon. Therefore, proper planning and engineering were required to optimize future lagoon habitats, and to plan for adaptive management with the goal of maintaining an acceptable habitat regime for the mostly likely scenario. Tidal hydraulic modeling was done for both immediate post-construction conditions and for future 50-year conditions in 2065 estimated using a rate of sea level rise of 2 feet from 2015 (Moffatt & Nichol 2014 and 2015). Although no probability was associated with this projection at the time, recent science has found this scenario to have approximately a 5% chance of occurrence (OPC 2018).

Designing wetland restoration in the face of sea level rise requires a balance of near-term and long-term benefits. In the case of SELRP, near-term benefits include the expansion of subtidal area for tidal conveyance, and the expansion of vegetated marsh, including low-, mid-, and high-marsh for the benefit of carbon sequestration and habitat value for threatened and endangered species. Long-term benefits include the continued stabilization of an open inlet to continue tidal circulation, and the unimpeded transgression of vegetation and wildlife upland in strategically designed transitional habitat and in upstream undeveloped watershed areas as sea level rises. The potential for wetland transitional habitat was identified in the higher elevation areas within the Reserve, as well as the open space available to the east within the existing stream canyon. Distilling the overarching goals into SLR design criteria led to the design of the entire site to:

1. Function as a tidal wetland under existing sea levels; and

2. Provide vegetated salt marsh areas if sea level rises two feet.

Criteria number 1 was accomplished by setting elevations and distributions for different habitat types at the upper ends of their respective elevation ranges. Design elevations for proposed habitat types were determined based on the inundation frequency analysis and coordination with the local biologists (Table 3). The elevations in Table 3 represent immediate post-construction conditions. These elevations were proposed to consider the actual conditions due to tidal muting over time, and effects of sea level rise. Habitat areas were created to be relatively level “benches” to maximize their surface area. The benches are designed and constructed to slope gently towards the channel to promote drainage. Slopes between the habitat areas are designed to be variable, but should be approximately 3:1 (H:V) or flatter. Wetland habitat areas transition with sea level rise, but a suitable proportion of habitats remain and are distributed appropriately over the site due to the design approach. Habitat target elevations were set at the high end of their vegetation range (the upper three-quarters of the range), so that they transition slowly during sea level rise with lesser transition than would be the case if elevations were lower. A 0.5-foot contingency was added for low marsh to promote the success of wetland habitat under the early stages of sea level rise. Dredging and grading tolerances also provide a non-uniform and more natural finished surface while still meeting the target design elevations for each specified habitat. Wetland habitat areas in 2015 are represented by a predominance of high intertidal types, while a large portion convert to mid- and lower intertidal types by 2065 with high intertidal still existing from conversion of transitional habitat.

Table 3. Existing and Proposed Habitat Elevation and Tidal Inundation Frequency

Habitat Type	Tidal Inundation Frequency	Existing Conditions (ft, MLLW)	Proposed Elevation (ft, MLLW)	Target Elevation (ft, MLLW)
Subtidal	100%	2.11	Below 1.60	Below 1.6
Mudflat	45-100%	2.11 to 3.4	1.60 to 3.20	2.44
Low Marsh	20-45%	3.4 to 4.1	3.20 to 3.90	3.73 (raised to 4.09 for contingency)
Mid & High Marsh	Mid: 5-20% High: 0-5%	4.1 to 5.8	3.90 to 5.50	5.31
Transitional	0%	5.8 to 7.8	5.50 to 7.50	Between 5.81 to 7.81
Supra-tidal	0%	6.3	Above 6.3	Above 6.3

Criteria number 2 was accomplished by inclusion of two higher-elevation fill areas to act as transitional habitat in the short-term and wetland habitat in the long-term as sea level rises. Also, the lagoon valley extends inland several miles and gradually rises in elevation to provide a suitable ramp for wetland habitat transgression during sea level rise. Transitional and supra-tidal uplands are graded to between +12 and +15 feet NAVD88, with the highest point in the center of the mass (centroid) of the polygon to guarantee available space for habitat transgression in the long-term SLR scenario. They show a constant slope from the lowest point on the perimeter of the polygon (a minimum of +4 feet NAVD88 that is just above the average high tide) to the high point. This slope helps regulate the distribution of habitat types, ensuring all types have an appropriate elevation available for growth no matter the sea level rise scenario. This also means the slope of transitional habitat will vary across the site depending on available space. Ultimately, the high salt marsh will migrate into transitional areas, mid marsh will migrate into high marsh areas, and so forth. Pre- and predicted post-construction habitat acreages are presented in Table 4.

Most significantly, freshwater/brackish marsh and mid-marsh are reduced in area, giving room for subtidal, mudflat/low marsh, and transitional area. Subtidal habitat is essential for achieving the hydraulic goals of the Project. Mudflat and low marsh were given preference due to their current scarcity and their ecological value as seen by resource agencies. Given that the Reserve area is one of the largest remaining wetland and ecological habitats in San Diego County, a wide area of transitional habitat was pre-existing. An additional 7 acres was designed to facilitate wetland transgression. Increased transitional habitat area is intended to benefit future conditions of sea level rise by providing areas of future salt marsh conversion as water levels increase.

The proposed wetland design creates a similarity of tidal hydrology across all three basins. Therefore, habitat design elevations do not vary dramatically from basin to basin. Additionally, model results showed that tidal muting in wetland basins consistently decreases as sea level rises. This is to be expected because raising the water level produces a similar effect to deepening and widening the inlet. While the model shows this as a result, the actual magnitude of this effect in the future is uncertain because shoaling may occur and partially offset these effects to tides.

Table 4. Pre- and Predicted Post-Construction Habitat at San Elijo Lagoon

Habitat Type	Acreages Pre-Construction (2010)	Acreages Post-Construction	Difference (+/-)
Channel (Subtidal)	71	62	-9
Mudflat	50	32	-18
Low Marsh (Cordgrass)	27	73	+46
Mid-Marsh (Pickleweed)	140	110	-30
High Marsh (Pickleweed)	120	125	+5
Transitional (Above the Highest Tide by 2 Feet)	0	7	+7
Upland and All Else (Everything above Transitional)	299	295	-4
Nest Site	0	2	+2
Berms and Roads	23	14	-9
Beach	15	15	0
Riparian	71	69	-2
Salt Panne	37	32	-5
Freshwater/Brackish Marsh	132	100	-32
Coastal Strand	5	5	0
TOTAL	**960**	**960**	**0**

The SELRP was a prime project to adapt to SLR due to its large bordering area of transitional and upland habitat, and public ownership that allowed preservation of transitional areas. The Project area boundaries extend relatively far from existing habitat areas, enabling design to rely on natural transgression of habitat inland and upward as sea level rises as a sort of "self-mitigation." Site geomorphology is characterized by a long lagoon axis oriented east to west (coast to inland) that gradually slopes upward from wetland to upland elevation ranges. Approximately 1/3rd of the site is wetland habitat now, and the remainder is split between transitional and upland habitats. As sea level rises, some transitional areas would convert to wetland, and some upland would convert to transitional areas. In 2065, nearly ½ of the site would be wetland and the remainder would be split between transitional and upland. Sufficient space exists for this site to transition under sea level rise while still providing a suitable habitat mix. As such, the site is resilient to effects of sea level rise.

Beneficial Reuse

Geotechnical studies and sediment characterization of the Project site identified two basic stratigraphic layers; one is a relatively thin surface layer of silts and clays that overlies the other, a deep layer of sand that extends to the depth of approximately 80 feet below existing grade (Moffatt & Nichol 2010b). The lower layer of sand was found to be a relic deposit of beach sand, well-suited for direct littoral zone placement. However, the surficial fine-grained, organic-rich, and potentially chemically compromised silts and clays were not compatible for direct placement in the littoral zone. The SELRP Sampling and Analysis Plan Results Report (Moffatt & Nichol 2013) further analyzed 1.2 MCY of potential export material to be generated from construction. A sampling plan was initiated that collected 10 borings within the areas to be dredged. The compatibility of export materials were evaluated for beneficial reuse options were considered. Options for reusing the dredged material included beach placement, nearshore placement, and offshore placement. The sampling plan was coordinated with the USACE, USEPA and RWQCB.

A contingent agency approval of compatibility was received for placement of materials on the beach and/or in the nearshore. The lower layer of sand was confirmed as appropriate for beach and nearshore placement;

however, the vast majority of channel grading was proposed to remove surficial silts and clays only. The solution was to design a 15.6-acre dredge area that was 45 feet deep i.e., an overdredge pit (OD Pit). The plan was to use the OD Pit during construction for onsite sequestering of excavated earthen materials. Beneficial reuse of 446,000 cubic yards of sandy material excavated from the OD Pit was transported by dredge pipe to the nearby Cardiff and Fletcher Cove beaches for nourishment. Then, the silty dredge material from wetland restoration was subsequently placed in the OD Pit. Additionally, a portion of excavated fill was placed onsite to construct "man-made transitional" habitat areas and a nesting site. Finally, a cap of sandy material was specified to lie over the OD Pit to return it to the proper grade for habitat.

PERMITTING

Project planning required the collaboration of all owners, consultants, stakeholders, and resource agencies. The Project design accomplished the many goals of each group from physical restoration of the lagoon, biological restoration of habitat and species, and enhancement of recreational opportunities. The environmental permits required to construct the Project are provided in Table 5. All permits were successfully obtained through clear communication with resource agencies during SAC meetings. All permit approvals hinged on the content of the Final EIR/EIS for the San Elijo Lagoon Restoration Project (AECOM 2016).

Out of the permit process emerged environmental constraints which became major controls over project planning. Endangered bird nesting seasons required that certain elements of the overall project be phased or timed, most significantly were dredging and inlet closure events. Manual inlet closure was necessary for the restoration project to ensure that water levels were maintained at the elevations necessary for dredging, planting, transportation, bridge foundation construction, and more. A Project activity schedule was prepared to coordinate with seasonal avian activity. This "Project schedule" was an important part of the permits, and engineering contract documents (plans, specifications, and estimates for contractor bidding), as well as assurances to the resource agencies that the Project was implemented without incurring unanticipated incidental impacts. Table 6 shows an example of the environmental windows developed for Project implementation, and an early version of the construction approach. The construction approach was later changed to be a sequence of doing as much work in the dry as possible by maintaining low water levels using dikes prior to dredging, and then flooding the site and dredging material to nourish the beach and backfill the OD pit. Actual construction activities and water level controls varied from this example with permission of the resource and permit agencies in an effort to keep the ocean inlet open as long as possible.

Additionally, construction footprints were strictly controlled to mitigate environmental impacts. Existing habitat at the lagoon is highly sensitive. Wetlands extend over the majority of the site, with perimeter transitional habitat extending upward into upland habitat. Wetlands include tidally-influenced areas and those influenced more by freshwater. Salt marsh habitat exists in the West, Central and East Basins. Brackish marsh and freshwater habitat exist in the eastern portion of the East Basin. Limited upland habitat exists in the West and Central Basins, but more extensive areas of upland exist in the East Basin. Existing habitat and active nesting areas are home to several sensitive species of birds. The federally endangered Ridgeway Rail exists in low marsh throughout the lagoon, and the state-endangered Belding's Savannah Sparrow also exists in mid and high marsh throughout the lagoon. The sensitivity of the habitat required design that avoided and minimized impacts where possible, and also required protection and care during construction. Channel geometry design not only considered the hydraulic improvement but also aimed to minimize impacts to such identified sensitive habitats. A 100-foot buffer zone was determined between active avian nesting areas and land-based construction. Further discussion of the accommodation of such restrictions is discussed in the following section on construction.

Table 5. SELRP Permits

Federal	
U.S. Army Corps of Engineers (USACE)	Permit under Section 404 of the Clean Water Act, 33 USC Section 1344 Section 10 of the River and Harbors Act of 1899, 33 USC Section 403 Issue Record of Decision (ROD) Fish and Wildlife Coordination Act, 16 USC Sections 661–666
National Marine Fisheries Service (NMFS)	Magnuson-Stevens Fishery Conservation and Management Act, as amended 1996 (Public Law 104-267)
State Historic Preservation Officer/Tribal Historic Preservation Officer (SHPO/THPO)	National Historic Preservation Act of 1966 (NHPA), Section 106 Consultation with SHPO/THPO (36 CFR Part 800)
U.S. Coast Guard /Department of Transportation (DOT)	Navigation Permit 33 CFR 66
U.S. Fish and Wildlife Service (USFWS)	Endangered Species Act, 16 USC Sections 1531–1544 Section 7 Consultation with the federal lead agency (i.e. USACE)
State	
California Coastal Commission (CCC)	Coastal Development Permit Consistency Certification, Section 30600(a) of the California Coastal Act, or Waiver of Federal Consistency Provisions
California Department of Fish and Wildlife (CDFW)	Streambed Alteration Agreement, Section 1601 of the California Fish and Game Code California Endangered Species Act Section 2081 Incidental Take Permit
California State Parks (CSP)	Use Permit(s) for construction activities
Caltrans District 11	Encroachment Permit for access to I-5
Regional Water Quality Control Board (RWQCB)	Water Quality Certification under Section 401 of the Clean Water Act
State Lands Commission (SLC)	Lease for access
Local/Regional	
San Diego Air Pollution Control District (APCD)	Authority to Construct/Permit to Operate
County Department of Parks and Recreation (DPR)	Certify EIR File NOD Issue Right of Entry
City of Encinitas	Encroachment and grading permits LCP coastal development permit Noise variance or exemption letter
City of Solana Beach	Encroachment and grading permits LCP development permit Noise variance or exemption letter
North County Transit District (NCTD)	Encroachment permit for access to railroad right-of-way

Table 6. Environmental Constraint Schedule

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Snowy Plover & Least Tern Cycle	Shorebirds Wintering		Breeding					Shorebird Fall Migration			Wintering	
Water Level (WL) Management	WLs Maintained up to +5.5' MSL		WLs Maintained at 2’ MSL (i.e. Closed Inlet)					WLs Maintained at 2.5’ ± Mean Sea Level & Rising (i.e. Closed Inlet)			WLs Maintained up to +5.5’ MSL	
Dredging	Dredging		Dredging Allowed to Continue if Initiated Prior to Breeding Season						Dredging			
Other Construction	Work All Areas		Maintain 100-foot Buffer Zone Between Active Nesting Areas and Land Based Construction						Dredging			

CONSTRUCTION

The SELRP was the largest single effort to restore the lagoon, requiring approximately $10 million to plan, permit, design, and monitor, and approximately $100 million to construct. Construction activity was scheduled and phased to minimize impacts to fish and wildlife resources, coastal traffic, and beach recreation. Throughout construction biological monitors observed activities for compliance with the environmental constraints and mitigation measures adopted in the Final EIR/EIS as well as all regulatory permits. Additionally, coordination was maintained with the two major infrastructure projects at the lagoon (I-5 widening and the NCC rail double-tracking projects) by contracting the construction under Caltrans, with Caltrans as the construction manager. The contractor was the joint venture of Flatiron/Skanska/Stacy & Witbeck (FSSW) and marine construction of the entire lagoon project was done by Marathon Construction and their subconsultants (Ross Island Dredging, Dixon Marine, and Pacific Restoration Group). All the contractors gathered for weekly meetings with Caltrans to coordinate each project. Phasing of activities was key to successful construction as it allowed for uninterrupted progress while maintaining environmental compliance, (limited) public access, properly timed vegetation planting, and beneficial use of sediment.

Construction of the Project required management of water levels throughout the lagoon to ensure water depths accommodated activities. A series of temporary dikes were constructed to strategically flood certain areas of the lagoon. This allowed for cutterhead dredging via barge to occur within the lagoon. The barge for dredging required a draft of 5 feet; therefore, dikes were constructed to a height of approximately 8 feet, NAVD88. The construction of these dikes occurred in phases to provide adequate draft in various regions of the Project site while maximizing tidal flux to areas of the lagoon that were not occupied.

The first phase was the dredging of the over dredge (OD) pit, prior to the initiation of shallow dredging proposed throughout the lagoon. A total export volume of approximately 446,000 cy of beach quality material was dredged from the 45-foot-deep OD pit. Export materials were primarily placed on local beaches and repurposed on-site for transitional and nesting habitat. Design of the OD Pit was determined by volume capacity required to sequester the quantity of channel excavation. Its location was based on avoiding sensitive habitat to the greatest extent, and a designed 3:1 (H:V) side slope was kept as steep as possible to minimize impacts to existing low marsh vegetation. The subsequent dredging of habitat areas disposed of finer grained materials into the OD pit.

After the over dredge pit was completed, the second construction phase, shallow dredging in primary and secondary channels of the Central Basin began. Thus, began construction in a very soft and wet environment. To fine-tune channel geometry and habitat grades, a piece of equipment known as an amphibious excavator was used in conjunction with the hydraulic dredge/barge system. The amphibious excavator was able to operate both on land and floating in-water, and was key to realizing the design while minimizing impacts to existing habitat and vegetation.

The third construction phase was shallow dredging in primary and secondary channels of the East Basin. The fourth construction phase involved shallow dredging of silts, clays, and sands from the West Basin. At this phase, silts and clays were repurposed within an in-basin nesting site location. The temporary construction dikes were removed during this phase, and vegetative planting was initiated as well. As the last phase, sand from the main channel was dredged and placed as a 3-foot-thick cap over the nest site. Additional material may end up being placed at the OD Pit is post-construction monitoring indicates settling of the pit surface to elevations below those targeted. Dredging of the main channel under the I-5 Bridge is planned for Fall of 2021 and that sandy material may go to the beach at Cardiff and/or to the OD Pit.

The construction process generally followed projected timelines and met the necessary milestones, and the completion was accelerated by omitting sand placement at an approved offshore receiver site. The volume of sand dredged was limited to that quantity that could be re-used on-site and placed at the beach, so offshore construction was not necessary. Significant savings were realized in both time and costs by omitting this project component. The 2019/2020 winter rainy season tested the Project with significant fluvial flows. On April 10^{th} and 11th, 2020, a storm occurred coincident with high tide and water levels reached 4 feet above open ocean, and peak ebb flow velocities in the main channel (typically ~2-3 ft/s) exceeded 5 ft/s. This event caused significant erosion and deposition across fluvially constrained and open sections, respectively. As a result, "clean-up" maintenance dredging was implemented to re-dredge severely accreted areas which may otherwise impact the targeted tidal/fluvial flow capacities.

Construction of the Project was completed in June of 2020, totaling a construction period of approximately 2.5 years for the nearly 1,000 acres wetland restoration project. A five-year monitoring program for physical parameters (topography, bathymetry, and hydrology), water quality, and biology funded by SANDAG is in progress. Monitoring will track Project success by metrics including: measured tidal prism, channel flow velocity, biological speciation and distribution, attraction of threatened/endangered species, persistence and diversity of vegetative species, and achievement of target habitat distributions. Reporting of the five-year monitoring program will be in report format to resource agencies and will be made public through SANDAG.

CONCLUSIONS

The San Elijo Lagoon Restoration Project successfully dredged lagoon channels and graded wetland habitat at the downstream end of the Escondido Creek watershed in San Diego County. Uniting the various goals and constraints of over five landowners and many more stakeholders, the project restored hydrologic functions, enhanced habitat and species distribution and function, improved public access and recreation opportunities, and planned for long-term management and sustainability. Key design components which contributed to the success of the project included 1) the pairing of the project with regional transportation improvement projects, and 2) the creation of an overdredge pit for beneficial reuse of material. Wetland restoration was planned alongside the I-5 widening and railroad double tracking projects, and as a result the lagoon channel at the critical I-5 bridge underpass was able to be optimized through modeling and subsequent design. The dredging of an overdredge pit yielded 446,000 cy of beach quality material which was beneficially placed on two nearby beaches. Lagoon channel dredge sediment, which otherwise would have been costly to dispose of, was then placed and sequestered in the pit. The lagoon restoration project is currently in the beginnings of the long-term monitoring program to ensure it continues to provide critical salt water and freshwater habitat into the future resilient to climate change.

REFERENCES

AECOM (2016). *Final EIR/EIS for the San Elijo Lagoon Restoration Project (SCH #2011111013)*. Prepared for the Army Corps of Engineers (USACE) County of San Diego Department of Parks and Recreation, and San Elijo Lagoon Conservancy.

Mclaughlin, K., M. Sutula, J. Cable, and P. Fong (2010). *Eutrophication and Nutrient Cycling in San Elijo Lagoon: A Summary of Baseline Studies for Monitoring Order R9-2006-0076*. Southern California Coastal Water Research Project. Technical Report 636.

Moffatt & Nichol (2010a). *Sea Level Rise Analysis, Draft Report*. Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol (2010b). *SELRP Sediment Characterization Study, Draft Report.* Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol (2011a). *SELRP Ebb Bar and Flood Shoal Study*. Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol (2011b). *SELRP Tidal Muting Study, Draft Report*. Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol. (2012a). *San Elijo Lagoon Bridge Optimization Study*. Prepared for Dokken Engineering and California Department of Transportation.

Moffatt & Nichol (2012b). *SELRP Tidal Inlet Stability Study*. Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol (2013). *SELRP Sampling and Analysis Plan Results Report*. Prepared for San Elijo Lagoon Conservancy and U.S. Army Corps of Engineers.

Moffatt & Nichol (2014). *San Elijo Lagoon Restoration Project (SELRP) Hydrology/Hydraulic Study*. Prepared for San Elijo Lagoon Conservancy.

Moffatt & Nichol (2015). *Bridge Hydraulics Study of I-5 Bridge Over San Elijo Lagoon*. Prepared for SANDAG and Caltrans.

Ocean Protection Council. (2018). State of California Sea-Level Rise Guidance 2018 Update.

CITATION

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DATA AVAILABILITY

Some data, models, or code generated or used during the study are available from the authors.

ODESS: AN INTERACTIVE DECISION-MAKING TOOL FOR ENDANGERED SPECIES DATA COLLECTION, REPORTING, AND RISK ASSESSMENT

Michael G. Sessions[1]

ABSTRACT

Each year, routine dredging of U.S. inland and intracoastal waterways by cutterhead pipeline, hopper, and mechanical dredges has the potential to impact the well-being of many Threatened and Endangered Species (TES). For this reason, the U.S. Army Engineer Research and Development Center (ERDC) created the Sea Turtle Data Warehouse (STDW) in 1992 as a research database for manually collected data related to dredging impacts on sea turtles. To automate data collection, expand the variety of TES monitored, and provide an interactive decision-making tool to measure the impacts of hopper dredging activities on TES, the U.S. Army Corps of Engineers (USACE) National Dredging Quality Management Program (DQM) replaced the STDW in 2017 with the newly developed Operations and Dredging Endangered Species System (ODESS). ODESS provides a platform to centralize and archive TES data from dredging activities for long-term continuity and data evaluation across regions and under multiple negotiated Biological Opinions (BiOps).

In coordination with DQM, ODESS supports several USACE South Atlantic Division (CESAD) dredging projects by supplying TES incident reports. The incident data submitted electronically by the onboard observers can help them better understand the dynamics of the dredge instrumentation, reduce dredge downtime, and complement USACE Districts' risk assessment reporting. Although the overall impact to TES by dredging activities is relatively small, USACE and the dredging industry are committed to the reducing these impacts even more.

ODESS consists of three core components—the data collection tools, a USACE-only intranet website, and a public website. The tablet-based load, tow, and incident collection tool and the mobile trawling data collection app are both used by onsite observers to compile and transmit data to DQM. The intranet website is used by USACE District personnel to review and evaluate the field information. The public website, which provides information regarding reported incidents and TES status with respect to the various BiOps, features a home page that provides navigational items with an emphasis on search functionality, a dashboard showing the status of current ODESS operations and incident data, a queryable list of current active dredging projects using ODESS, and a BiOp reporting page to support regional and project-specific BiOps.

The purpose of this paper is to discuss the system's importance to the various BiOps, specifically the South Atlantic Regional Biological Opinion (SARBO) and to describe the components of the system in detail, focusing specifically on Version 2 (V2), which will be released later this year.

Keywords: Biological Opinion, dredging, Endangered Species Act, sea turtle, TES

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INTRODUCTION

From snails to whales, approximately 2,270 species are listed as endangered or threatened globally under the U.S. Endangered Species Act (ESA), approximately 150 of which live in the ocean in U.S. waters (Smithsonian 2021). While routine dredging of U.S. inland and intracoastal waterways by cutterhead pipeline, hopper, and mechanical dredges is necessary to maintain navigation depths and construct new waterways, these actions may also impact the well-being of many Threatened and Endangered Species (TES). The U.S. Army Corps of Engineers (USACE) strives to maximize the protection of these valuable species and their habitat while also maximizing dredging, and the data collected by Endangered Species Observers (ESOs) helps to support this important balance. The Operations and Dredging Endangered Species System (ODESS) is an automated tool used to collect information on the impacts of dredging on endangered and threatened marine species (such as those identified in Figure 1), and the data from this system can be analyzed to make informed decisions regarding dredging operations and balance the needs of both the economic benefits of performing the dredging and protecting our natural ecosystems.

Figure 1. (L-R) Some of the species tracked by ODESS: Loggerhead Sea Turtle, Shortnose Sturgeon, Hawksbill Sea Turtle, North Atlantic Right Whale, Leatherback Sea Turtle.

Hopper dredging along the southeastern United States potentially impacts five species of threatened or endangered sea turtles, three species of sturgeon, several species of whales, and a number of other TES. Some of the impacts of this submarine excavation can be entrainment or crushing of animals and their larvae, smothering and degradation of habitat from sedimentation, and burial of animals and their habitat (Todd et al. 2015).

BIOLOGICAL OPINIONS

To be compliant with Section 7(a)(2) of the ESA of 1973, as amended (16 U.S.C. §1531 et seq.), USACE and the National Marine Fisheries Service (NMFS) have adopted a variety of Biological Opinions (BiOps) that determine whether a proposed action is likely to jeopardize the continued existence of a Federally listed species, or destroy or adversely modify Federally designated critical habitat. The BiOps also identify the number or extent of listed species incidental takes that may occur and develop nondiscretionary measures that the action agency must perform to reduce the effects of the anticipated or authorized takes.

Early consultations tended to be project-specific and turtle-centric; however, USACE has been moving to a broader based approach to managing dredging operations with respect to TES by adopting Regional Biological Opinions (RBOs). The most prominent RBOs are the South Atlantic Regional Biological Opinion (SARBO) and the Gulf Regional Biological Opinion (GRBO). By adopting a risk-based approach to multiple species management, USACE is better able to balance the competing needs of its dredging program with the needs of the TES. Negotiating RBOs provides many benefits to the Government and the TES community. More consistent process and results are applied to a larger range, eliminating the need for numerous project-by-project consultations, and creating more flexibility and adaptability to individual projects as the focus is broadened to a big picture framework. Looking at a larger range also provides a more effective way to view cumulative effects over an area and standardizes data collection and implementation of scientific and technological innovations. Instead of being held to the traditional range of protective measures available to help mitigate the risk of impacting TES—such as restricting the type of dredge to be used, using environmental windows, adapting dragheads, and relocating captures—dredging planners can now take into consideration such data as population distributions and the needs and situations of other projects.

To effectively administer the BiOps, the collection of near-real-time data is of great importance. Section 01 57 20, "Environmental Protection," of the dredging specification lays out the requirements for monitoring of Endangered Species during a dredging contract or permit operation. Endangered Species observers, approved by the NMFS, shall be aboard a dredge to monitor for the presence of sea turtles, sturgeon, whales, and other listed species 24/7. During transit to and from the disposal area, the observer shall monitor from the bridge for the presence of endangered species. Observers shall physically inspect dragheads and inflow and overflow screening boxes for threatened and endangered species takes. Other abiotic and biotic debris found in the screen during their examination shall be recorded and then disposed of so as not to impede the functioning of the screens during the next load cycle. The results of the monitoring shall be recorded using the ODESS system. Records shall be maintained for each load, as well as daily and weekly summaries. Observations shall be recorded regardless of whether any takes have occurred. If a take has been observed, appropriate incident reporting shall be completed, and all specimens photographed with a digital camera as attachments to the incident record. Dredging of subsequent loads shall not commence until all appropriate reports are completed from the previous dredging load to ensure completeness and thoroughness of documentation associated with the incidental take. Reports shall be submitted to USACE within 24 hours of a take.

INITIAL DEVELOPMENT

USACE recognized in the early 1990s that it would be valuable to have this data stored in a centralized location to be easily retrievable. Consequently, the Sea Turtle Data Warehouse (STDW) was established. under the leadership of Dena Dickerson at the U.S. Army Engineer Research and Development Center (ERDC) to collect, store, and evaluate this information. Over the years, USACE, the NMFS, and the dredging industry have all used this data to develop protocols, operational methods, and modified dredging equipment to reduce dredging impacts to sea turtles and other TES. At inception, historical records primarily consisted of turtle take data, which were digitized and entered into the STDW database. Subsequently, handwritten observer reports were entered into a central computerized database to allow the analysis of information regarding historical sea turtle incidents and takes. Information about a given take could be reviewed or summary information could be retrieved by species, USACE District, or year. To automate data collection and provide an interactive decision-making tool to measure the impacts of hopper dredging activities on TES, ODESS was developed in conjunction with the National Dredging Quality Management Program (DQM) and the USACE Mobile District, Operations Division, Spatial Data Branch, (CESAM-OP-J), further expanding on the work of the STDW.

COMPONENTS

Moving away from a reliance on paper forms, which caused delays in decision making and operations, ODESS seeks to include the tracking of all endangered species as well as more fully automate the process of collecting, storing, and visualizing the impacts of the data. ODESS can be divided into three components, based on the user type (Figure 2). The first component, data collection, consists of the electronic gathering of load/tow and incident records by on-site Endangered Species Observers (ESOs). The second component consists of a USACE-only intranet site, where USACE District personnel review and evaluate information received from the field. The final component consists of a public website, which provides current information regarding reported incidents and status with respect to the various regional BiOps. The following sections describe each of these components in detail; all screens are from ODESS V2, which will be released later this year.

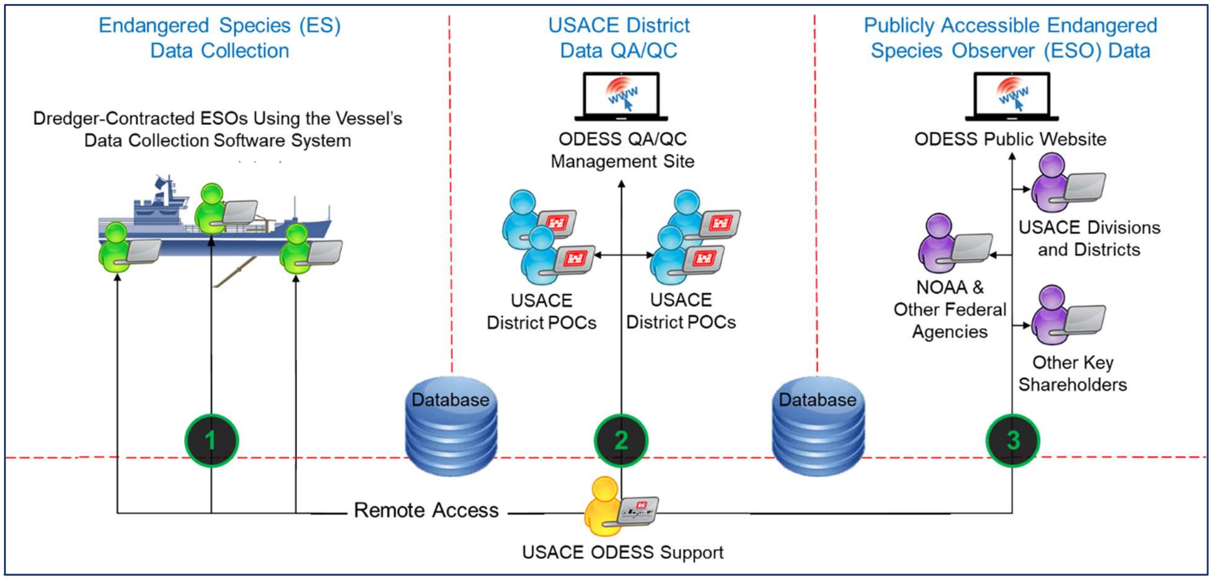

Figure 2. The three components of ODESS: ES Data Collection, USACE District Data QA/QC, and the ODESS public website for access to ESO Data.

DATA COLLECTION

Within the ODESS system, observers aboard hopper dredges enter data for each dredging load on a portable tablet, including general information on site conditions (such as weather and sea conditions) and a description of cage contents. This data is correlated with DQM data regarding dredging locations and slurry quantities for the corresponding load. In the case of an incident, additional data is entered, and the tablet can be used to take photographs to attach to the report. These reports are transmitted to the database via the Internet after completion or when telemetry is available (Figure 3).

Figure 3. ES Observers use the Dredging Data Collector to digitally collect data within the ODESS system, which uploads the data to the ODESS database.

Observers are the eyes on the scene and are asked only to impartially document the observed conditions; it is not the observers' responsibility to determine whether a take has occurred—that responsibility lies with the USACE District personnel. The Dredging Data Collector software can be remotely loaded into the observer contractor's tablet. Once installed and activated, the home page consists of a picture of a sea turtle and a series of tabs and buttons. The buttons in the middle of the landing page act like a wizard to walk the observer though the data collection process (Figure 4).

Figure 5. ODESS Dredging Data Collector component descriptions.

The first button, Set Shift Default (Figure 4a), takes the user to a screen where basic information about the vessel, observer, and dredge conditions can be entered, eliminating the previous need for the observer to re-enter this standard information for every report. Shift defaults should be reviewed and updated at the beginning of the project and at the beginning of each observer's shift. In some cases, the project information fields are prepopulated from the DQM database, but they can also be manually entered or chosen from a drop-down menu.

The second button, Add Load (Figure 4b), opens a series of windows where data regarding different aspects of a load can be logged. The first of these windows records general information about the load—the assigned load number, when the load started and ended, material type, and whether trawling was conducted. Fields that are highlighted indicate they are pre-populated from the database, but all fields can be edited. By clicking the Continue button, the user continues through a series of windows to record information regarding the screens and their condition and content, and water and atmospheric conditions, such as sea state, wave heights, water depths and temperatures, wind speed and direction, and air temperature. There is also a space to enter general comments regarding the load that are not captured elsewhere. This information is used to understand the environment in which the dredge is working and the water conditions TES are experiencing. Upon completion of this window the user can save the load information to the load log for subsequent transmittal.

The final button, Add Incident (Figure 4c), walks the observer through entering an incident record for a particular load, including attaching any incident report documentation, photographs, and diagrams showing impacts to the TES or parts recovered.

The observer can also use the tabs across the top of the screen to go directly to some of the windows to enter data, investigate the status of the project and related BOs, or do some housekeeping. The first tab is the same as the Set Shift Default button (Figure 4a). The second tab, Daily log (Figure 4d), takes the user to a summary of the loads recorded for each date and the status of those loads – whether they are in progress, have been submitted or are awaiting submittal. The Load Log tab (Figure 4e) lists similar information for each individual load and also includes the observer's ID. The Incident Log window (Figure 4f) allows the observer to directly enter incident information, and the Daily Report window (Figure 4g) summarizes the loads, endangered species, and bycatch encountered. The final tab, Submit Reports (Figure 4h), shows whether an Internet connection is available, identifies which data is available to package, and provides an option to submit the daily reports to the ODESS database.

One of the mitigation solutions implemented over the last 30 years to reduce impacts to TES from trailing suction hopper dredging (TSHD) is relocation trawling. Trawling operations serve two purposes: (1) to assess pre-dredging species abundance and distribution, and (2) to capture and relocate species away from the dredging area, reducing risk of injury or mortality to protected species. Collecting near-real-time data from the trawlers can help to verify the efficacy of trawling efforts and provide valuable information when conducting risk analysis on dredging operations. To fill this need, ODESS has been developing and testing a mobile application for use on a cellular phone for observers to enter trawling tow data on trawlers assisting with relocating endangered species in the vicinity of a dredging operation to mitigate actual takes (Figure 5). Efforts are currently underway by the U.S. Geological Survey (USGS) to digitize historic trawling data, making it accessible through ODESS. The Bureau of Ocean Energy Management (BOEM) is currently initializing a study to evaluate the efficacy and potential impacts of relocation practices, combining their Analyzing Sea Turtle Entrainment Risk (ASTER) decision tool with other innovative technologies, including historical ODESS trawling data, in their evaluations.

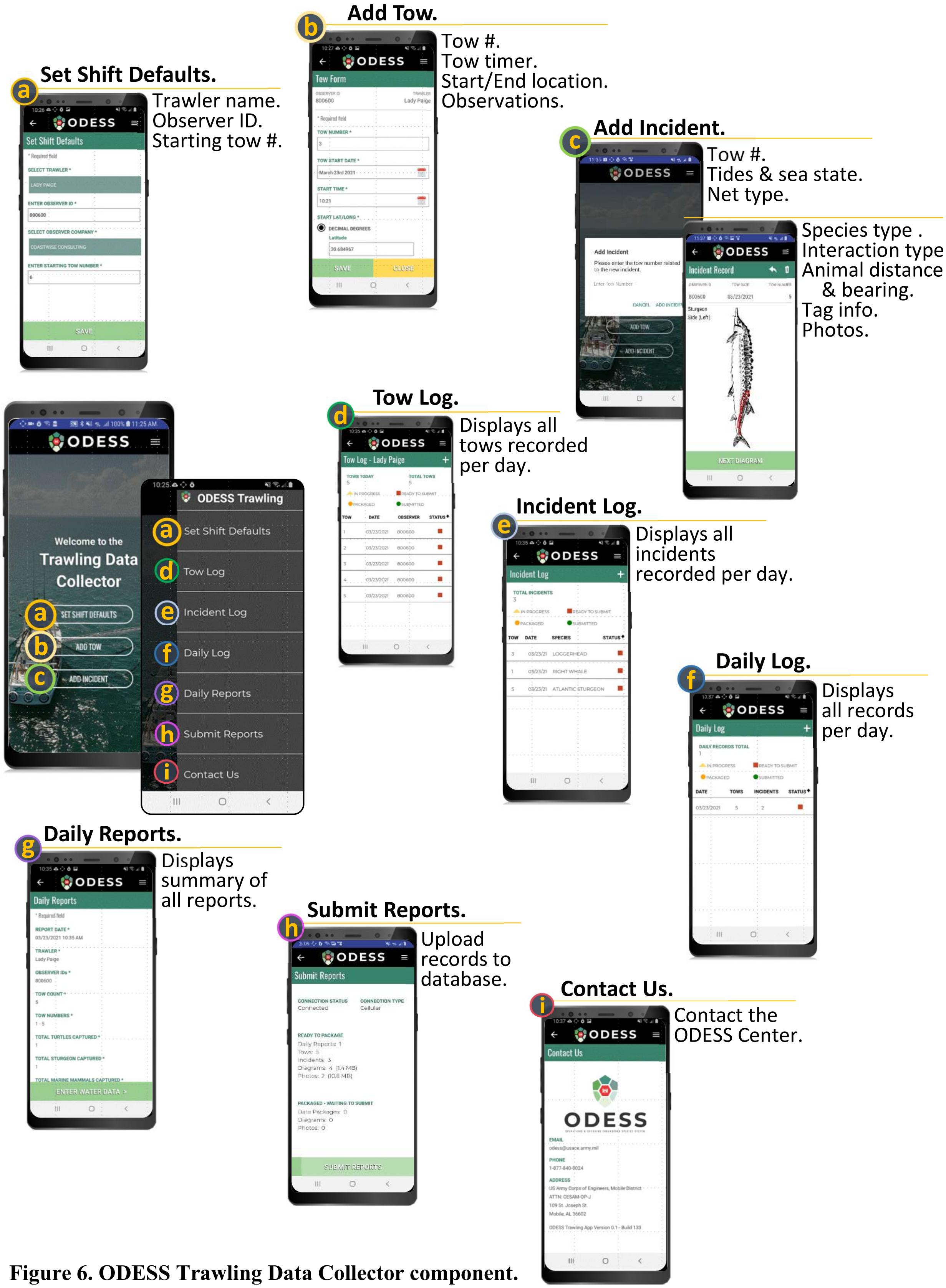

Figure 6. ODESS Trawling Data Collector component.

Instead of being installed on a tablet, the trawling app is designed specifically for use on a smart phone, which takes up less space and does not require a separate modem to transfer data (Figure 6). Observers can download the app onto the trawler-supplied smart phone and use the phone's GPS features to provide tracking for each transit through the dredge area. For each tow, the Trawling Data Collector can enter the number and species of encountered and relocated creatures.

Figure 7. ES Observers use the Trawling Data Collector to digitally collect data within the ODESS system and upload it to the ODESS database.

Similar to the Dredging Data Collector, the Trawling Data Collector allows the observer to enter tow information in a variety of ways. Buttons for the three most common types of inputs are presented in the middle of the home page (Figure 5). As in the Dredging Data Collector, Set Shift Defaults (Figure 5a) is filled out only once, at the start of the project and the beginning of each shift, and allows the entry of the trawler vessel and observer information. The Add Tow button (Figure 5b) opens a series of screens for the entry of data for each tow sailed. Although the observer can enter time and location data manually, the preferred option is to allow that information to be populated directly from the phone's GPS and clock. Reducing the number of keystrokes minimizes data entry errors and allows the observer to stay focused on observations. Additional information can be added about observed conditions affecting the tow. The Add Incident button (Figure 5c) allows recording of data surrounding an incident, either an observation or a capture, of a variety of marine species or abiotic debris. For a capture, information regarding the species and condition of the specimen are noted as well as whether the individual had previously been tagged. The location and the atmospheric and sea conditions surrounding the incident are described, and the disposition of the capture is also documented.

From the home page, a tab overlay can be activated by tapping the "hamburger" menu, the stack of three horizontal lines in the upper-right corner of the screen. In descending order, the menu choices are Set Shift Defaults, Tow Log, Incident Log, Daily Log, Daily Reports, Submit Reports, and Contact Us. Set Shift Defaults opens the same window as the button (Figure 5a). Tapping the Tow Log (Figure 5d) shows an overview of the tows that have been run for the given trawler vessel. The Incident Log (Figure 5e) summarizes information regarding tows that resulted in species observations and captures/relocations. The Daily Log (Figure 5f) shows the number of tows and incidents recorded for each day worked. The Daily Reports (Figure 5g) combines information from other tabs to show not only the captures for a given day but also information about the trawler vessel and tows without events, and it allows the entry of sea conditions for the day. The Submit Reports tab (Figure 5h) is used to review and transmit collected reports. The final tab, Contact Us (Figure 5i), allows the trawler to contact the DQM Support Center with questions or to report any issues encountered with the use of the application.

INTERNAL QA/QC MANAGEMENT SITE

The second component of ODESS (Figure 2), the QA/QC management site, is available only to USACE personnel through the USACE intranet; it is not available to the public. Within this component, USACE District POCs can view load and incident information recorded by the on-site observers and record their decisions regarding the magnitude of a TES incident. To assist in their evaluations, the District personnel have access to a range of DQM tools. Although risk assessment is conducted to determine whether to continue dredging after a take, this is not the same as the Risk Assessment measures outlined in the SARBO.

USACE District POCs also use internal QA/QC management site to select a project from a list of active projects, review the observer-submitted data (Figure 7), and publish appropriate details to the ODESS public website. Once an incident record is published and designated as a lethal or non-lethal incident, the associated BiOp take allowance is adjusted to reflect the decision. When incidents are published, attachments can be added to the report. It should be noted that once a report is published, the information cannot be changed, so it is important for the District Point of Contact (POC) to ensure that the information is accurate before publishing it.

Figure 8. ODESS internal USACE intranet site for USACE POC data access and review.

On the entry page, Manage Data—Project Review, the user can review current projects for a chosen District and fiscal year. Contracts are listed by contract number, start date, project name, and whether it is a Civil Works project, new work, or maintenance. If Edit is toggled, a separate window opens, where the user can enter the project description, the governing BiOp, and summary information regarding the contract, including total of cubic yards dredged and hours and days of dredging. If no incident has occurred, the USACE representative can mark the report as "Read," which saves it to the database. If there are published incidents for the contract, they are listed below the alerts. The incidents list documents the species, dredge, recovery date, and incident type, and it provides a link to the project details. V2 of the intranet site, which will be released later this year, enhances the functionality of V1 by providing additional controls to allow modifications throughout the reporting process.

Per protocols established by the recognized BiOps, USACE must conduct a risk assessment pursuant to an incident report to determine the likelihood that other takes will occur on the project. Part of the assessment involves a determination of where within a load a take may have occurred and whether the dredge was being operated in compliance with the BiOp requirements. Other factors considered include the water temperatures (available from local National Oceanic and Atmospheric Administration [NOAA] buoy/tide stations, the status of the TES population, and the dredge take history). Information on how the dredge has been operating during the period of time in question can be gleaned directly from graphs on the DQM Online Data Viewer; however, the hour-by-hour and load summary plots, often referred to as a Turtle Report, makes this assessment easier (Figure 8). The report can be requested directly from the DQM Center and may take a few hours to produce; however, an "easy button" is planned so field personnel can run the reports directly from the ODESS website.

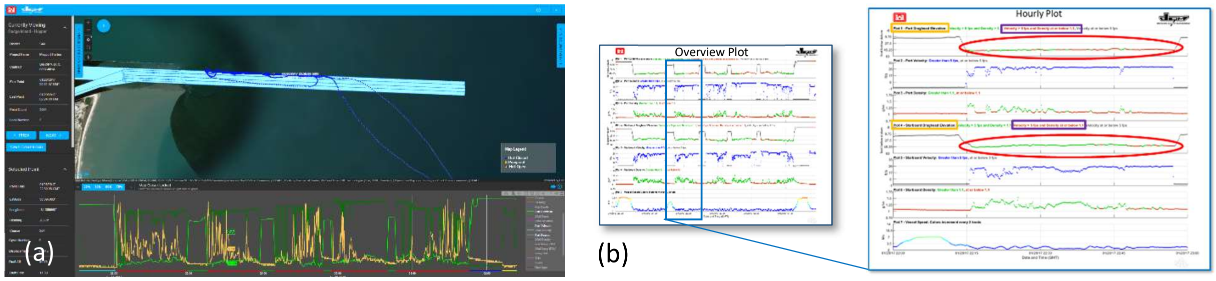

Figure 9. (a) The DQM Online Data Viewer can be used to review project data in the case of an incident. (b) TES plots use thresholds to highlight conditions to be examined more closely.

During the risk assessment analysis, the reviewer uses the load/hourly plots to evaluate two key elements of the dredging activity: whether the dragheads maintained contact with the bottom and whether measured velocities and densities indicated that the dragarm was primarily sucking water, which increases the potential of taking TES. To conduct this evaluation, the reviewer focuses on the following components of the operational plots: the Draghead Elevation and the Velocity and Density Thresholds. On the operational plots (Figure 8b), the graph indicating draghead elevation is color-coded using thresholds that are provided by the reviewer to the DQM Center to indicate vulnerable time periods for a potential turtle take. The line is green when both the Slurry Velocity is greater than a threshold (typically 5 fps) and the Slurry Density is greater than a threshold (the inputted density of the material—generally 1.1), increasing the potential for a take. The line is red when the Slurry Velocity is greater than a threshold (5 fps) and the Slurry Density is at or below a threshold (the inputted density of the material), indicating that the draghead was sucking mainly water. When the draghead does not stay in complete contact with the bottom and is pulling a high amount of water and a very low amount of dredged material, the possibility of a potential take increases. It is important to recognize whether the default material density is reflective of actual conditions, whether the dragheads are maintaining the correct elevation during cleanup, and whether the dredge was digging on a steep toe of the channel, preventing full contact of the draghead with the bottom.

Other considerations for a risk analysis include regional impacts of an acknowledged take, including the time of year and the estimated duration of the dredging season. When the review is complete, the District POC makes a call on whether incident is a take and if it is counted against the BO, and the ODESS website is updated.

PUBLIC WEBSITE

The final component of ODESS (Figure 2) is the public website, where anyone review the impacts of dredging on TES. The website (Figure 9) includes the ability to view maps of civil and regulatory boundaries; export actual observer's reports; view a dashboard correlating various metrics regarding takes, limits, and locations; and download a variety of forms used by observers. Other reports that can be viewed on the website include a Biological Opinion Tracking report, Historical District Annual Reports, and a District Annual Summary Report, which includes a map view of take locations as well as a tabular display of take/limit occurrences. Searches can be conducted to focus on a specific area of interest.

Some users may already be familiar with the V1 public website, which consists of four major pages. The home page provides a description of the program; tabs along the left panel enable users to display the Map, Dashboard, and Reports pages as well as export data, download information, and contact ODESS Support. On the Maps page, civil and regulatory heat maps display the total takes (with the number of USACE Districts represented within each category). Using the Dashboard, viewers can see data correlated by USACE Division, District, species, BiOp, and quantity of material, either in tabular or graphical format.

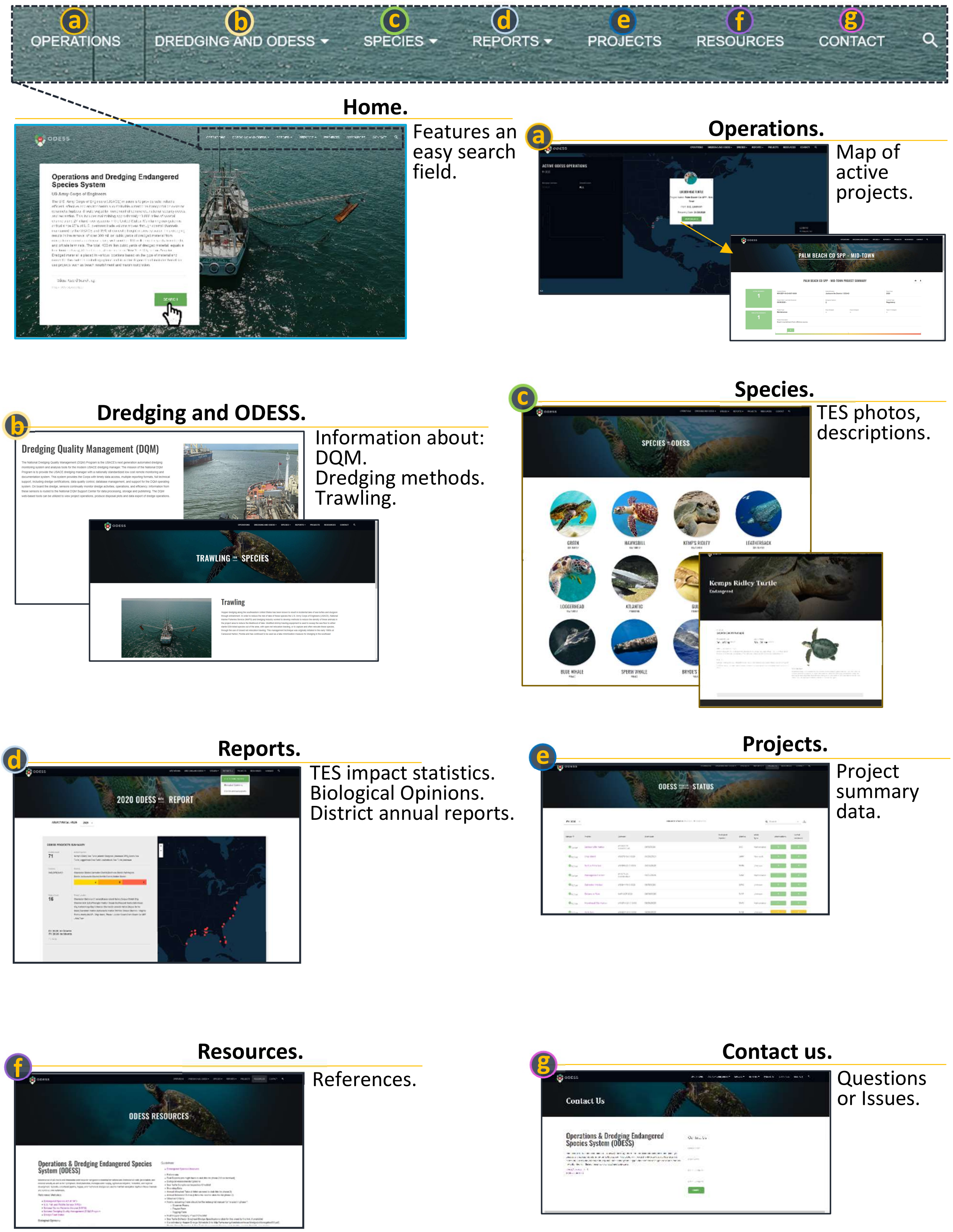

Figure 10. ODESS Public Website.

In the Reports section, District Annual Summary Reports can be generated by District. These reports present a map overview of reported takes as well as additional tabular information concerning the takes. Other reports available from the Reports tab are the Biological Opinion Tracking Report and the Historical District Annual Reports.

Later this year, V1 of the public website will be replaced by V2, which places greater emphasis on search capabilities (Figure 9—Home). The description banner on the Home page contains a search box, in which users can start typing key words for the data they want to access. As they type, a drop-down menu displays below the search bar with suggestions of things/places to search. Once the correct search terms are identified, a click of the Search button opens a new window detailing the search results.

If a user ever gets confused as to where he or she is within the website, clicking the ODESS logo in the upper-left corner always returns to the Home page. Tab selections across the top of the screen offer a variety of other pages to visit. Clicking the Operations tab (Figure 9a) displays a map of the active projects being tracked by the ODESS. Although the default is to show all active projects, the user is also given the option of showing only those projects governed by a particular BiOp in the drop-down selections on the left side of the screen. On the map itself, projects are designated by blue boxes, and reported incidents are shown as red dots. Clicking either opens a pop-up window describing the project at that location and giving some basic information regarding the species of interest at that location (including a representative picture). From this window, the user is also given the choice to go directly to records regarding this project. This project summary displays a general project description as well as the number of lethal and non-lethal incidents for that contract.

Selecting the Dredging and ODESS tab (Figure 9b) provides a drop-down menu that takes the user to a variety of educational information pages that reference information pertinent to dredging and its impacts of threatened and endangered species. Pages also include a glossary and a list of Frequently Asked Questions (FAQ) regarding the program.

Selecting the Species tab (Figure 9c) allows the user to read up on overview information concerning the species of concern for dredging. The reader can either choose to see a lineup of species or can focus on a particular species of interest. In addition to a picture of the animal, the viewer is given a physical description, average size, a habitat description, and some basic facts regarding the animal.

The next tab, Reports (Figure 9d), provides a drop-down menu to view three different types of reports: a Fiscal Year ODESS Data Report, a Biological Opinions Report, and District Annual Reports. The Fiscal Year ODESS Report contains a written summary of the total number of incidents reported, where they occurred, and a list of the project locations which experienced an incident. Graphical depiction of takes by USACE Division, District, and month are included. Additionally, a comparison of takes versus their limits under the major BiOps is provided. The Biological Opinions Report for a chosen fiscal year, gives background information and a map showing the area governed by a particular BiOp. Further, there is a summary of incidents, a project summary, and a description of how those were determined. Additionally, there is listed the takes by species and a Regional “Report Card,” which compares the number of actual incidents to the BiOp’s limits. Searchable Summaries of the BiOp’s incidents is also listed and can be exported. Lastly, a District Annual Report is also available. In addition to some of the summary statistics provided in the FY ODESS Data Reports, and the Biological Opinions report card, a searchable list of incidents can be identified by the USACE District in which they occurred.

The Projects tab (Figure 9e) provides a list of all active and completed projects monitored by the ODESS program per fiscal year. This table includes project status, the project name, the contract number, the start date of the project, the governing BiOp, USACE District, work types and a count of recorded observation and lethal/non-lethal incidents. Clicking on a particular project opens a window to the same project Report as can be accessed from the map on the Operations page. In addition to the project and statistics summaries, there is a summary of dredging and trawling conditions and an incident and observation summary report, from which details of the reported incidents can be viewed, including load summary observations.

The final two tabs, Resources (Figure 9f) and Contact Us (Figure 9g), take the user to either the same resource page accessed from the Dredging and ODESS selection or to a page where the public can contact ODESS Support with questions. The Resource page provides links to related websites, pertinent Techniques Manuals, and Observer Guidelines.

CONCLUSIONS

The Operations and Dredging Endangered Species System (ODESS) is committed to providing automated support to assist in the collection and storage of data relative to dredging impacts on TES. Although it originated as a repository for sea turtle-specific data, ODESS has the capability of handling a range of TES. It has become a valuable tool in performing risk analysis for observed incidents and enabling better dredging decisions on a regional basis in cooperation with the governing BiOps. The automated components of the system are user friendly, utilizing tablets and smart phones to collect data and allowing the public to review the severity of reported incidents. ODESS regularly conducts training on the use of the tools and provides informational presentations through DQM.

REFERENCES

ODESS: Operations and Dredging Endangered Species System, https://dqm.usace.army.mil/odess/.

Smithsonian Institution. Ocean: Find Your Blue. https://ocean.si.edu/conservation/solutions-success-stories/endangered-ocean.

Todd, V.L.G., Todd, I.B., Gardiner, J.C., Morrin, E.C.N., McPherson, N.A., DiMarzio, N.A., and Thomsen, F. "A review of impacts of marine dredging activities on marine mammals," *ICES Journal of Marine Science*, 72:2, Jan/Feb 2015, 328–340. https://doi.org/10.1093/icesjms/fsu187.

CITATION

Sessions, Michael G. "ODESS: An Interactive Decision-Making Tool for Endangered Species Collection, Reporting, and Risk Assessment," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual Conference, June 15-18, 2021*.

DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

THE SKINNY ON FILL PLACEMENT - CHOOSING SEVEN FILL AREAS FROM SEVENTY AND 45 MILLION C.Y. OF BORROW AMONGST 200 MILLION

Benjamin Hartman[1], Gordon Thomson[2], Brad Miller[3], Dain Gillen[4], and Travis Byland[5]

ABSTRACT

The BA-203 Barataria Basin Ridge and Marsh Creation - Spanish Pass Increment is located near Venice, LA, in Plaquemines Parish. This project is being led by the Louisiana Coastal Protection and Restoration Authority (CPRA), with funding and implementation through the Natural Resource Damage Assessment (NRDA) restoration planning effort to restore for damages caused by the Deepwater Horizon oil spill. The scope of the project involves the restoration of approximately 132 acres of historic ridge and 1,538 acres of marsh that have been degraded due to eustatic sea-level rise, high subsidence rates, diminished sediment supply, and extreme storm events. The initial conceptual project was developed from a 12,000-acre area identified as being suitable for project construction and extended 9.9 miles from Venice to Scofield Island. The intent was an elongated marsh creation footprint with a ridge feature mimicking the natural levee adjacent to the historic Spanish Pass distributary. The team developed 69 fill sub-areas for evaluation. The sub-areas were developed based on existing features such as existing marsh edge, canals, oil and gas infrastructure, and to meet construction budget. These sub-areas were screened and 7 areas were selected for construction and labeled Marsh Creation Areas A-H. Initial borrow area screening metrics included evaluation of likely material type, available quantity, and unit fill cost. The two offshore borrow sources, Grand Liard East and West contained less than 5% sand and 4.2 million cubic yards (MCY) and 2.5 MCY of material, respectively. The Mississippi River borrow sources varied greatly in material type and quantity. Baptiste Collette Bayou and Tiger Pass contained less than 50% sand and 1.0 MCY and 1.5 MCY of material, respectively. The Hopper Dredge Disposal Area (HDDA) contained nearly 8.0 MCY of sand with less than 2% fines. The B2 borrow area, an area immediately adjacent to the federal levee along Boothville-Venice, contained 16 MCY of material with sand contents ranging from 92% in the north to 55% in the south. Two additional borrow sources, the Venice and Pilottown anchorages, were added to project after initial data collection and contained an average of 87% sand and 40 MCY and 125 MCY, respectively, based on initial assessment. Nine different borrow sources (two offshore and seven in the Mississippi River) containing over 200 MCY have been evaluated with the closest borrow sources B2, DDDD, BBBB being included in final design. It is estimated that the project will require up to 17 MCY of sediment to construct. This effort highlighted the cost effectiveness of identifying and developing additional borrow areas within the Mississippi River to meet the $88.5M construction budget.

Keywords: Dredging, beneficial use, slurry transport, dredged material disposal, contaminated sediment.

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INTRODUCTION

Marsh areas provide valuable ecosystem services. Louisiana's wetlands buffer storm impacts, absorb nutrients and contaminants, and are a highly productive ecosystem, providing spawning grounds for fish and nurseries for shrimp, oysters and crabs. In terms of natural services, biologic productivity and infrastructural investments, the value of Louisiana's coastal wetlands exceeds $100 billion (Force, 1993). Many coastal populations, especially those in Louisiana, rely on these functions for their livelihood. The Spanish Pass project will restore areas of marsh that have been degraded due to eustatic sea-level rise, high subsidence rates, diminished sediment supply, and extreme storm events.

The construction of a ridge is designed to replace functions of historic ridges associated with natural tidal waterways and other naturally raised landforms within the intertidal zone. These raised landforms typically had a moderating effect on storm surges from tropical events and served to reduce wave-induced erosion in tidal marshes by reducing open water fetch. Habitat qualities of ridges range from subtidal aquatic habitats at the toes of the ridges in open water, wetlands in the zone of frequent inundation up the slopes of the ridge, to non-wet uplands in areas above the tidal range. Natural ridges typically demonstrated forested upland habitats with a range of woody species similar to bottomland hardwood wetlands. Upland or facultative shrub species are also typical of supratidal ridge elevations.

The BA-0203 Barataria Basin Ridge and Marsh Creation - Spanish Pass Increment (herein referred to as the Spanish Pass project) is located near Venice, LA, in Plaquemines Parish (Figure 1). The original scope of the Spanish Pass project was to create and nourish approximately 120 acres of historic ridge and 1,134 acres of marsh within a $120M budget. The proposed restoration of marsh and ridge habitat will be performed by dredging from sources in reasonably close proximity to the project area, conveying sediment to the project site, and placing sediment in a fill area(s) to a specific shape and elevation.

Figure 1. Initial Area Under Consideration for Project Extents

CONCEPTUAL PROJECT LAYOUT AND PRELIMINARY DESIGN

Marsh and Ridge Fill Area Development

The design team conducted topographic, bathymetric, and magnetometer surveys within potential marsh and ridge creation subareas, equipment access corridors, and dredge pipeline alignments in order to facilitate the design of the fill areas. Initial topographic and bathymetric transects completed during reconnaissance surveys were collected on a 2,500 ft by 1,500 ft grid and used to inform early cost estimates and field data collection plans. Subsequent data collection transects for engineering plans included surface and magnetometer surveys and were oriented north to south and were spaced at 250-ft intervals across open water, broken marsh, and pipeline canals within the proposed marsh fill areas. An overview of fill area data collection transects can be seen in below Figure 2.

Figure 2. Reconnaissance and 30% Design Data Collect Transects

The elevation and water depth were recorded at a minimum of every 50 ft along each transect or where elevation changes of greater than 0.5 ft occur. Where open water met land, topographic and bathymetric transects overlapped by 50 ft and were merged at the land/water interface. Magnetic anomalies were cross referenced against pipeline databases compiled from Coastal Use Permits, National Pipeline Mapping Systems, plus data from adjacent marsh creation projects and use to verify the location of pipelines. A total of 159 transects, running north to south across marsh creation subareas, were surveyed during this design level survey phase of the project. Following the general guidance and the project area boundary (Figure 1) marsh creation sub-areas were delineated based on natural features such as ridges, creeks and channels. The areas were further delineated based on oil and gas infrastructure, allowing for exclusion of an area should access to fill on top of or cross the pipeline not be granted. Subarea layout also considered construction access to the area. Large areas were broken into smaller elements in order to provide flexibility with respect to construction cost. A total of 69 potential fill sub-areas were developed as shown in Figure 3. A number of the fill sub-areas were excluded during an initial screen that considered exposure, constructability, pipeline overlap, flushing and maintaining tidal flows along historic Spanish Pass, overlap with the proposed extension of the nearby Beneficial Use of Dredge Material (BUDMAT) project, and cost.

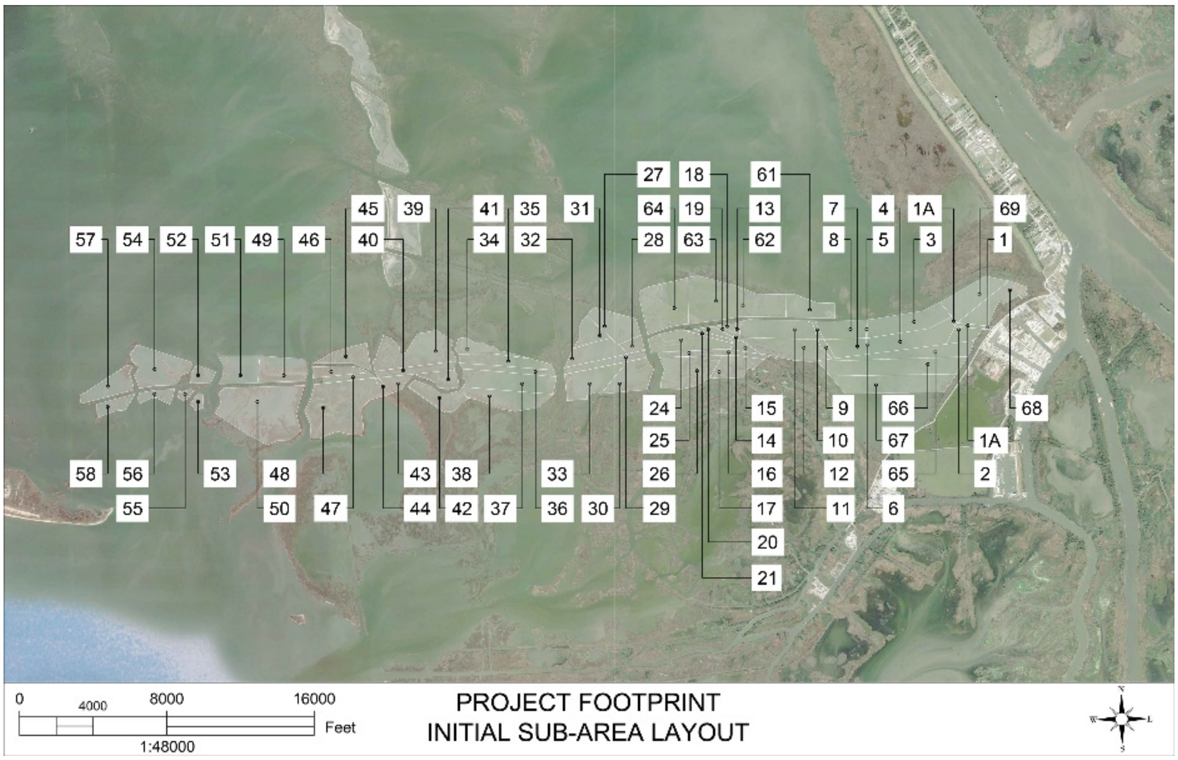

Figure 3. Initial Marsh Creation Subarea Layout

The sub-areas were then combined to develop alternatives. The alternatives initially followed conceptual development such as constructing only north or only south of Spanish Pass, or constructing only the most cost-efficient areas. However, the initial concept of an elongated project was weighted heavily during the development of the alternatives and ultimate selection of the preferred alternative.

Borrow Area Development

Multiple borrow areas were screened during the design process, as shown in Figure 4. Mississippi River sources included Baptiste Collette Bayou, Tiger Pass, Grand Pass, B2, DDDD, BBBB, and the Hopper Dredge Disposal Area (HDDA). Offshore borrow areas that were considered included Grand Liard East and Grand Liard West, which were previously used for an adjacent restoration project. The material type, available volume, and pump distance for each borrow source were primary metrics used in developing cost estimates for the initial screening. Available volume was a significant consideration as mobilizing to multiple borrow areas to meet the volumetric needs would drive up project cost. There was also a requirement to minimize the number of Mississippi River crossings with a dredge pipeline due to the disruption to navigation. The Baptiste Collette Bayou, Tiger Pass and Grand Pass borrow areas were eliminated while Figure 4 shows the location of the borrow areas that passed the initial screening.

Figure 4. Borrow Areas that Passed the Initial Screening

Following the initial screening, the design team collected topographic, bathymetric, magnetometer, sub-bottom, geotechnical, and side scan survey data in the B2, BBBB and DDDD borrow areas to support the design process. The HDDA borrow area is being dredged and refilled by the USACE so additional data would have been outdated by the time of construction. Historical data was used to evaluate this borrow area further. Bathymetric data was collected in the Grand Liard borrow areas to determine any infilling.

At the initial stages of design, over 200 MCY of sediment was identified to support a full range of design options for the fill area. The original footprints of DDDD and BBBB had dredge depths of -85 NAVD88, resulting in available dredge volumes of 40 MCY and 125 MCY, respectively, though this was reduced during the design and permitting process. Table 1 summarizes material type and volume available for design. The required borrow area excavation volume will ultimately depend on dredging losses, unforeseen conditions within the borrow areas, potential infrastructure and cultural resource conflicts, and background erosion of the fill area during construction. For design and cost-estimating decisions, a volumetric need of 50% more than the design volume was assumed, thus the estimated neat volumes for the borrow areas were reduced by 33.3% to determine estimated effective volumes. Grand Liard East volume was further reduced, because it had been previously dredged so the infilled material is unconsolidated. This unconsolidated sediment is unlikely to provide the required in-situ volume.

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Table 1. Borrow Area Summary

Borrow Source	Neat Volume (CY)	Effective Volume (CY)	Est. Sediment Classification	Est. Sand Fraction (%)	Borrow Centroid to Nearest Subarea. (ft)
B2	7,800,000	5,200,000	Mostly sand	>92 to 43%	30,000
DDDD	17,036,000	11,357,000	Mostly Sand	87%	19,500
BBBB	20,250,000	13,500,000	Mostly Sand	87%	36,000
HDDA	8,000,000	5,333,000	Sand w/ silt	45%-85%	65,500
GLE	4,182,000	2,788,000	Clay / silt and sand	0%-50%	21,500
GLW	2,494,000	1,663,000	Clay w/ silt and sand	0%-50%	29,000
Tiger Pass	1,524,000	1,016,000	Sand w/ silt	50%	45,000
Baptiste Collette	975,000	650,000	Clay w/ silt and sand	0%-50%	62,500

It was determined that sandier sediment provides an advantage over sediment with high fractions of silt and clay. The higher fall velocity of sand through the water column compared to silts and clays, which can remain suspended for long periods of time, allows for the construction of marsh platform without the need for containment dikes if predominantly sandy material is dredged. Oil and gas infrastructure conflicts will be reduced when constructing with sand by eliminating the need to excavate to construct containment. Furthermore, a land bridge and access road can be constructed over pipelines using sandy fill rather than requiring dredged access channels to move personnel and equipment to and from the fill area. Sand content varies between borrow areas, but is generally higher for Mississippi River sources and lower for Grand Liard sources, as shown in Table 1.

Several riverine borrow sources were excluded after preliminary design. Tiger Pass and Baptiste Collette were shown to have inadequate volume while the HDDA's remote location made transport significantly more expensive. B2, DDDD, BBBB, and Grand Liard borrow areas passed the initial screening and evaluated further during detailed design. Cost modeling during this second phase eliminated offshore sources as illustrated in the following sections. The remaining riverine sources were included in final design to provide flexibility during bidding and resilience through construction.

PREFFERED ALTERNATIVE DEVELOPMENT AND DETAILED DESIGN

Unit Fill Cost Model Development

Unit cost of fill by subarea was used to develop marsh cost per acre that served as the primary basis for selecting fill area layout. The cost effectiveness of marsh area configurations was based on the fill volume and anticipated unit fill costs. The unit fill costs were partially based on the Corps of Engineers Dredge Estimating Program (CEDEP). CEDEP includes multiple variables including but not limited to the dredge type and size, dredge material, cut thickness, pump distance, economic conditions, fuel price, etc.

The first step was to calibrate the CEDEP model using similar projects in southeast Louisiana and compare the CEDEP cost to the bid cost. The CEDEP unit price outputs were calibrated by comparing historic low (contracted) bids to CEDEP-developed unit costs for similar previous projects. To calibrate marsh fill (offshore) CEDEP accuracy, CEDEP unit prices were developed for eight previous projects considering the elements specific to that project (pump length, fill material, bank height, economic conditions, fuel price, etc.) that affect the dredge unit cost. The low bid unit cost for each project was compared to the CEDEP-developed unit price to develop an accuracy ratio. The ratios were averaged to determine a calibration factor of 1.60, which was then applied to the offshore borrow area unit prices developed for the Spanish Pass project. A similar process was undertaken to develop a calibration factor of 1.12 for Mississippi River fill using data from five previous projects.

The CEDEP model was then populated using data for the Spanish Pass project. A table of unit costs was developed for each borrow area for a range of pumping distances using CEDEP. Costs were provided for 14 different shore pipe distances, ranging from 1,500 ft to 48,000 ft of shore pipe. A floating pipe length of 2,500 ft was assumed for all borrow areas. The submerged and shore pipeline distance was unique for each borrow area and subarea. These distances were applied in CEDEP. General input assumptions for all borrow areas included indirect costs of 20.8%, a minimum cost effective dredge prism volume of 2 MCY, minimum number of boosters that could be used, and fuel costs of $3.50/gal.

Marsh Creation Area Alternative Development

A number of the fill sub-areas were excluded during an initial screen that considered exposure, constructability, pipeline overlap, flushing and maintaining historic Spanish Pass, overlap with the proposed extension of the BUDMAT project, and cost. Alternative 1 (Figure 5) sought to match the initial project length and locate the project north of Spanish Pass. Alternative 2 (Figure 6) followed the same concept as Alternative1, but placed the project south of Spanish Pass. Purple fill areas were originally considered to be constructed using fill from the Mississippi River while cyan fill areas were going to use sediment from the Grand Liard borrow areas; the project team theorized that western subareas would be more economical to construct from offshore borrow, while eastern subareas would be constructed from riverine sources.

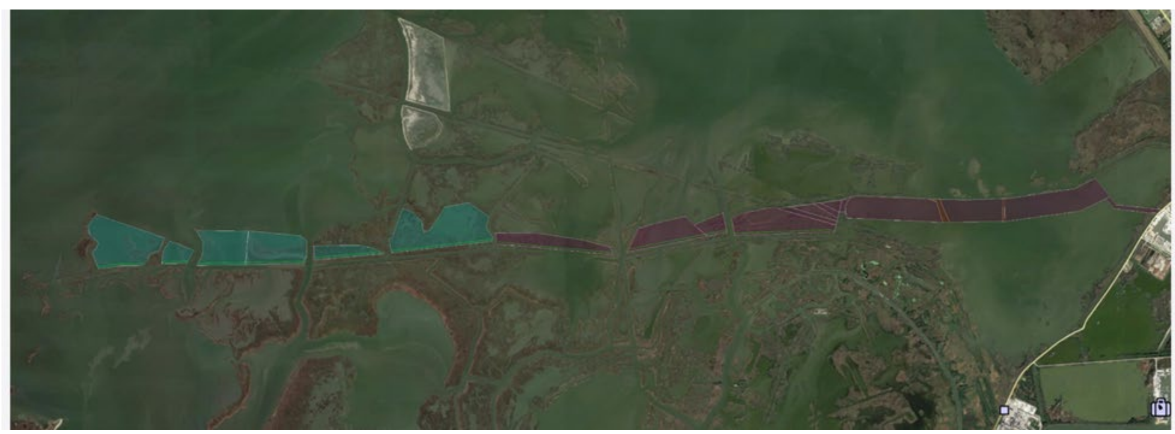

Figure 5. Alternative 1 – Project north of Spanish Pass

Figure 6. Alternative 2 – Project south of Spanish Pass

The sub areas were then combined to develop alternatives that met the target acreage and cost. Alternative 3 (Figure 7) was developed by selecting the most cost-effective marsh cells. These were naturally larger cells and were cost effective due to less containment being required to construct the cell. Alternative 4 (Figure 8) sought to decrease cost, removing sub-area 39 and adding sub-areas 34 and 35. A thinner section was also considered at the eastern side of the project area. Alternative 5 (Figure 9) removed sub-area 54, because there was concern about it being too exposed to waves developing across Barataria Bay, and a living shoreline concept or hardened structure was considered too expensive when other, more natural sheltered sub-areas, could be constructed more economically. A more northern position of the fill was considered at the eastern end. Sub-areas 34 and 35 were removed due to cost.
A comparison of the initial alternatives can be seen in Table 2. Alternative five was the only iteration to meet the overall project acreage and cost targets.

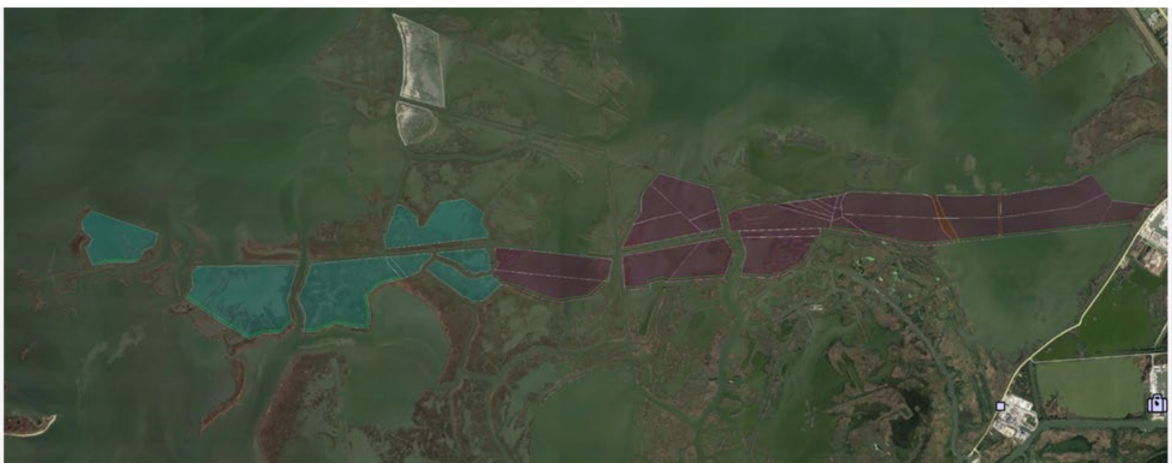

Figure 7. Alternative 3

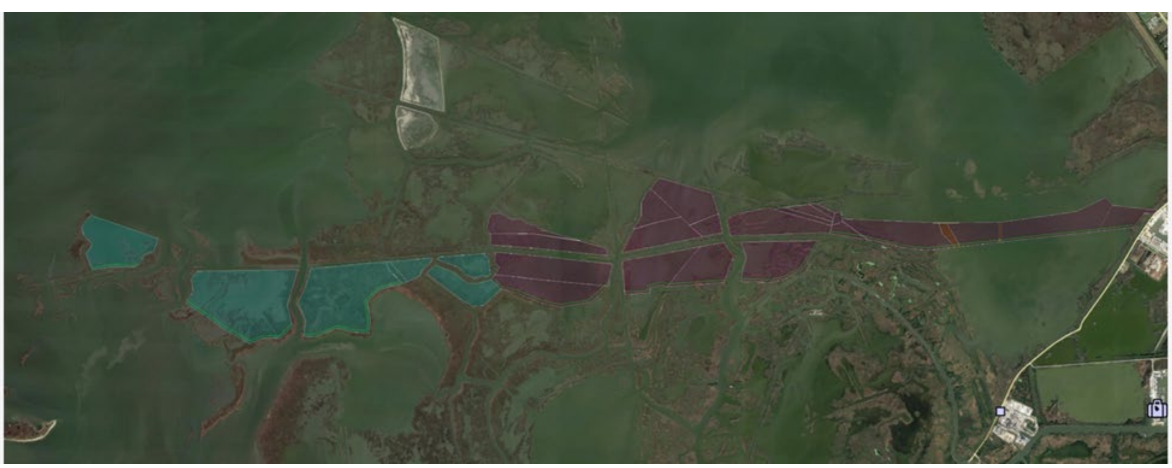

Figure 8. Alternative 4

Figure 9. Alternative 5

Table 2. Screening of Initial Alternatives

	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Marsh Area (ac)	946	1,191	2,167	1,727	1,240
Ridge Area (ac)	49	64	69	69	109
Total Acreage (ac)	995	1,255	2,236	1,796	1,349
Total Volume (cy)	10.5M	11.3M	20.8M	16.3M	12.2M
Cost	$92.6M	$101.4M	$176.3M	$144.6M	$108.6M

Following this analysis, further optimization considered pumping the entire project from DDDD or BBBB, leading to a significant reduction in project cost.

Optimizing Borrow Sources - Grand Liard vs DDDD

While initial cost estimates theorized that pumping western marsh creation areas (MCAs) from Grand Liard borrow would be more economical than pumping the entire project from riverine sources, clay fill required containment dikes, geotextile fabric, larger dredge prisms per acre, and a second mobilization. Moreover, a consolidation analysis of each MCA using offshore clay and riverine sand at 60% design led to a preference of sandy fill material. This meant that a dredge pipeline from the river would be installed nearly the entire length of the project, adding costs for pumping material into western subareas. Subsequently, CEDEP estimates of pumping western MCAs (A, C, D1, and E – see Figure 9) from the closest riverine borrow source, DDDD, were compared to combined costs of filling the same MCAs using Grand Liard material.

Table 3. Cost Analysis of Grand Liard vs DDDD

	Grand Liard (+3.0’ NAVD88)			DDDD (1.6’ NAVD88)		
MCA	Volume (CY)	Unit Price ($/CY)	Amount	Volume (CY)	Unit Price ($/CY)	Amount
A	1,526,000	$3.75	$5,722,500	457,000	$7.50	$3,427,500
C	1,250,000	$4.00	$5,000,000	49,000	$7.50	$367,500
D1	569,000	$4.25	$2,418,250	141,000	$7.00	$987,000
E	305,000	$4.25	$1,296,250	76,000	$7.00	$532,000
	Total Cost		$14,437,000	Total Cost		$5,314,000

Mobilization costs also needed to be considered. The distance from the borrow area to the fill area suggests that a cutterhead dredge would be used and booster pumps would be required. Other options, including hopper dredge and cutterhead/scow systems, were considered but estimated to be more expensive given the large fill volume and long pump distances. It was also assumed that a bucket dredge would be mobilized to construct containment dikes for marsh subareas filled with sediment from the Grand Liard borrow areas. An additional $150,000 in mobilization cost was included to facilitate access dredging in Bayou Jacques due to the shallow water. Thus, the additional mobilization cost was estimated to be $5.5M

Lastly, CPRA bid tabs were utilized for contingency analysis of containment dikes, incorporating the average containment cost (including inflation) of 9 similar projects. The average unit price for any CPRA project utilizing containment was approximately $45/LF with the single highest unit price observed to be $184/LF. A unit rate of $75/LF was used for base bid based on these projects. With approximately 29,750 LF of potential containment length, it could potentially cost a contractor $2.2M to construct containment. In total, pumping the entire project from the closest riverine borrow source would save $16.8M.

Final Project Layout

Alternative five had been updated since initial screening to omit subarea 50 in favor of subarea 3, 8, 18, 20, 21, 39. With the cost savings from eliminating Grand Liard borrow, the project contingency increased and a slimmed version of subarea 61-64 were developed as additive alternates. To simplify future discussions, the continuous marsh cells were grouped and relabeled A through G. The MCA H layout was reworked to accommodate the BUDMAT Tiger Pass footprint, which had completed final design by September 2019. The final project layout and BUDMAT layout can be seen in Figure 10.

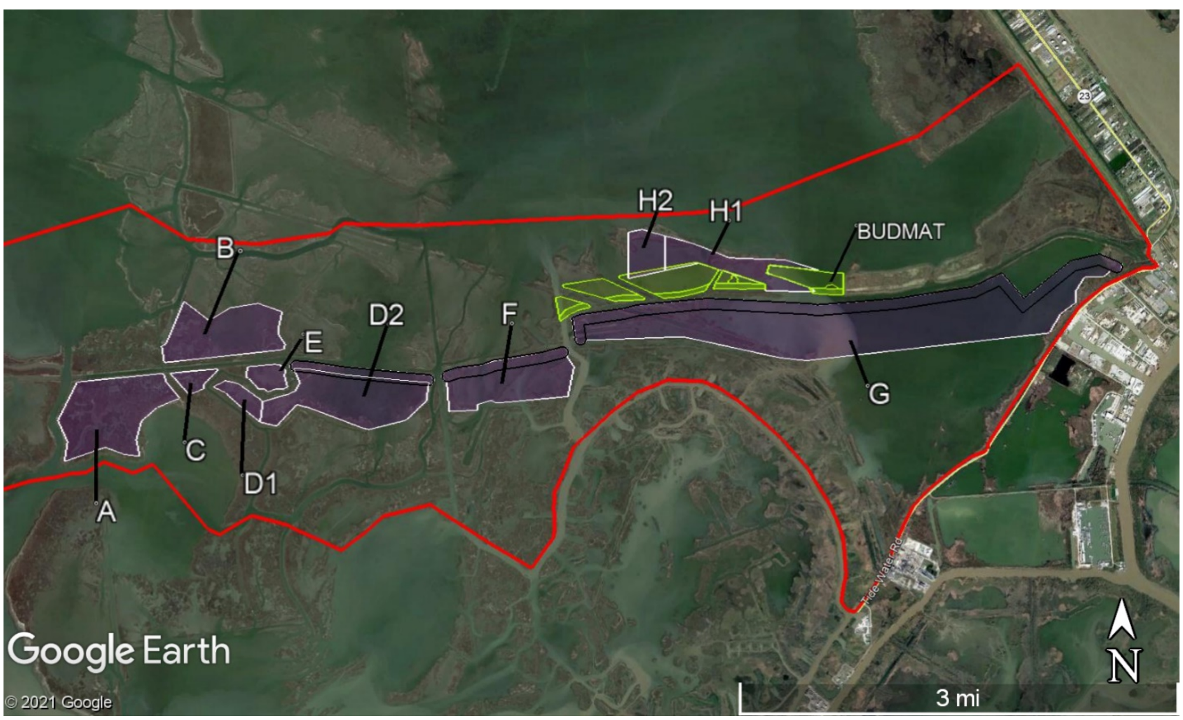

Figure 10. Final Project Layout.

Lastly, MCA B transitioned from the base bid into the first additive alternate. This decision was made due to uncertainty in industry dredge demand and associated dredge cost. The eastern and center MCA H cells were renamed H1 and the western MCA H cell was renamed H2. H1 and H2 were included as additive alternates 2 and 3. The base bid of the final design layout includes 1,358 acres of marsh habitat and 132 acres of ridge habitat. The additive alternates increase the marsh acreage by 325 acres, to 1,683 acres. In total, the BA-0203 project could create approximately 1,815 acres of land.

CONCLUSION

The project footprint has been designed to meet the project goals of creating or nourishing 1,134 acres of marsh and 120 acres of ridge habitat. The project footprint was developed by breaking the fill areas into 69 sub-areas, developing a cost and volume need for each sub-area, and then combining the sub-areas into a constructible project footprint. The base bid of the final design layout includes 1,358 acres of marsh habitat and 132 acres of ridge habitat. It is estimated that 9.75 MCY of sediment will be needed to construct the base bid project. The alternates add 325 acres of marsh and 1.95 MCY of sediment, bringing the total marsh acreage to 1,683. In total, the BA-0203 project could create approximately 1,815 acres of land. The project is currently in construction and the first additive alternate (MCA B) was awarded, increasing the base bid marsh acreage by 180 and the fill volume by 0.96 MCY.

Numerous borrow areas have been identified and screened for incorporation in the final design. Borrow areas B2, DDDD, and BBBB, are located in the Mississippi River. B2 is furthest borrow source and provides the least amount of sandy material amongst riverine borrow sources. DDDD is located closest to the fill area and is expected to provide the cheapest fill due to its proximity. DDDD contains approximately 17.04 MCY of sediment, which is sufficient to construct the base bid and additive alternates assuming a 1.5 cut to fill ratio. The BBBB borrow area contains the greatest fill volume of the three borrow areas at 20.25 MCY. A geotechnical and geophysical investigation show that the DDDD and BBBB borrow areas contain sandy sediment. Two borrow areas, Grand Liard East and Grand Liard West, are located in the Gulf of Mexico. Grand Liard East was dredged for the Grand Liard project. The borrow areas contain very soft clays with trace amounts of silt and sand. Together, the borrow areas contain almost 6.7 MCY of sediment though after considering cut to fill ratio and that much of the Grand Liard East sediment is unconsolidated, the effective volume may be closer to 3.3 MCY. These offshore sources were abandoned due to cost considerations.

The opinion of probable construction cost ranged from \$76M to \$91.05M depending on the inclusion of additive alternates. The original construction budget was \$115M. Additive options were included in the design to allow flexibility in bidding should the lowest construction bid fall within the available budget allowing for increased marsh acreage. Weeks Marine Inc. was the low bidder, offering a base bid construction price of \$80.8M. The inclusion of additive alternate one increased the total project cost to \$86.8M.

REFERENCES

Force, L. C. (1993). Louisiana Coastal Wetlands Restoration Plan. New Orleans.

Hartman, B., Thomson, G (2020) “BA-0203 Barataria Basin Ridge and Marsh Creation - Spanish Pass Increment” *Coastal Information Management System*, CPRA, Baton Rouge, USA

DATA AVAILABILITY

Data, models, or code generated or used during the study are available from the authors upon request.

CITATION

Hartman, B., Thomson, G., Miller, B., Gillen, D., Byland, T. (2020) "The Skinny On Fill Placement - Choosing Seven Fill Areas From Seventy And 45m C.Y. Of Borrow Amongst 200m," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21,* June 15-17, 2021.

HARVESTING OF BEDLOAD MATERIAL AND POTENTIAL APPLICATIONS FOR COASTAL RESTORATION

R.L. Tucker[1], A.J. Risko[2], T.L. Welp[3], Z.J. Tyler[4], N.J. Reins[5], and N.J. Kirk[6]

ABSTRACT

The concept of Regional Sediment Management (RSM) is an integrated approach to sediment management strategies that enables agencies, communities, academia, and consultants to work together in leveraging financial and technical resources for the purpose of developing and promoting systemwide solutions and specialized tools; to facilitate the application of natural and generated sediment supplies to protect, restore, and conserve water and coastal resources infrastructure and ecosystem habitats. Based on RSM's strategies, it is the goal to employ alternative tools to harvest and deliver sediments for water and coastal resources restoration projects, which are cost effective and innovative. An innovative sediment management technology, designated the Sediment Bedload Collector, has been developed that achieves sand harvesting by relying on natural physical processes to capture sediments by gravity as they are transported over the collector's embedded hopper. The sand harvesting system is a complimentary technology to dredging and excavating platforms that allows for targeted collection (or harvesting) of coarse-grained bedload in a non-disruptive, non-intrusive, and sustainable manner from within streams, rivers, coastal, and other dynamic aquatic environments. The Sediment Bedload Collector is a stainless-steel hopper set into the waterbody bottom that collects coarse-grained sediment as it is moved by hydrodynamic forces. As material is continuously extracted and is naturally replenished from the constant movement of bed material traversing the embedded hopper. A manifold system then pumps sediment slurry via a pipeline to a placement area or re-handling station. This paper describes how the Sediment Bedload Collector system works, how it has been applied in various environments, as well as how it was customized for each individual application, and how it is currently being explored in Louisiana for deployment for beneficial use of harvested materials and sediment removal respectively.

Keywords: Regional sediment management (RSM), sediment management technology, sediment bedload collector, sand harvesting system, coastal resources restoration

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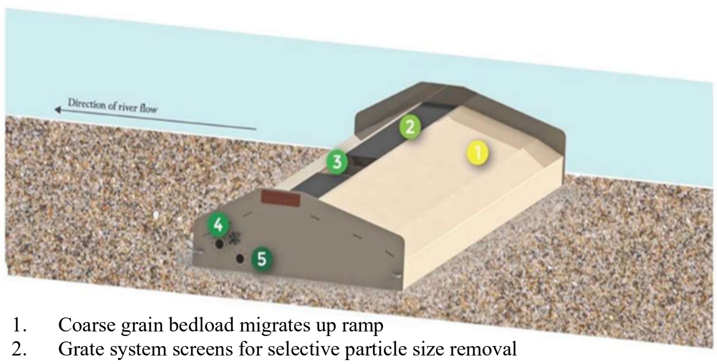
INTRODUCTION

The Sediment Bedload Collector (SBC) technology is an innovative and alternative sediment management tool, which has the capability to non-disruptively capture (harvest) naturally transported bedload sediment, and to subsequently convey and beneficially use the captured (harvested) sediments for coastal resources restoration projects.

The SBC uses the energy of streams and coastal longshore and cross-shore currents to selectively capture bedload sediment using simple physical principles. Coarse-grained sediment — fine sands to gravel — migrates as bedload, travels up the SBC's ramp, passes through the grate system and collects within hoppers (Figure 1). Finer sediments — silts and clays — as well as other organic matter remain in suspension and pass over the SBC. As the hoppers fill, the sediment is pumped to a placement or dewatering site for beneficial reclamation of harvested sediments (Figure 2).



1. Coarse grain bedload migrates up ramp
2. Grate system screens for selective particle size removal
3. Hopper retains the sediment until pumped
4. Harvest sediments are pumped as slurry to placement site

Figure 1. Operation of SBC Unit.

Figure 2. SBC Dewatering System.

The broader uses for the SBC include: 1) watershed management to intercept and harvest in-stream sediments to reduce sediment loading into lakes and reservoirs; 2) intercepting bedload sediment flow into ports, navigation channels, waterways, and floodways to reduce maintenance dredging needs; 3) harvesting riverine materials for beneficial use (commercial or environmental); 4) intercepting and harvesting sediment to protect downstream ecosystems, 5) intercepting contaminated sediment from mining and other activities before it negatively impacts downstream water quality; and, 6) harvesting sediments within the marine environment for beach or nearshore nourishment, coastal restoration, and beneficial use.

APPLICATIONS

Riverine Application

Application of the SBC system within the riverine environment was first demonstrated at Fountain Creek, Colorado, which provided the basis for evaluating the system's sediment bedload capture rate performance and its resiliency to storm-induced high-flow conditions within the creek. A subsequent deployment of the SBC system at Cuyahoga River, Ohio provided additional performance data parameters. Both operations are described below.

<u>Fountain Creek, Pueblo, Colorado</u>

In 2011, a 30-foot-long, high-capacity collector was installed at Fountain Creek, CO (Figures 3 & 4), for sediment management and flood risk reduction. The objectives of this project were to reduce sediment deposition, to lower the downstream grade, to reduce flooding and to commercially reuse the captured bedload sediments. The installed system consisted of six main parts: (1) 30 ft wide bedload collector, (2) 50 HP, submersible variable frequency drive

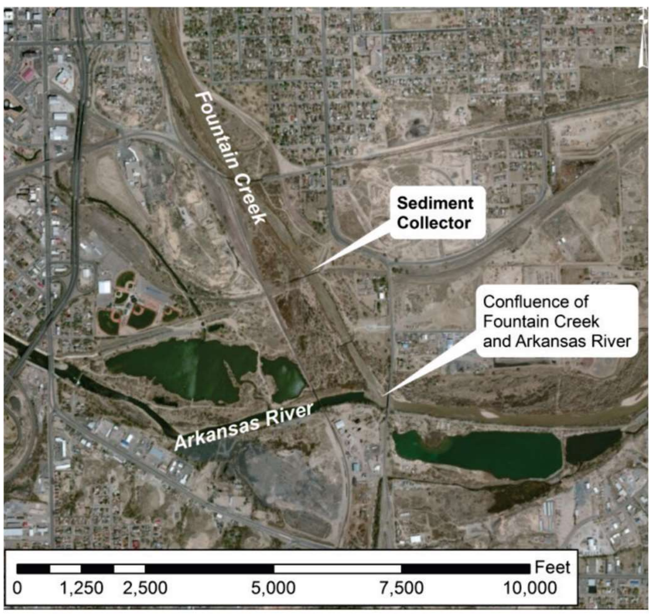


Figure 3. Location Fountain Creek Installation.

Figure 4. Collector Installation.

(VFD) pump, (3) electronic controls with internet access and remote interface, (4) 6-inch discharge and 8-inch water return DR 11 (160 pounds per square inch [psi]) high-density polyethylene (HDPE) pipelines, (5) sediment separator with 100 tons/hour (hr) capacity, and (6) a radial stacker capable of storing approximately 765 cubic meters (m^3) (1,000 cubic yards (yd^3)). The Fountain Creek operation was subsequently evaluated by the US Army Engineer Research and Development Center (ERDC) with findings published in a Dredging Operations Environmental Research (DOER) Technical Note (ERDC TN-DOER-T13) (USACE 2017). USACE 2017, concluded the installed system demonstrated the SBC: a) is able to effectively capture coarse bedload sediments in a shallow unidirectional flow environment, b) had minimal maintenance costs over a one (1) year operational duration, c) able to survive floodwater flows with minimal damage, d) capable of producing up to 76.5 m^3/hr (100 yd^3/hr) with a single 30-ft collector (as reported by the local operators), and e) can be cost-effectively deployed and operated.

Cuyahoga River, Cleveland, Ohio:

The Cleveland-Cuyahoga Port Authority aimed to reduce sediment influx into its port complex. A 30-ft collector unit was installed in the river to intercept sediment inflow into the downstream navigation channel (Figure 5). Collected sediments are sold as construction grade material.

Figure 5. Cuyahoga River Installation Site.

The Cuyahoga River installation occurred in July 2015, and in general consisted of one 30-ft SBC unit, a submersible discharge slurry pump mounted inside a land-based precast concrete vault wet-well pumping station, skid-mounted sand washer, and a radial stacker for stockpiling sand (Figure 6). The total cost for the Cuyahoga River installation was $1.2 million, and included the costs for engineering, acquisition, installation and a 2-year operation and maintenance period. Production rates have achieved up to 2.5 m^3/min (3.3 yd^3/min) (Tucker 2018) or approximately 153 m^3/hr (200 yd^3/hr).

Figure 6. Cuyahoga River Material Harvested.

Marine Application

Application of the SBC system within the multi-directional current marine environment has been through field-scale model studies at Galveston Island. Two field-scale model studies have been accomplished to date at Galveston Island, the first included the deployment of 2-ft and 4-ft scale model collector units over two seasons (summer and winter), and the second included the short-term deployment of a modified 8-ft scale model marine collector unit.

Galveston Island, Galveston, Texas

In 2017, through the U.S. Army Corps of Engineers (USACE) Planning Assistance to States (PAS) program, the USACE Galveston District and the City of Galveston Park Board of Trustees entered into an agreement to update the 2016 Sand Management Plan for Galveston Island (ERDC 2016), with the intent of evaluating sediment management techniques and tools as alternatives to offset the costs of nourishing beaches, which included evaluating a field-scale model of the SBC system to determine the feasibility of harvesting bedload sediments from within Galveston Island's surf zone and beneficially conveying the harvested sediments to the beaches.

A site evaluation field-scale model study was conducted during the summer and winter 2017 at three (3) sites along Galveston Beach (Figure 7) to investigate which location would provide the most suitable conditions for a possible full-scale installation and to validate the applicability of the SBC system within the marine/coastal environment.

Figure 7. Site Evaluation Pilot Study Locations and Scaled (2-ft & 4-ft) Collector Systems

The work was performed in collaboration with the newly established Coastal Science and Engineering Collaborative (CSEC) group, which is a group of engineering researchers and practitioners dedicated to the advancement of coastal resources science, with USACE Galveston District, ERDC, and Texas A&M University-Galveston serving as founding members.

The first deployment included the utilization of 2-ft and 4-ft field-scale model collector units (Figure 7) in varying orientations, at various geographic locations, and through two-sampling seasons, for the purpose of defining potential configurations to productively harvest sediments from within Galveston Island's surf zone. The riverine field-scale model collectors utilized during these sampling events highlighted which collector components needed refinement for an improved marine installation. For example, to optimize capture efficiency of marine collector units, it was concluded the grate width distance should be increased by a factor of 6.6 times in comparison to the riverine units, which was estimated to improve the capture efficiency of the hopper by a factor of 2.

Rough order extrapolation calculations, which included a ±25% uncertainty range, and an averaging between locations and variation between winter and summer installations, yielded an approximate harvesting rate of 16,820 m^3/year (22,000 yd^3/year), utilizing a single modified 20-ft SBC unit.

In 2019, an 8-ft modified field-scale marine model collector unit incorporating the geometric changes to the unit as recommended from the 2017 evaluation was deployed at East Beach, Galveston Island to capture and sample bedload transported sediments within the swash zone. The sampling period was limited to a 7-hour period. For this sampling duration, the 8-ft field-scale model collector yielded an average collection rate of 24.2 kg/min (53.3 lbs/min), which equates to 0.76 m^3/hr (1.0 yd^3/hr), of 0.15 mm average size sand. When extrapolated to a full-scale 20-ft marine collector unit, the production rate equated to approximately 17,202 m^3/year (22,500 yd^3/year) per unit. Although, this extrapolated production rate closely aligns within the range of the 2017 calculated estimates, given the short field sampling duration, the production rate estimates remain uncertain without additional sampling time series data sets.

EVALUATION PROCESS OF NEW SITES FOR COLLECTOR INSTALLATION

A phased approach is recommended when evaluating the viability of a full-scale bedload collector application and planning for its installation.

<u>Phase 1</u>. The Pilot Study phase involves deploying field-scale model collector units (between 2-ft to 8-ft) to gather sediment transport and potential sediment capture rate data at proposed locations. During this phase, collected data is analyzed to ascertain the potential physical suitability of the proposed locations for the installation and operation of a full-scale collector system. If extrapolated annual sediment capture production rates predict the application of the collector technology as suitable for the proposed sites, then the second phase can be initiated.

<u>Phase 2</u>. The Regulatory and Feasibility phase allows for determining the regulatory, permitting, and agency and stakeholder coordination requirements for a full-scale system installation. However, it should be noted that there may be instances where regulatory clearance is required prior to initiating field activities for the Pilot Study phase. In addition, during Phase 2, the life-cycle cost and benefits of a full-scale system is developed to ascertain the feasibility of a project as compared against existing sediment management practices. Preliminary designs and plans are developed during this phase to inform the permitting actions and the collector system feasibility analysis.

<u>Phase 3</u>. The Final Design phase entails the preparation final design documents and opinion of probable construction cost for a full-scale collector system. Final Design phase activities include the preparation of a final design report in conjunction with the final design level plans and specifications for installation. In addition, an operations and maintenance (O&M) manual for the full-scale system is prepared.

<u>Phase 4</u>. The Implementation and Operation phases consists of implementation of a full-scale collector system involving system components acquisition, components installation, system commissioning, post-installation operation, monitoring, and adaptive operations.

Example Performance Time Guidance for New Phased Projects

While every project has unique conditions and needs, for planning purposes Figure 8 provides an example schedule for a standard phased approach to execute the implementation of a new SBC system.

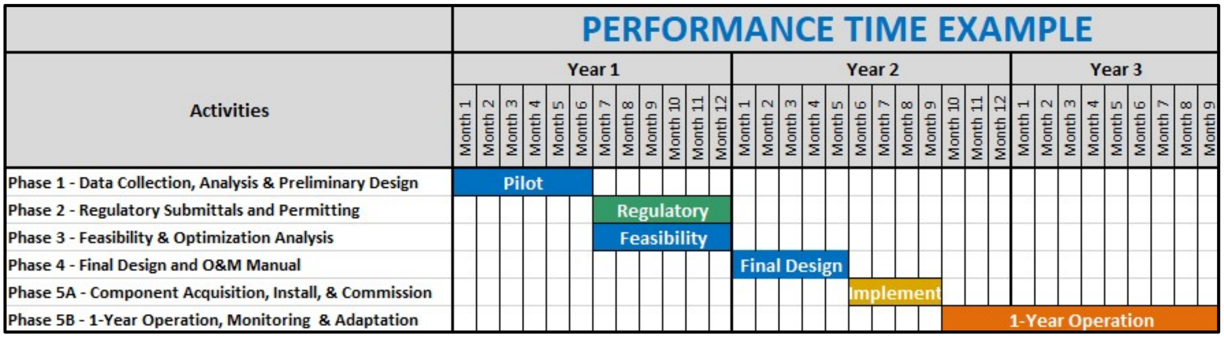


Figure 8. Schedule Example for Phased Approach

CONCLUSIONS

The Sediment Bedload Collector system is a new technology that operates on the principle that bedload sediment can be trapped by gravity and excavated at the natural rate of transport. This technology has been successfully used in riverine settings, where unidirectional water current is the primary sediment transport driver, and is now being evaluated in marine settings, where directionally variable waves and currents drive sediment transport processes.

A phased approach is recommended to validate the system suitability for a specific site and sedimentation condition, and to effectively guide the cost-benefit analysis, design and implementation of a full-scale deployment. The Sediment Bedload Collector system and its components should be individually designed for each new project based on location, site specific constraints and requirements, and beneficial sediment use opportunities.

REFERENCES

Engineer Research and Development Center (ERDC). 2016. "Galveston Island, Texas, Sand Management Strategies." *ERDC/Coastal Hydraulics Laboratory TR-16-13*, U.S. Army Corps of Engineer, Engineer Research & Development Center, Vicksburg, Mississippi. July.

ERDC 2017. "Sediment Management Methods to Reduce Dredging: Part 2, Sediment Collector Technology." *ERDC TN-DOER-T13*, U.S. Army Corps of Engineer, Engineer Research & Development Center, Vicksburg, Mississippi. April.

Paine, J.G., Caudle, T., and J. Andrews. 2014. "Shoreline Movement along the Texas Gulf Coast, 1930's to 2012." Bureau of Economic Geology, Austin, Texas. August.

Tucker, R. L., Trevino, R.A., Welp, T.L., Maglio, C.K., Risko, T.J., Tyler, T.J., Moya, J., Weber, C.K., Figlus, J., Fuller, W.P., and Thomas, R.C. 2018. "Evolution of an Innovative Dredging Technology for Harvesting Coarse-grained Sediment," *Proceedings of the Western Dredging Association Dredging Summit & Expo '18, Norfolk, VA,* USA, June 25-28, 2018.

CITATION

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DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

ACKNOWLEDGEMENTS

We wish to acknowledge the US Army Corps of Engineers Galveston District, the US Army Engineer Research and Development Center (ERDC), The Park Board of Trustees of the City of Galveston, Texas General Land Office, and Texas A&M University at Galveston for varying contributions to the content of this paper.

ROCK PLACEMENT AND STABILITY FOR OFFSHORE WINDMILL FOUNDATION

S.A. Miedema[1]

ABSTRACT

The foundation of offshore windmills, often monopiles, has to be protected from scour, so pieces of rock or stones are dumped around the monopile. When dumped, these stones penetrate into the soil, resulting in a certain penetration depth. This requires more stones to be dumped than theoretically required.

The paper will focus on two topics. The stability of the rock once on the seafloor, regarding currents and orbital velocities and rock placement and the penetration of the rock in the sea floor. The first topic determines the minimum size of the pieces of rock/stones in the armor layer in order not to be eroded, while the second topic determines the additional volume of rock pieces (stones) due to penetration in the seafloor. For both topics models are presented.

Keywords: Renewable energy, Rock dumping.

INTRODUCTION

The last decade a large transition has occurred in the world energy exploration and exploitation. The decade started with mainly fossil fuels and now the whole world is focussing on renewable energy. Renewable energy in fact is everything that is sustainable. So, one can think of OTEC (Offshore Thermal Energy Conversion), based on energy differences in the oceans in tropical areas. Wave energy, (tidal) current energy, salinity gradient and biomass. Last but not least we have wind energy. The energy transition also changed the fields of interest of dredging companies. Most types of offshore renewable energy require long electricity cables to shore and these cables must be buried. So trenching is needed. If constructions have foundations in the seabed, these foundations must be protected, usually with rock placement through fall pipes. The dredging companies are also specialised in these activities and in offshore wind installation.

To install offshore wind turbines safely, one must take care that around the support structure (the monopile) no scour can occur. Scour is the result of currents, turbulence, eddies, and waves as they act on the soil around the support structure, see Figure 1, Figure 2 and Figure 3. Although there are different possibilities for the support structures, here monopiles are considered, see Figure 4. To protect the monopile from scour around it, pieces of rock are placed on the soil, large enough to withstand the scour forces. This can be done with an armor layer or with first a filter layer, to prevent the original sand to be washed away, with on top an armor layer, see Figure 5. Here the latter will be considered, so first a filter layer and secondly an armor layer.

There is already a lot of experience with this type of monopile scour protection. Five projects are considered here, and the data is mentioned in Table 1. The 5 projects are located at the coast of the United Kingdom,

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the Netherlands, Denmark, the Netherlands and Ireland. The data originates from Dolores Esteban et al. (2019, 7, 440).

This paper gives a lot more data on the wind farms considered. The data give enough information to determine the size of the armor layer rock pieces, the velocity of the rock leaving the fall pipe and the additional amount of filter layer rock penetrating the sea floor. This way the most important design parameters are covered and an impression of the orders of magnitude of the design parameters is given.

Table 1. Foundation, scour protection and metocean characteristics.

Characteristics	Arklow Bank	Egmond aan Zee	Horns Rev	Princess Amalia	Scroby Sands
Mean sea level (m)	8	20	14	24	12
Foundation diameter (m)	5.0	4.6	4.2	4.0	4.2
Driving length of pile	35	30	34	30	30
Soil type	Sand	Sand	Sand	Sand	Sand
Soil d_{50} (mm)	0.20	0.20	0.15	0.45	0.40
Filter d_{50} (m)	0.05	0.05	0.20	0.17	0.15
Filter thickness (m)	0.60	0.40	1.00	0.90	1.00
Filter layer diameter (m)	45	53	44	52	54
Armor d_{50} (m)	0.42	0.40	0.55	0.50	0..45
Armor thickness (m)	1.20	1.80	1.80	1.50	1.300
Armor layer diameter (m)	35	41	34	40	34
Significant wave height (m)	5.6	3.6	5.2	7.7	3.2
Wave peak period (s)	9	8	6.3	9.7	8.1
Current velocity (m/s)	2.0	0.6	1.2	1.3	1.7
Orbital velocity bottom (m/s)	2.7	0.7	1.2	1.6	1.1
Relative roughness (-)	0.05	0.02	0.04	0.02	0.04

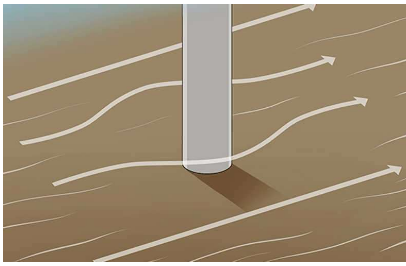

Figure 1. No scour.

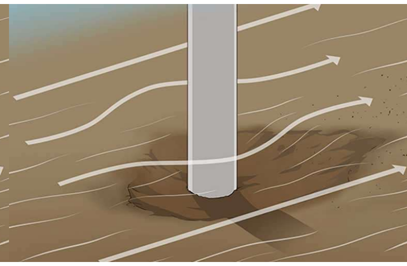

Figure 2. Scour.

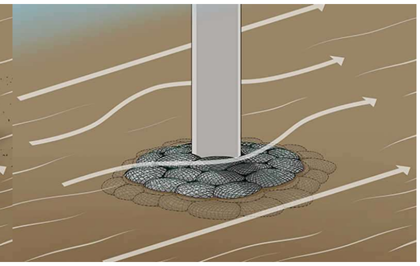

Figure 3. Scour protection.

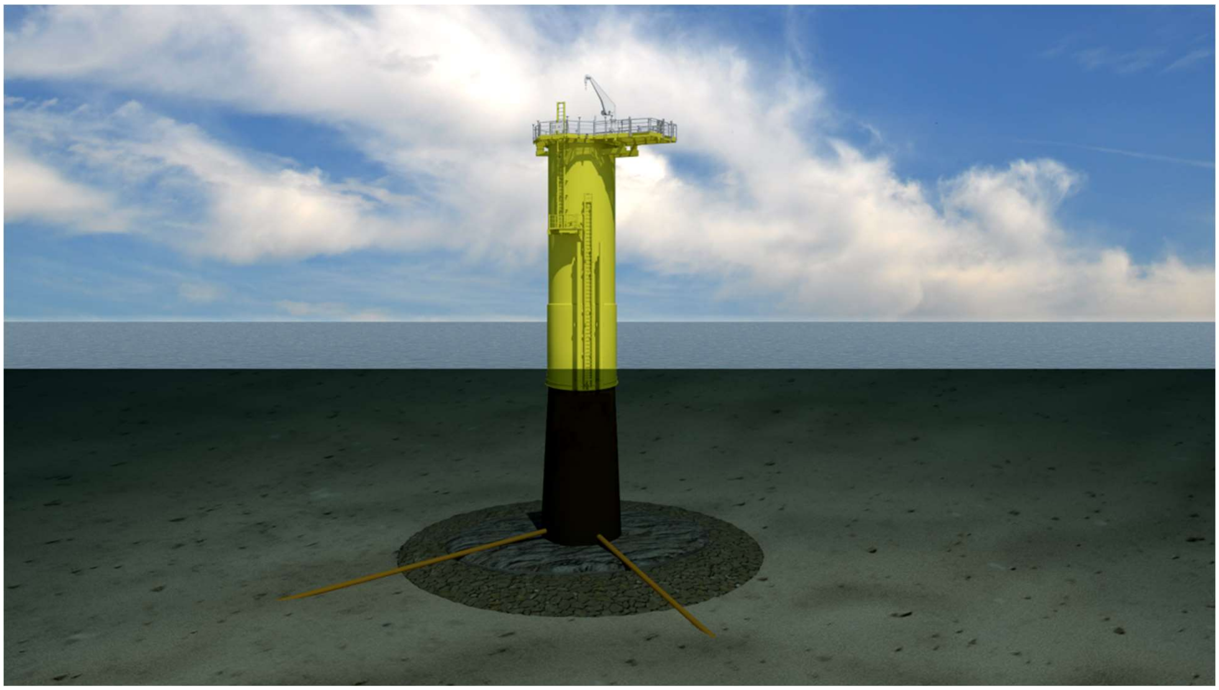

Figure 4. A monopile with scour protection.

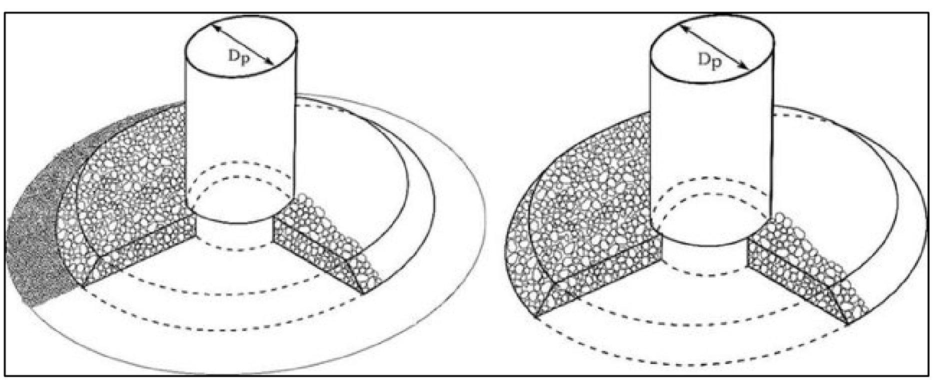

Figure 5. Filter and armor layer or armor layer only.

INITIATION OF MOTION

The first step in designing the protection of the seabed around monopiles is the determination of the size of the pieces of rock in the armor layer. Since the rock is assumed to be dumped by a rock dumping vessel through a pipeline, the rock will penetrate the soil. The larger the rock pieces the deeper the penetration, resulting in higher cost. Also, to avoid washing out of the seabed sand between the armor rock pieces, first a filter layer with smaller rock pieces is placed, with an intermediate size. For determining the size of the pieces of rock in the armor layer, the Shields approach is used. For large pieces in a turbulent flow, initiation of motion will occur at a critical Shields number of 0.056. Miedema (2012A), (2012B), (2013) and (2010D) derived an analytical approach for determining the so called Shields curve for sand/gravel, silt and clay. It is important to understand that the location of the critical Shields curve depends on the protrusion/exposure level of the particles. The well-known Shields curve matches the model derived for an exposure level of $0.5 \cdot d$ and a protrusion level of $0.3 \cdot d$, assuming the flow starts $0.2 \cdot d$ below the top of the particles. Also, a water worked surface is assumed, meaning that particles having a larger protrusion level after being dumped than the $0.3 \cdot d$, are moved over the bed into holes in the bed, resulting in smaller protrusion levels. The latter may take a short while. Under the conditions described here, the value of 0.056 to 0.06 is valid for sliding initiation of motion. Rolling requires a slightly higher Shields number. These values are derived for spherical quarts particles. For real sand and gravel particles the value is about 0.03 due to the larger drag coefficient and the effective lower submerged weight because of the angular shape of the particles, see Miedema (2012B). The Shields parameter is defined as:

$$\theta = \frac{u_*^2}{R_{sd} \cdot g \cdot d} \tag{1}$$

The relative submerged density is:

$$R_{sd} = \frac{\rho_q - \rho_l}{\rho_l} \tag{2}$$

Finally, the friction velocity is defined as:

$$u_* = \sqrt{\frac{\tau_b}{\rho_w}} \tag{3}$$

Where τ_b is the bed shear stress, which is equal to:

$$\tau_b = \sqrt{\frac{\lambda_b}{8}} \cdot v_b \tag{4}$$

In order to be able to determine the Shields number or reversely the rock piece diameter, the bed friction factor must be known. Over the whole range of Reynolds numbers above 2320 the Swamee Jain (1976) equation gives a good approximation:

$$\lambda_b = \frac{1.325}{\left(\ln\left(\frac{\varepsilon}{3.7 \cdot D_p} + \frac{5.75}{Re^{0.9}}\right)\right)^2} = \frac{0.25}{\left(\log_{10}\left(\frac{\varepsilon}{3.7 \cdot D_p} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \tag{5}$$

Instead of the pipe diameter D_p, the hydraulic diameter should be used which is roughly 4 times the water depth. Because of the high Reynolds numbers, the second term in the logarithm can be neglected. The original equation used the 10 logarithm, the modern equation the natural logarithm. So basically, the bed friction factor depends on the ratio of the size of the rock pieces ε to the water depth, the relative roughness. The relative roughness's of the 5 projects considered is between 0.02 and 0.05. This gives bed friction factors from 0.05 to 0.07, on average 0.06, see Miedema (2019). The "diameter" of the armor layer rock pieces (stones) can now be determined by:

$$d = \frac{\frac{\lambda_b}{8} \cdot v_b^2}{R_{sd} \cdot g \cdot \theta} = \frac{\frac{0.06}{8} \cdot v_b^2}{1.65 \cdot 9.81 \cdot 0.056} = 0.0083 \cdot v_b^2 \tag{6}$$

For the effective current velocity, one should take at least the sum of the real current velocity and the orbital velocity (the velocity due to circular movement of the water due to waves). Since the flow is turbulent with Reynolds numbers in the order of magnitude of 10 million, the momentary velocities can be a factor 2.3 higher. Since damage is an accumulation of individual stones being removed. Another approach is to use the Shields number for real sands and gravels of about 0.03 and multiply the effective current velocity with a factor of 1.15. Both approaches give the same result. Table 2 gives the resulting stone diameters.

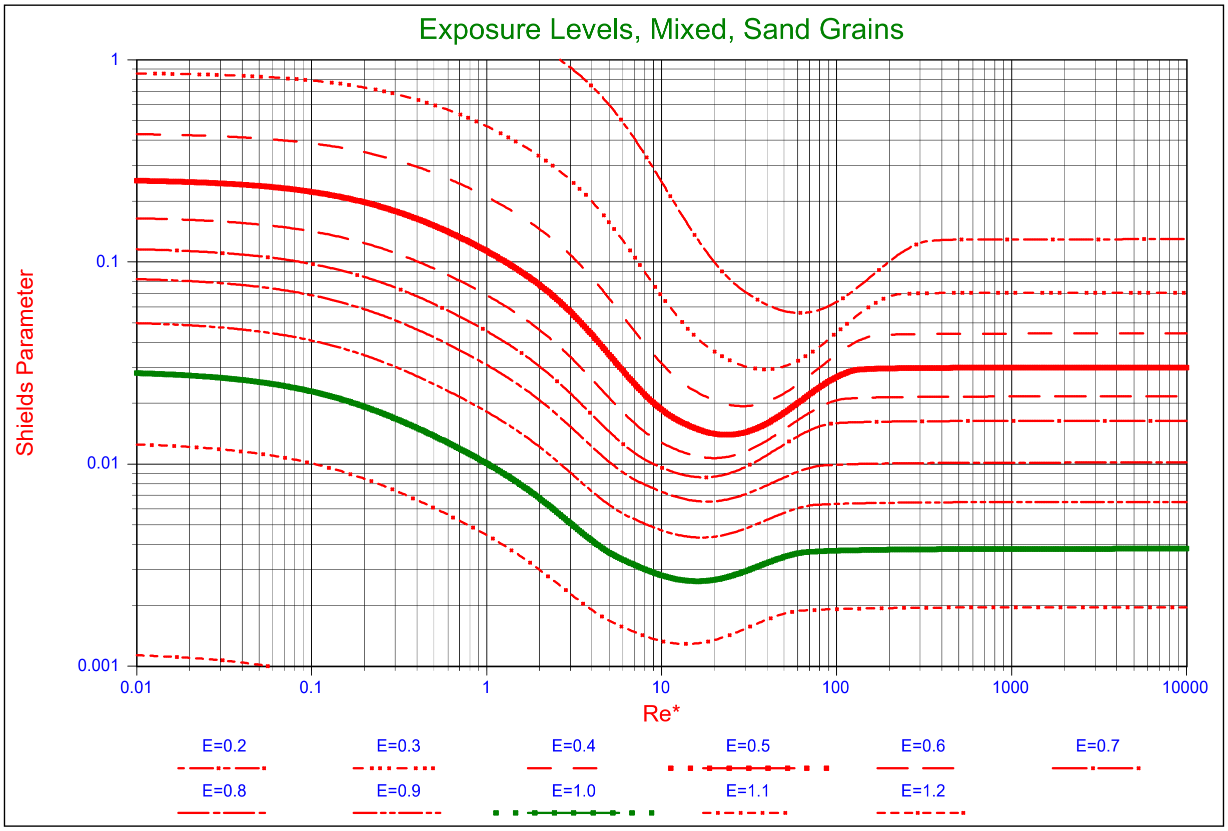

Figure 6. The Shields curves for sands and gravels at different exposure levels.

Analyzing the Shields curve, Miedema (2019), shows that the curve in literature is for spheres and an exposure level of 0.5. The model with which this is simulated already contains momentary velocity fluctuations as a result of turbulence. So, using a factor 2.3 takes this effect into account two times, which is incorrect. Scientifically it is purer to use the Shields curve for sands and gravels (higher drag coefficient and lower submerged weight) and an exposure level of 0.5-0.6. This gives Shields number values of 0.022-0.030 for large Reynolds numbers. In this case, no factor is required to determine the size of the stones dumped. Just the Shields number for large Reynolds numbers is sufficient.

Table 2. Stone size versus the flow velocity.

v_b (m/s)	d (m)
1	0.044
2	0.176
3	0.395
4	0.703
5	1.098
6	1.580

THE KINETIC ENERGY OF THE STONES

Now that the size of the stones (pieces of rock) in the armor layer can be determined, the velocity of these stones hitting (colliding with) the seafloor can be calculated. This velocity is required to determine the kinetic energy of the stones. Once the kinetic energy is known, it is assumed that this kinetic energy equals the work carried out by the stone penetrating the soil. Of course, if a filter layer is applied, the penetration into the soil should be determined based on the diameter of the filter layer stones. One should consider that stones penetrating the soil results in soil either moving upwards or sideways. The volume of the stones must go somewhere. Here it is assumed that the soil pushed upwards will occupy the pores in between the stones.

The fall pipe is assumed to consist of steel and synthetic buckets, a telescopic pipe and an ROV at the end. This is normal for deep waters. For rock dumping around monopiles most probably only the buckets are required. Figure 7 shows a bucket-based fall pipe of van Oord. The advantage of this type of fall pipe is, that the velocity in the pipe is small compared to a normal straight pipe, giving less kinetic energy to the stones. Less kinetic energy results in less penetration and thus a smaller amount of stones to be dumped. One can also reduce the total amount of stones by using smaller filter layer stones giving less penetration.

The velocity in the pipe can be determined by taking the equilibrium of the gravity and the resistance forces. The submerged gravity force is just the weight of the mixture in a piece of pipe, or in this case the weight of the mixture in one bucket. The resistance comprises of the Darcy-Weisbach resistance and the so-called Carnot resistance. The additional Carnot resistance results from the fact that buckets have a change in diameter, so straight pipes do not have this resistance. The Darcy-Weisbach resistance is calculated with, for very low concentrations:

$$\Delta p_{DW} = \lambda_{DW} \cdot \frac{L_b}{D_{mb}} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2 \qquad (7)$$

The Darcy Weisbach friction coefficient can be determined with equation (**5**). Where the mean bucket diameter is taken and the mean velocity in the pipe or bucket. In case of a straight pipe without buckets, the mean is just the velocity. The Carnot resistance term can be determined by:

$$\Delta p_C = \left(1 - \frac{A_{min}}{A_{max}}\right)^2 \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2 \qquad (8)$$

Figure 7. A bucket-based fall pipe (copyright van Oord).

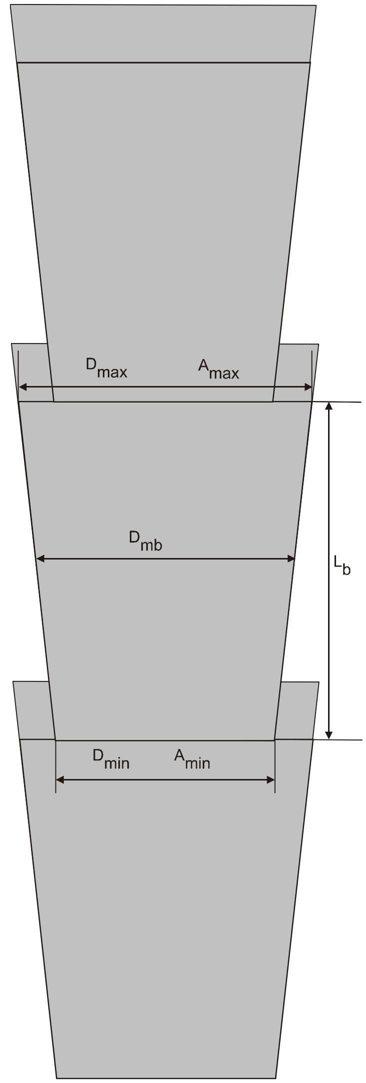

Figure 8. The bucket dimensions.

$$\Delta p_C = \lambda_C \cdot \frac{L_b}{D_{mb}} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2$$

$$\lambda_C = \left(1 - \frac{A_{min}}{A_{max}}\right)^2 \cdot \frac{D_{mb}}{L_b} \tag{9}$$

In these equations it is assumed that the buckets have a maximum diameter and cross section at the top and a minimum diameter and cross section at the bottom. The derivation of the Carnot friction factor is based on the Law of Bernoulli. This gives for the total resistance:

$$\Delta p_{tot} = (\lambda_{DW} + \lambda_C) \cdot \frac{L_b}{D_{mb}} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2 \tag{10}$$

If the maximum and minimum diameters of the buckets do not differ to much, the mean diameter is the average of the maximum and minimum diameter. The gravity pressure equals to:

$$\Delta p_g = (\rho_m - \rho_l) \cdot g \cdot L_b \tag{11}$$

So, the mean velocity in the fall pipe can be determined by solving the equilibrium equation:

$$\Delta p_g = \Delta p_{tot}$$

$$(\rho_m - \rho_l) \cdot g \cdot L_b = (\lambda_{DW} + \lambda_C) \cdot \frac{L_b}{D_{mb}} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2 \tag{12}$$

$$v_{mm} = \sqrt{\frac{(\rho_m - \rho_l)}{\rho_l} \cdot \frac{2 \cdot g \cdot D_{mb}}{(\lambda_{DW} + \lambda_C)}}$$

In case there is a fixed mass flow of stones entering the fall pipe, the mixture density must be determined by iteration, since in this case the mixture density depends on the flow velocity and the flow velocity depends on the mixture density, creating an implicit set of equations. The detailed derivation of the mean velocity in the fall pipe can be found in Beemsterboer (2013). The liquid velocity of the mixture exiting the fall pipe must be corrected for the fact that the exit diameter and the mean diameter are not equal, so:

$$v_{exit} = v_{mean} \cdot \left(\frac{D_{mb}}{D_{min}} \right)^2 \tag{13}$$

The stones move faster that the liquid. The difference is the terminal settling velocity of the stones. This terminal setting velocity can be determined by:

$$v_t = \frac{10 \cdot \nu_l}{d} \cdot \left(\sqrt{1 + \frac{R_{sd} \cdot g \cdot d^3}{100 \cdot \nu_l^2}} - 1 \right) \tag{14}$$

$$v_{th} = v_t \cdot (1 - C_{vs})^{2.4} \cdot e^{-\frac{d}{D_{mb}}}$$

This Zanke equation can be found in Miedema (2019) and gives a good approach of the terminal settling velocity for real sands and gravels. Because of the volumetric spatial concentration C_{vs}, the stones hinder each other, resulting in a smaller terminal hindered settling velocity, see Richardson & Zaki (1954). Although there is a downward flow, for hindered settling its all about the relative velocity between the carrier liquid and the stones. The stones move faster than the cross-sectional averaged line speed, while the carrier liquid moves slower. However, with the very low concentrations during rock dumping, the effect of hindered settling will be small. If the particles are large with respect to the mean bucket diameter, an additional reduction must be applied, see equation (14). The exit velocity of the liquid (water) may be reduced by divergence of the jet flow leaving the "nozzle" of the fall pipe and depends on the distance between this "nozzle" and the sea floor. If this distance, the standoff distance (SOD), is less than 6.3 times the minimum bucket diameter, the exit velocity is assumed to be the vertical liquid velocity at the seafloor.

If the SOD is larger than 6.3 times the minimum bucket or nozzle diameter, the liquid velocity at the seafloor must be corrected by:

$$\text{if } SOD<6.3\cdot D_{min} \text{ then } v_{sf}=v_{exit}$$
$$\text{if } SOD>6.3\cdot D_{min} \text{ then } v_{sf}=\frac{6.3\cdot D_{min}}{SOD}\cdot v_{exit} \tag{15}$$

The velocity of the stones at impact with the seafloor is now:

$$v_{stone}=v_{sf}+v_{th} \tag{16}$$

The kinetic energy can now be determined by:

$$E_{kin}=\frac{1}{2}\cdot m\cdot v_{stone}^2=\frac{1}{2}\cdot\rho_q\cdot\frac{\pi}{6}\cdot d^3\cdot v_{stone}^2 \tag{17}$$

Since the stones are not spherical, some shape factor should be applied for the weight reduction of the stones in the kinetic energy equation. This was not necessary for the terminal settling velocity equation, since this equation has been derived for real sands and gravels, so the shape is considered there.

Again, it should be mentioned that in case of a straight pipeline, the minimum and maximum bucket diameters should be taken equal, resulting in a Carnot friction factor equal to zero. So, this method works well for both straight pipe-based fall pipes and bucket-based fall pipes.

THE WORK CARRIED OUT IN THE SOIL

In order to determine the penetration depth D_p, there are at least two concepts. The first concept makes use of the equilibrium equation of motion of the stone. This concept is executed in the time domain. Each time step the difference between the gravitational force and the resisting force on the stone results in a deceleration, so the vertical downwards velocity of the stone decreases. This is repeated for several time steps until the vertical velocity of the stone equals zero within a certain accuracy. This approach has been applied by Beemsterboer (2013). The second concept is based on the assumption that the resisting force does not or hardly depends on the penetration depth of a stone. In this case, the resisting force is a constant and the work carried out by the soil on the stone is a constant resistance force times the penetration depth. Since the kinetic energy of a stone just before hitting the soil and the work carried out by the soil are equal, the penetration depth equals the kinetic energy before hitting the soil divided by the constant resisting force. This results in an explicit solution and does not require iterations or time domain simulations. Even if there is a minor dependency of the resisting force on the depth, this concept is useable.

The kinetic energy can be determined with equation (17), while the resisting force can be determined with one of the following equations of Terzaghi (1943) and (1964):

$$\text{Strip footing: } F_{BC}=A_{stone}\cdot\left(c\cdot N_c+\gamma\cdot p_d\cdot N_q+0.5\cdot\gamma\cdot W\cdot N_\gamma\right)$$
$$\text{Square footing: } F_{BC}=A_{stone}\cdot\left(1.3\cdot c\cdot N_c+\gamma\cdot p_d\cdot N_q+0.4\cdot\gamma\cdot W\cdot N_\gamma\right) \tag{18}$$
$$\text{Circular footing: } F_{BC}=A_{stone}\cdot\left(1.3\cdot c\cdot N_c+\gamma\cdot p_d\cdot N_q+0.3\cdot\gamma\cdot W\cdot N_\gamma\right)$$

A stone is not a strip, but also not exactly a square or a circle. The best way to use this is to calibrate this equation based on experiments, which Beemsterboer (2013) carried out, this gives.

$$\text{Stone footing: } F_{BC} = A_{stone} \cdot \left(1.2 \cdot c \cdot N_c + \gamma \cdot p_d \cdot N_q + 0.4 \cdot \gamma \cdot W \cdot N_\gamma\right) \quad (19)$$

The coefficients N_q, N_c and N_γ are determined by the following equations:

$$N_q = \frac{\left(e^{(3\cdot\pi/4-\varphi/2)\cdot\tan(\varphi)}\right)^2}{2\cdot\cos^2\left(\pi/4+\varphi/2\right)} \quad (20)$$

$$N_c = \frac{\left(N_q - 1\right)}{\tan(\varphi)} \quad (21)$$

$$N_\gamma = 1.5 \cdot \left(N_q - 1\right) \cdot \tan(\varphi) \quad (22)$$

Table 3. Terzaghi's bearing capacity factors.

φ	N_c	N_q	N_γ
0	5.7	1	0
5	7.3	1.6	0.5
10	9.6	2.7	1.2
15	12.9	4.4	2.5
20	17.7	7.4	5
25	25.1	12.7	9.7
30	37.2	22.5	19.7
35	57.8	41.4	42.4
40	95.7	81.3	100.4
45	172.3	173.3	297.5
48	258.3	287.9	780.1

Table 3 shows the values of the Terzaghi bearing capacity factors. Lambe & Whitman (1969) and (1979) give an overview of the modifications of the Terzaghi equations in literature.

The penetration depth of a single stone can now be determined by dividing the kinetic energy by the sum of the bearing capacity force and the submerged weight of the stone:

$$p_d = \frac{E_{kin}}{F_{BC} + F_g - F_b} \quad (23)$$

Of course, when dumping rock, there is not just a single stone, but after the first stone there is a second stone and a third stone and so on. The next stones will transfer their kinetic energy into work of the soil resulting in more penetration. The penetration of the next stones however is less than the first stone and after about 5 stones on top of each other there is hardly any additional penetration anymore. Beemsterboer (2013) assumes that the collision of a next stone with the previous stone(s) is plastic, meaning conservation of momentum, but not conservation of energy. Conservation of momentum means that before the collision the single stone has a momentum of mass times velocity and after the collision two times the mass times half the velocity. The kinetic energy of two stones after collision is thus half the kinetic energy of a single stone, resulting in half the penetration. For the third stone this gives one third of the penetration of a single stone and so on. Applying this methodology still results in a significant additional penetration if more than 5 layers of stones are used, while experiments show this is not the case. Apparently, the collision of a next stone is also not purely plastic, but the momentum is also reduced. Assuming the resulting momentum of the second stone is half the momentum of a single stone and the third stone has a resulting momentum of one third and so on, gives good results compared to the experiments of Beemsterboer (2013). This gives:

$$\text{Momentum } n^{th} \text{ stone} = n \cdot m \cdot \frac{v_{stone}}{n^2}$$

$$p_{d,n} = \frac{p_{d,1}}{n^2} \tag{24}$$

For the total penetration, the penetrations of the subsequent stones have to be added up. Visser and van der Meer (2008) still added an additional term for the penetration due to short term consolidation. The equation they use is derived in Beemsterboer (2013), however this is only valid for clay and not for sand. The projects considered here are all for a sandy sea floor. So, this last equation is not considered here.

If the dimensions of the filter layer and the armor layer are known, the volumes of filter rock and armor rock, including the initial penetration can be determined. Table 4 gives all the inputs of such a calculation, while Table 5 gives all the outputs. This example of a calculation in sand, shows that the additional volume due to the penetration for the filter layer is significant. The additional volume for the armor stones due to penetration is negligible.

CONCLUSIONS

For the determination of the size of the stones in the armor layer, the Shields approach has been applied. However instead of using the standard Shields graph with a critical Shields value of about 0.056 for large Reynolds numbers (large stones), the Shields graph for real sands and gravels is used. The standard Shields graph is based on spherical particles and an exposure level of 0.5. The real sands and gravels graph is based on particles with a drag coefficient of about 1.5 instead of 0.4 for spheres, and an exposure level of about 0.55 instead of 0.5. Using this graph does not require any safety factors.

For the filter layer, stones with a size not too large should be chosen to avoid, washing away of the sand at the seafloor by flow through the pores. A smaller size also reduces the penetration and thus the additional amount of filter layer stones. In clay this is less critical.

Since during rock dumping the stones leave the fall pipe with a certain velocity, they will penetrate the soil, requiring an extra volume of stones to meet the demands. This penetration can be determined based on the conservation of energy and momentum. For the first stone penetrating the soil it is assumed that the work carried out by the soil on the stone, equals the kinetic energy of the stone just before impact. For the next stones it is assumed that there is a plastic collision where part of the momentum is conserved, but not all. For the resisting soil force the Terzaghi equations are applied. There are many modifications of the Terzaghi bearing force equations, but here the original ones are used. The penetrations calculated this way are validated with experiments of Beemsterboer (2013) and match well.

All in all, the methodology described here gives a good estimation of the stone size to avoid scour and a good estimation of the amounts of rock required for a specific case of monopile installation. The models can easily be modified and extended, however it is the question how much this will change the outcome.

Table 4. Inputs for the volumes of stones.

Carrier liquid parameters		
Density carrier liquid	1.025	t/m^3
Viscosity carrier liquid	1.300	$*10^{-6}\ m^2/s$
Rock Parameters		
Density of the rock	2.680	t/m^3
d_{50} of rock in filter layer	0.100	m
d_{15} of rock in filter layer	0.040	m
Accuracy of rock in filter layer	0.050	m
d50 of rock in armour layer	0.200	m
Accuracy of rock in armour layer	0.100	m
Mass flow of rock	1250.000	t/h
Porosity of rock	0.400	-
Fraction fines of rock	0.100	-
Pipe Parameters		
Length of pipe	400.000	m
Stand Off Distance (SOD)	10.000	m
Minimum bucket diameter	0.850	m
Maximum bucket diameter	1.100	m
Total length bucket	2.225	m
Effective length bucket	1.512	m
Wall roughness bucket	2.000	mm
Soil mechanical parameters		
Sea floor soil cohesion	0.000	kPa
Sea floor soil internal friction angle	30.000	deg
Sea floor soil density	2.000	t/m^3
Layer dimensions		
Monopile diameter	8.500	m
Filter layer diameter	37.300	m
Filter layer thickness	0.500	m
Amour layer diameter	26.700	m
Armour layer thickness	0.900	m

Table 5. Outputs giving the volumes of stones.

bucket output		
Effective maximum bucket diameter	1.020	m
Effective average bucket diameter	0.935	m
Labda bucket wall roughness	0.024	-
Labda bucket Carnot	0.058	-
Rock Concentration	0.046	-
Mixture density	1.101	t/m^3
Velocities jet stream/particles		
bucket line speed out	4.950	m/s
Terminal Settling Velocity	1.258	m/s
Terminal Hindered Settling Velocity	0.995	m/s
Mass flow velocity	5.945	m/s
Velocity at impact seafloor	3.646	m/s
Penetration seafloor		
Penetration depth single particle	0.197	m
Duration impact single particle	0.054	sec
Penetration depth second layer	0.246	m
Penetration depth third layer	0.268	m
Penetration depth fourth layer	0.280	m
Penetration depth fifth layer	0.288	m
Volumes		
Filter layer volume	602.009	m^3
Initial penetration depth filter layer	0.301	m
Added penetration depth filter layer	0.000	m
Total penetration depth filter layer	0.301	m
Penetration volume filter layer	329.069	m^3
Armour layer volume	578.650	m^3
Final penetration depth armour layer	0.012	m
Penetration volume armour layer	6.877	m^3
Total volume filter layer	931.078	m^3
Total volume armour layer	585.527	m^3
Weight of the rock		
Weight of the filter layer	1497.174	ton
Weight of the armour layer	941.528	ton
Total weight of rock	2438.702	ton
Weight of the filter layer incl. fines	1663.527	ton
Weight of the armour layer incl. fines	1046.142	ton
Total weight of rock incl. fines	2709.669	ton

REFERENCES

Beemsterboer, T. N. (2013). *Modelling the immediate penetration of rock particles in soft clay during subsea rock installation, using a flexible fallpipe vessel.* Delft, the Netherlands: Delft University of Technology.

Dolores Esteban, M., Santos Lopez Gutierrez, J., Negro, V., & Sanz, L. (2019, 7, 440). Riprap scour protection for monopiles in offshore wind farms. *Journal of Marine Science and Engineering*, 18.

Lambe, T., & Whitman, R. (1969). *Soil Mechanics.* John Wiley & Sons.

Lambe, T., & Whitman, R. (1979). *Soil mechanics, SI version.* New York: John Wiley & Sons.

Miedema, S. A. (2010D). Constructing the Shields Curve: Part D Cohesion by Clay. *Journal of Dredging Engineering*.

Miedema, S. A. (2012A). Constructing the Shields Curve: Part A Fundamentals of the Sliding, Rolling and Lifting Mechanisms for the Entrainment of Particles. *Journal of Dredging Engineering, Vol. 12.*, 1-49.

Miedema, S. A. (2012B). Constructing the Shields Curve: Part B Sensitivity Analysis, Exposure & Protrusion Levels, Settling Velocity, Shear Stress & Friction Velocity, Erosion Flux and Laminar Main Flow. *Journal of Dredging Engineering, Vol. 12.*, 50-92.

Miedema, S. A. (2013). Constructing the Shields Curve: Part C Cohesion by Silt, Hjulstrom, Sundborg. *OMAE* (p. 22). Nantes: ASME.

Miedema, S. A. (2019). *Dredging Engineering Special Topics.* Delft: Delft University of Technology Open Text Books.

Miedema, S. A. (2019). *The Delft Head Loss & Limit Deposit Velocity Framework.* Delft: Delft University of Technology Open Text Books.

Richardson, J. F., & Zaki, W. N. (1954). Sedimentation & Fluidization: Part I. *Transactions of the Institution of Chemical Engineering 32*, 35-53.

Swamee, S. E., & Jain, K. A. (1976). Explicit equations for pipe-flow problems. *Journal of the Hydraulics Division (ASCE) 102 (5).*, 657-664.

Terzaghi, K. (1943). *Theoretical soil mechanics.* New York: John Wiley & Sons.

Terzaghi, K., & Peck, R. (1964). *Soil mechanics in engineering practise.* New York: John Wiley & Sons.

Visser, R., & Van Der Meer, J. (2008). Immediate displacement of the seabed during subsea rock installation. *Terra et Aqua 110*, 6.

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DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are available from the author.

NOMENCLATURE

A_{min}	Minimum bucket diameter (bottom)	m^2
A_{max}	Maximum bucket diameter (top)	m^2
A_{stone}	Cross section stone	m^2
c	Cohesion	kPa
d	Particle or stone diameter	m
C_{vs}	Spatial volumetric concentration	-
D_p	Pipe diameter (pipe) or hydraulic diameter (seabed)	m
D_{mb}	Mean bucket diameter	m
D_{min}	Minimum bucket diameter (bottom)	m
D_{max}	Maximum bucket diameter (top)	m
E	Exposure level	-
E_{kin}	Kinetic energy stone	kJ
F_{BC}	Bearing capacity force	kN
F_g	Weight of a stone $m \cdot g$	kN
F_b	Buoyancy of a stone	kN
g	Gravitational constant 9.81	m/s^2
L_b	Effective bucket length, distance from D_{max} to D_{min}	m
m	Mass of a stone/piece of rock	ton
n	N^{th} stone hitting the previous stones	-
N_c	Terzaghi factor related to cohesion	-
N_q	Terzaghi factor related to penetration and overburden	-
N_γ	Terzaghi factor related to width of a strip footing	-
p_d	Penetration depth of a stone	m
$P_{d,n}$	Penetration depth n_{th} stone	m
Δp_{DW}	Darcy Weisbach pressure loss	kPa
Δp_C	Carnot pressure loss	kPa
Δp_{tot}	Total pressure loss in a bucket	kPa
Δp_g	Pressure du to gravity in a bucket	kPa
Re	Reynolds number	-

Re_*	Roughness Reynolds number	**-**
R_{sd}	Relative submerged density	**-**
SOD	Standoff Distance	**m**
u_*	Friction velocity	**m/s**
v_b	Velocity over the seafloor (the bed)	**m/s**
v_{mm}	Mean mixture velocity	**m/s**
v_{exit}	Exit velocity last bucket	**m/s**
v_{sf}	Jet velocity at sea floor, collision velocity	**m/s**
v_t	Terminal settling velocity	**m/s**
v_{th}	Terminal hindered settling velocity incl. stone to pipe diameter ratio effect	**m/s**
v_{stone}	Collision velocity stone with the sea floor	**m/s**
W	Width of strip footing, in case square or circular, the diameter	**m**
ε	Wall or seabed roughness	**m**
γ	Specific weight of soil	**kN/m^3**
φ	Internal friction angle	**rad**
ρ_q	Density of quarts	**t/m^3**
ρ_l	Density of water or liquid	**t/m^3**
ρ_m	Mixture density	**t/m^3**
λ_b	Darcy Weisbach friction factor on seafloor (the bed)	**-**
λ_C	Carnot friction factor	**-**
λ_{DW}	Darcy Weisbach friction factor buckets	**-**
θ	Shields number	**-**
τ_b	Bed shear stress	**kPa**
ν_l	Kinematic viscosity	**m^2/s**

DEVELOPMENT & IMPLEMENTATION OF A DRAG RIPPER DEVICE

Aiden Horan[1], Norman Bourque[2] and Aaron Barton[3]

ABSTRACT

In 2018, Cashman Dredging & Marine Contracting Ltd. set a goal of creating a new commercially viable method for agitating and loosening glacial tills, desiccated clays and stiff materials on capital improvement dredging projects without the need for an excavator or cutterhead dredge. By examining the problem from first principles and looking outside the industry for inspiration and ideas, a drag ripper carriage was designed and constructed by Cashman Dredging entirely inhouse.

With the use of a ripper shank from a bulldozer attached to a special carriage and through some careful design considerations. the shank can penetrate and advance through hard materials within a dredge template and agitate the soil so it can later be removed in a more cost-effective manner. The ripper shank sticks below the ripper carriage in a similar fashion to how the ripper shank sits below the lower track elevation of a bulldozer. This entirely fresh approach was achieved by combining already existing multi-disciplinary technologies to create something new.

The drag ripper was debuted in April 2019 on the Boston Harbor deepening project. Some materials on the job were difficult to remove in a cost-effective manner with clamshell dredges and had to be skipped over in anticipation of removal using an excavator dredge at a later stage. Cashman Dredging used these troublesome areas as test locations for the new drag ripper whereby the ripper carriage repeatedly passed over the material multiple times with the ripper shank engaged in the material. After treatment with the drag ripper in these troublesome areas, it has been found that the material was then easier to remove using a clamshell bucket.

The drag ripper has proven to be a success. The addition of this new innovative piece of equipment and technology to our fleet is another example of how challenging the status quo and thinking outside the box can lead to novel new solutions to everyday problems.

Keywords: innovation, excavator, cutterhead, glacial till, improvement dredging, ripper, ripping

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INTRODUCTION

The treatment of hard or difficult areas (excluding competent rock) on capital improvement dredging projects can involve a great deal of removal effort and in some instances delay a project's completion time. Cashman Dredging & Marine Contracting Ltd. wished to challenge the existing mindset surrounding the pretreatment of hard or difficult ground conditions that cannot be easily removed with traditional clamshell dredging. A goal was set to develop a different more cost-effective method to treat these areas which predominately consist of glacial tills, desiccated clays, stiff materials and weathered rock using a new approach. The final concept, a drag ripper carriage was designed and constructed by Cashman Dredging entirely inhouse. This radical innovation in the dredging sphere was a first of its kind development whose technology has since been patented.

The drag ripper is similar in concept to a standard drag beam that is used for levelling or relocating material on the seafloor. By using the drag beam as the base technology and marrying it with a ripper shank from a bulldozer, the shank is able to penetrate and advance through hard materials within a dredge template and agitate the soil so much so that it can then be removed with a clamshell in a more cost-effective manner. The ripper shank sticks below the ripper carriage in a similar fashion to how the ripper shank sits below the bottom track elevation of a bulldozer.

The drag ripper was launched in Spring 2019 on the Boston Harbor deepening project, a project which includes numerous pockets of hard packed glacial tills and desiccated clays within the improvement template. These materials can be difficult to remove in a cost-effective manner with clamshell dredges and in some instances had to be skipped over in anticipation of removal at a later stage using an excavator dredge. Cashman Dredging used these troublesome areas as test locations for the new drag ripper whereby the ripper carriage repeatedly passed over the material multiple times with the ripper shank engaged in the material. After treatment with the drag ripper in any of these troublesome areas, it has been found that the material can now be removed using a clamshell bucket, thereby making removal cost effective once more and eliminating a great deal of excavator work.

BACKGROUND

Understanding the issue at hand was the first step in developing a solution. When observing a traditional excavator mounted ripper, it can be difficult to determine the forces which act on the shank. It is therefore difficult to propose alternative solutions when the fundamentals of what is taking place is not understood.

Figure 1 shows a section through a traditional excavator mounted ripper as well as a simplified free body diagram of the forces acting on a ripper shank as it advances through a given soil matrix. Assuming that the shanks in Figure 1 are moving from left to right on the page, they will want to overturn as shown on the right-hand side of the Figure as the shank encounters virgin ground. It is not entirely obvious that this is the system of forces at play when viewing the excavator mounted ripper on the left. The excavators hydraulics, arm, orientation and direction of operation somewhat camouflage what is taking place.

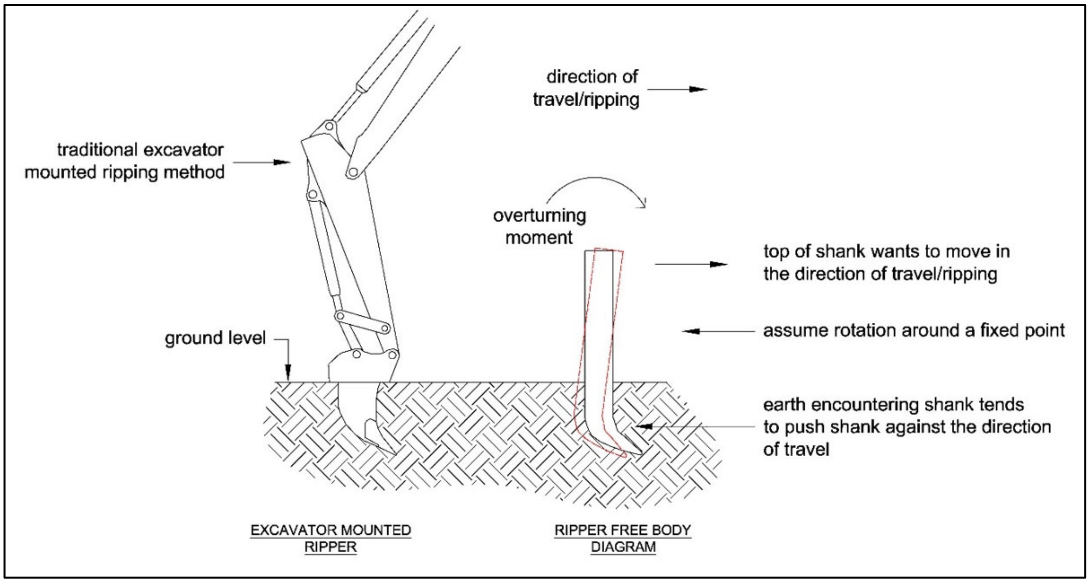

Figure 1. Excavator mounted ripper (left) and free body diagram of forces on a ripper shank (right)

With this simple understanding of how a ripper shank behaves when moving through a soil matrix, we can begin to think logically about practical alternative solutions.

The practice of using a large excavator cutterhead dredge to remove or loosen difficult materials simply serves to increase the amount of energy which can be put into the ground per unit area above what is available with traditional mechanical clamshells. Through looking at the input forces and reactions generated when using either an excavator or cutterhead it becomes possible to understand what is being done which then allows us to arrive at a similar result but in a different way.

APPROACH

The use of large excavators or cutterheads on capital improvement dredging works can result in high unit cost removal, an uncertain schedule as outputs can vary from location to location and a large amount of wear and tear on equipment because the removal effort imparts a lot of stress into the components. As a lot of the work performed by excavators and cutterheads is sometimes performed on the boundary between hard material and competent rock, the process may also have the added step of having to prove competent rock exists in refusal areas which in turn adds time, effort and expense to the dredging process.

While the drag ripper carriage described herein does not attempt to offer a substitution to all of these issues mentioned, it does attempt to short circuit at least some of the process namely the loosening of the material for later removal by more economical means. When necessary, the proving of rock would still need to be performed with an excavator.

LAND VS WATER

One of the first and most important questions that needed to be answered before proceeding was would we have the ability to advance the ripper through the seafloor or would it just become an anchor point. A bulldozer on land generates its traction from a large track surface area which physically sits on and interacts with the ground it is ripping. This physical traction and interaction is not available when the target material is submerged below a deep body of water. For this reason, a different method to advance the ripper was needed. There already existed an analogous situation in dredging whereby a drag beam was hung from a deck barge and was advanced through the target material with the propulsion offered by a tugboat. It was at this stage that we decided to explore the possibility of loosely fashioning the drag ripping device on the already existing drag beam technique. An example of this idea in concept can be seen in Figure 2.

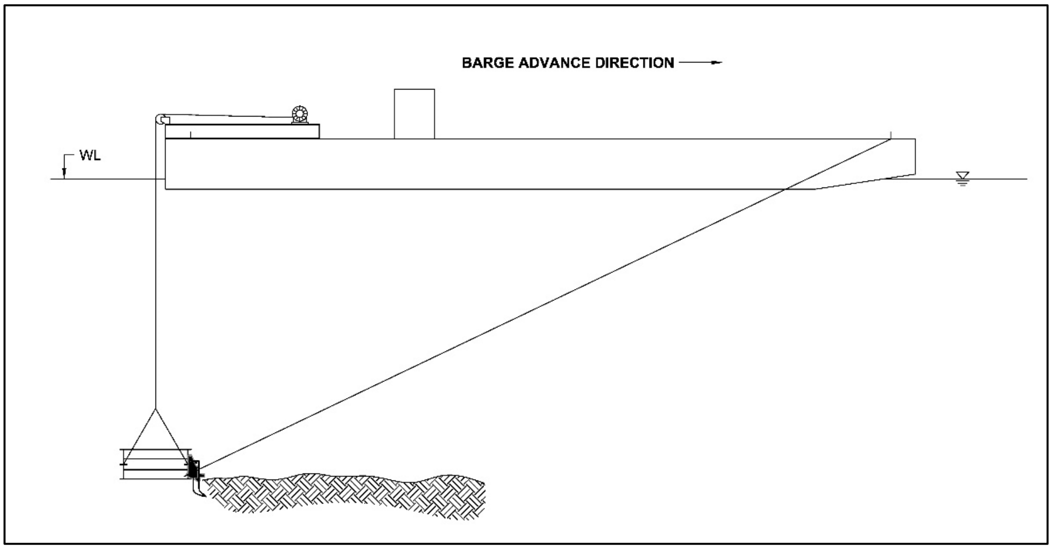

Figure 2. Initial Concept of Drag Ripping Device

When a bulldozer is ripping on land, the ideal speed of travel for the equipment is 1 – 1½ mph (CHR, 2000). For a large bulldozer (CAT D10 or equivalent) the drawbar pull at this speed is in the order of 100,000 lbs (CPH, 2018). For the drag ripper system to work, a tugboat would need to be able to move a deck barge with a comparable amount of force. The equivalent measure for the drawbar pull on a tug boat is the bollard pull. After consideration of the bollard pull ranges available on various sized tugboats, it emerged that a typical 3,000hp tugboat had bollard pull capabilities in the region of 100,000 - 120,000 lbs. Upon first examination, there appeared to be equivalence between what was needed and what was available, however, there are other considerations not taken into account in this paper such as cavitation of the propellor when advance is negligible as well as other losses. Nonetheless, it appeared that the propulsion forces available on water seemed to be in the approximate range needed.

MODEL TESTING

With the free body diagram from Figure 1 having identified the forces at play, albeit in their most basic form, several drag ripper concept carriages were then developed during an initial review. From these concepts, several small-scale physical models were fabricated and tested at Cashman's Quincy, MA headquarters.

While testing the models, several variables were adjusted to determine how the system reacted globally and which derivative gave the best performance. These variables included the number, location and cutting depth of the ripper shanks; the positioning and quantity of any carriage weights; the overall geometry of the ripper sled and the positioning of the stay-back wires to most efficiently pull the carriage and advance it through the material. During small scale testing, the model ripper was advanced through a densely packed damp sand to mimic cutting through real material. By testing the model at scale, it became apparent that some geometries and arrangements worked better than others to promote the cutting of the material while keeping the carriage stable.

From this small-scale testing, the advantages of each carriage type were merged into one design which was then advanced through discussion and internal review. A section through the final carriage proposal can be seen in Figure 3. A picture of the final constructed ripping device can be seen in Figure 4.

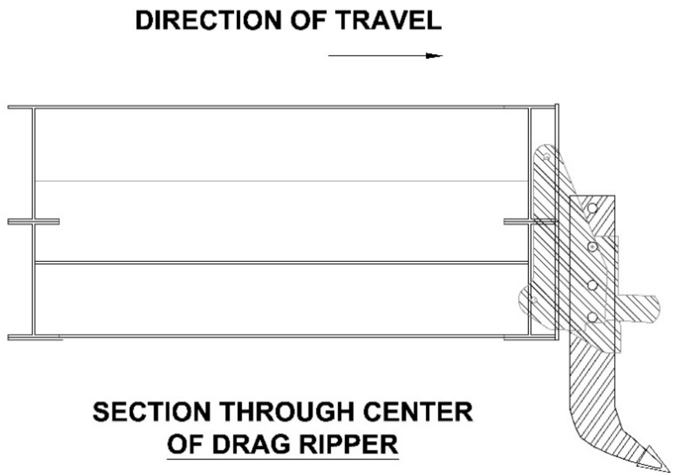

Figure 3 Initial Cross Section Through Drag Ripper Carriage

Figure 4. Picture of Completed Drag Ripping Device before Hanging from Barge

DEPLOYMENT

The drag ripper was deployed on the Boston Harbor Phase 2 deepening project in the Spring of 2019. Initially, the ripper was tested in previously “skipped over” areas of densely packed glacial tills. Once the intricacies of using this new piece of equipment were established, the ripper and drag barge was crewed round the clock for several weeks in order to cover as much of the previously skipped areas as possible. Once the ripper had caught up on the areas it was able to successfully work in, it was then used on an as-needed basis. Follow on clamshell dredging in the ripped areas showed favorable productions therefore indicating that the ripper had been successful in disturbing areas of previously low output.

For the duration of the Boston Harbor Phase 2 project, the ripper was used in glacial tills of all types, weathered rock and desiccated clays. Owing to the relatively small zone of influence that the ripper shank has when engaged in the material, numerous passes were needed in every location in order to agitate the material enough to make follow on dredging economical once more. In other words, the same area had to be covered multiple times and sometimes from multiple directions to adequately loosen the material.

CONCLUSIONS

The development and deployment of the drag ripper device by Cashman Dredging was done to test new ways of completing repetitive tasks. By challenging the existing mindset around how a given type of work is usually completed, a new and novel piece and equipment and a new dredging technique created.

The successful development and introduction of the ripper has given us an innovation template that we can use time and time again to examine different ways of doing things. It is often very easy to simply use the everyday tools available to an industry to get the job done as it has always been done and it is very difficult for a company to spend the time, money and resources on an endeavor that may or may not work using unproven theories, methods and technology. In the case of the ripper described in this paper, that endeavor was shown to be a success.

Thanks to the successful introduction of this new patented piece of equipment, Cashman Dredging now have another unique tool available in our dredging fleet for use whenever needed.

REFERENCES

Caterpillar Inc., “Caterpillar Handbook of Ripping”, Edition 12, Industry Publication, 2000

Caterpillar Inc., “Caterpillar Performance Handbook”, Edition 48, Industry Publication, 2018

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution made by all team members at Cashman Dredging from senior management to the field personnel. An additional acknowledgement is made to the members of the Boston Harbor Deepening team from the project management staff to the field personnel who initiated the use of the drag ripper in the field and persevered through the many teething problems that arise from using new and untested equipment. A wide cross section of the company came together to make this endeavor a success.

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FINDING THE SILVER LINING IN COVID-19 IMPACTS ON NATIONAL DREDGING QUALITY MANAGEMENT PROGRAM (DQM) QA PRACTICES

B.P. Allen[1] and W.M. Rae[2]

ABSTRACT

Since the new techniques implemented during 2019 had begun to increase the efficiency of the annual quality assurance (QA) dredge instrumentation checks, 2020 started out with heightened excitement for the U.S. Army Corps of Engineers (USACE) National Dredging Quality Management Program (DQM). By mid-April, however, everything had changed. This paper describes the actions DQM put in place to mitigate risks once COVID-19 took on pandemic proportions, the opportunities the pandemic opened to enhance DQM's involvement with the dredging safety community, and the ways that data analysis, technology, and accumulated experience are being used both to maintain data quality and to further improve the efficiency of the DQM QA process through the current pandemic and into the future.

In the spring of 2020, when all field checks were suspended due to USACE travel restrictions imposed to reduce the spread of COVID-19, DQM decided to extend the certification of all current dredge plants and to issue conditional certification to all new and expired plants, based on certain documentation criteria. After consulting with safety professionals and reviewing the pandemic plans of dredging industry players, DQM developed a COVID-19 response plan, which includes a risk analysis matrix and a safety survey that are being used to evaluate when QA field checks can safely resume.

As local USACE Districts moved to reduce or eliminate viral exposure to their field personnel, they increased their use of DQM online tools, such as the Online Data Viewer, to monitor contract activity in real time. DQM responded by automating much of the evaluation of incoming data in order to provide more timely feedback on potential issues. DQM has also streamlined its processes to inform both contractors and USACE personnel of these issues. The data analysis tools developed under COVID-19 limitations have enabled DQM to detect developing trends in data and instrumentation issues, and they will help drive post-pandemic strategies for checking data and maintaining the high level of data quality that is so important for supporting the needs of the dredging community. The suspension of field activities allowed DQM field personnel the opportunity to digitize a large backlog of field data and Dredge Plant Information Plan (DPIP) records, and to conduct analyses in order to optimize QA check trip efficiency and to identify common sensor issues and data quality trends.

Keywords: Coronavirus, field inspection, pandemic, quality assurance, safety

INTRODUCTION

The new decade appeared to start with optimism for the field operations of the National Dredging Quality Management Program (DQM). New techniques were being tested and utilized as part of the quality assurance (QA) checks that promised to increase efficiencies, and the U.S. Army Corps of Engineers (USACE) mandate to include pipeline dredges in the program had the DQM Center preparing for a rigorous

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schedule to accommodate all of the additional QA check trips expected for the year. However, within a few short months, the program, along with the entire nation, was grappling with how to deal with a once-in-a-hundred-year pandemic. Looking at an indefinite suspension of a significant portion of its workload, DQM nevertheless took advantage of the situation to thrive and grow.

ADVANCEMENTS IN FIELD TECHNIQUES

One of the most promising field processes being tested before the advent of the pandemic was replacing the traditional draft sensor check on scows with a simulated draft sensor check—the pressure sensor used to report the scow's draft is checked at a range of water depths inside a temporary test well (Figure 1). This new method provides a more effective and efficient opportunity to test and calibrate the sensor in a controlled environment, and it removes the need for the DQM field team to remain on site for a complete dredging cycle for each scow. By analyzing the data from the plants where this change was made, including the long-term behavior of the sensors, DQM has been able to determine that these procedures successfully test the accuracy of the pressure sensors and result in regularly calibrated instrumentation.

To improve the safety and accuracy of performing draghead and cutterhead depth sensor checks, the DQM Data Acquisition Team purchased portable pressure sensors (Figure 1) that are regularly calibrated and verified for accuracy. As a result, very accurate readings can be collected even in adverse sea conditions, and personnel are no longer at risk from leaning over the side of a vessel while holding onto a chain to check cutterhead and draghead depth elevations.


Figure 1. (L) Pressure sensor testing and calibration inside a temporary test well, and (R) depth check of a cutterhead using a portable pressure sensor for data validation.

In November 2019 the USACE Civil Works Directorate (CECW) issued a Memorandum for Commanders, Major Subordinate Commands and District Commands, Chiefs of Operations mandating DQM monitoring on unrestricted (Full and Open Competition) pipeline dredge contracts. This Memorandum requires that all contractors, including small business contractors, meet DQM pipeline dredge monitoring specifications and requirements when bidding on unrestricted contracts. This mandate meant that USACE Civil Works contracts would start requiring the installation and certification of DQM instrumentation on a much larger scale in the fall of that year.

DQM had already been implemented on USACE hydraulic pipeline dredges and a few pilot contractor projects, which helped the DQM Data Acquisition Team optimize sensor testing and validation methods. The team was also fortunate to have the capability to install the DQM software remotely for new dredge plants as they came on line; however, field verification of the instrumentation setup was still an important component of assisting the contractors in becoming comfortable with the monitoring protocols.

A newly field-tested technique for pipeline dredges is the use of a portable velocity meter to measure slurry velocity (Figure 2). The previous method was to perform a traditional dye test, which is labor-intensive and causes dredging downtime. The portable meter can be strapped onto the discharge pipe and continue collecting slurry velocity data while other checks are completed on the dredge plant. The data results can then be compared with the reported readings from the dredge computer to evaluate its accuracy. During field testing, this technique garnered mixed results. While good readings can be acquired at lower velocities, some dredges do not have sufficient straight pipe lengths to give the laminar flow required for a good reading. For these reasons, dye tests continue to be a staple of velocity testing on pipeline dredges. It is greatly appreciated that many dredging companies have easy and innovative techniques for releasing the dye into the discharge pipe to assist in the testing process. However, even with these added efficiencies, this testing method can still be a significant effort, depending on the length of pipe involved.

Figure 2. (L) Installation of a velocity sensor on a pipeline and (R) the outflow during dye testing.

SUSPENSION OF ANNUAL QA CHECKS

In March 2020, as concerns about the spread of COVID-19 increased, the US Department of Defense (DoD) decided to suspend travel, and everything came to a screeching halt. DQM immediately posted a notice to its website advising all interested parties that all field operations, including all on-site QA checks, were temporarily suspended until the pandemic had abated. Due to the unknown duration of the virus's impact on field operations, the DQM Center decided to extend any certificates that were soon to expire. Special conditions were imposed on dredge plants that were not currently certified, including the requirement for submission of a current Dredge Plant Information Plan (DPIP) and proof that they could transmit a correctly formatted data string to the DQM database. For new scow installations, it was also requested that the system provider submit some indication that instrument calibrations were performed at the time of installation.

These new installations were issued a Conditional certification to get projects up and running in hopes that field checks would soon resume.

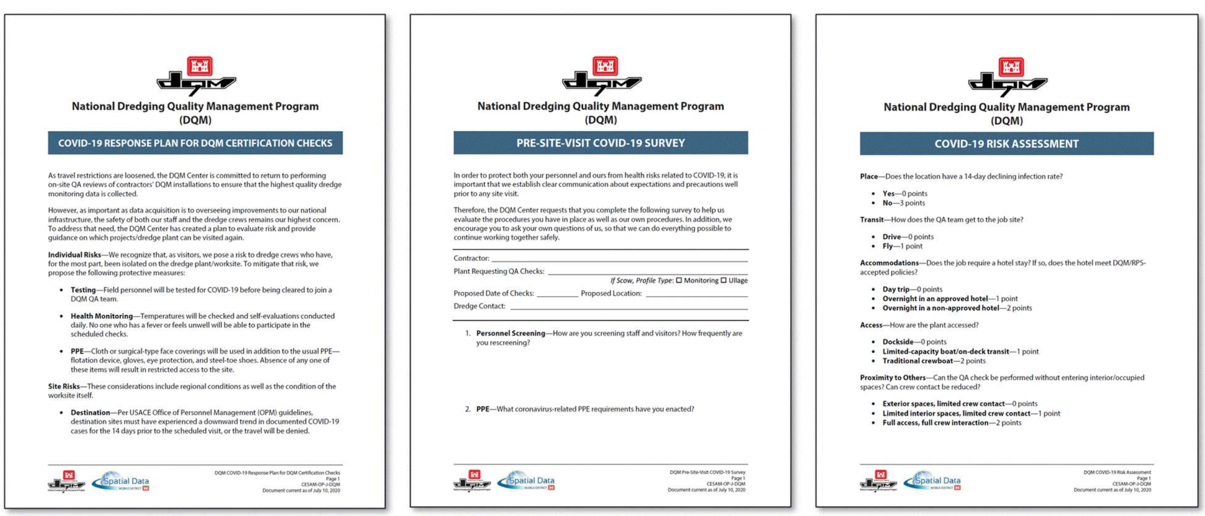
INVESTIGATION OF INDUSTRY RESPONSE TO COVID-19

It was clear that to best serve its clients and develop a plan for safely moving forward, DQM needed to ensure clear communications with participants of all types. Of utmost importance was to ensure no plan of action would impact the safety of individuals due to lack of proper consideration. In addition to the existing project management and instrumentation support contacts, the DQM team worked to establish lines of communication with safety departments and industry safety consultants.

Therefore, the DQM Center turned to Margaret Davis, vice president of Hile Group and a presenter for Texas A&M Dredging Short Course's Dredging Safety segment, for advice on how to develop a Pandemic Response Plan. Ms. Davis recommended reviewing the COVID-19 Resources page on the Council for Dredging & Marine Construction Safety (CDMCS) website for information on the virus and the dredging industry's response. The DQM Center contacted the CDMCS and received permission to join both their Quarterly Meetings and their biweekly Zoom meetings, which were focused on COVID-19. Listening to the industry-wide issues and concerns that participants shared during these virtual meetings helped the DQM team shape its response plans and risk analyses.

PREPARATION OF A PANDEMIC RESPONSE PLAN

It was deemed essential to address the fact that different types of jobs, different types of plants and different regions of the country are faced with a wide variety of conditions and concerns. Therefore, by June 2020 the DQM team had developed a response plan (Figure 3) based on USACE guidelines and coordinated with the dredging industry. As important as data acquisition is to overseeing improvements to the National infrastructure, the safety of DQM staff and the dredge crews safety has remained the highest priority. Therefore, the DQM plan both evaluated risk and provided guidance on when and which projects/dredge plants could be visited. The strategy adopted by DQM sought to balance individual risks (testing, health monitoring, and personal protective equipment [PPE] requirements), site risks (destination area, travel mode, accommodations, and dredge plant access), exposure risks (limited personnel and shorter duration of exposure), and procedure modifications (increased communications, pre-visit preparations, and modifications to the dredging cycle to reduce exposure). The best way for the DQM teams to account for this was with a risk analysis that weighted the various issues and generated a holistic assessment of the risk.



National Dredging Quality Management Program (DQM)

COVID-19 RESPONSE PLAN FOR DQM CERTIFICATION CHECKS

As travel restrictions are loosened, the DQM Center is committed to return to performing on-site QA reviews of contractors' DQM installations to ensure that the highest quality dredge monitoring data is collected.

However, as important as data acquisition is to overseeing improvements to our national infrastructure, the safety of both our staff and the dredge crews remains our highest concern. To address that need, the DQM Center has created a plan to evaluate risk and provide guidance on which projects/dredge plant can be visited again.

Individual Risks—We recognize that, as visitors, we pose a risk to dredge crews who have, for the most part, been isolated on the dredge plant/worksite. To mitigate that risk, we propose the following protective measures:

- **Testing**—Field personnel will be tested for COVID-19 before being cleared to join a DQM QA team.
- **Health Monitoring**—Temperatures will be checked and self-evaluations conducted daily. No one who has a fever or feels unwell will be able to participate in the scheduled checks.
- **PPE**—Cloth or surgical-type face coverings will be used in addition to the usual PPE—flotation device, gloves, eye protection, and steel-toe shoes. Absence of any one of these items will result in restricted access to the site.

Site Risks—These considerations include regional conditions as well as the condition of the worksite itself.

- **Destination**—Per USACE Office of Personnel Management (OPM) guidelines, destination sites must have experienced a downward trend in documented COVID-19 cases for the 14 days prior to the scheduled visit, or the travel will be denied.

DQM COVID-19 Response Plan for DQM Certification Checks
Page 1
CESAM-OP-J-DQM
Document current as of July 10, 2020

National Dredging Quality Management Program (DQM)

PRE-SITE-VISIT COVID-19 SURVEY

In order to protect both your personnel and ours from health risks related to COVID-19, it is important that we establish clear communication about expectations and precautions well prior to any site visit.

Therefore, the DQM Center requests that you complete the following survey to help us evaluate the procedures you have in place as well as our own procedures. In addition, we encourage you to ask your own questions of us, so that we can do everything possible to continue working together safely.

Contractor: ______
Plant Requesting QA Checks: ______
If Scow, Profile Type: ☐ Monitoring ☐ Ullage
Proposed Date of Checks: ______ Proposed Location: ______
Dredge Contact: ______

1. **Personnel Screening**—How are you screening staff and visitors? How frequently are you rescreening?
2. **PPE**—What coronavirus-related PPE requirements have you enacted?

DQM Pre-Site-Visit COVID-19 Survey
Page 1
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Document current as of July 10, 2020

National Dredging Quality Management Program (DQM)

COVID-19 RISK ASSESSMENT

Place—Does the location have a 14-day declining infection rate?

- **Yes**—0 points
- **No**—3 points

Transit—How does the QA team get to the job site?

- **Drive**—0 points
- **Fly**—1 point

Accommodations—Does the job require a hotel stay? If so, does the hotel meet DQM/RPS-accepted policies?

- **Day trip**—0 points
- **Overnight in an approved hotel**—1 point
- **Overnight in a non-approved hotel**—2 points

Access—How are the plant accessed?

- **Dockside**—0 points
- **Limited-capacity boat/on-deck transit**—1 point
- **Traditional crewboat**—2 points

Proximity to Others—Can the QA check be performed without entering interior/occupied spaces? Can crew contact be reduced?

- **Exterior spaces, limited crew contact**—0 points
- **Limited interior spaces, limited crew contact**—1 point
- **Full access, full crew interaction**—2 points

DQM COVID-19 Risk Assessment
Page 1
CESAM-OP-J-DQM
Document current as of July 10, 2020

Figure 3. DQM COVID-19 response planning documentation.

Prior to accepting a request for on-site checks, the DQM Center asks contractors/system providers to complete a questionnaire describing their pandemic precautions. The questionnaire would this then evaluated in the risk analysis process to decide whether to proceed with the appointment. It is uncertain at this time what effect more widespread vaccinations will have on restoring field QA checks.

At the beginning of the COVID-19 shutdown, the certifications were issued or extended only for periods of time not exceeding three months. However, as the pandemic grew more severe, the previous extensions were modified to extend first to the end of 2020 and then for a period of either 12 or 18 months from their original installation or expiration.

IMPORTANCE OF REMOTE MONITORING CAPABILITIES

One key role that quickly gained importance for DQM was providing USACE Districts with the tools to continue active monitoring of the projects that would typically have on-site inspectors. It was already a vital part of the established mission of DQM to deliver project monitoring and management tools for personnel not physically on-site; however, the sudden importance of reducing potential exposure for all parties placed a renewed emphasis on this function.

To further facilitate the move to remote monitoring for USACE field staff, the DQM Center established a series of online training presentations for system users to help educate them and ease the transition where possible. These training sessions provided detailed information on the data and reports available through DQM and the kinds of decisions that can be driven by them. Group Webex sessions familiarized USACE employees with the DQM Program and the support and tools they provide to USACE District personnel in administering a contract. PDF copies of the slides and script are available to District personnel for reference. A series of informational papers regarding various aspects of the program was also produced for educational purposes. In addition, DQM Center personnel also made themselves available for individual and small group tutorials, walking District users through the main features of the DQM Online Data Viewer and other DQM tools available for visualizing and evaluating the collected data.

ENSURING BEST QUALITY DATA RECEIVED

Since the DQM Program could no longer rely on the established field QA check system to verify that plants continued to meet program data quality requirements, there was a sudden need to focus on alternative techniques for monitoring data and the correct functionality of the sensors. There was an existing development program underway looking at the use of advanced data analysis and machine learning (ML) tools to perform a continuous sensor health check on the incoming DQM data. In response to the needs raised by the pandemic, the priority of this program was increased, and significant progress was made on reliably detecting sensor issues, flagging potentially bad data, and identifying data gaps. This "sensor health check," which is used to prepare weekly quality control (QC) reports to inform dredging contractors of any data problems, is currently being truth-checked by visual inspection of time series graphs of the collected parameters. The set of tests in the sensor health check suite was designed to assign flags to individual data points identifying specific problematic sensor behaviors that have been found to occur in the dredging data collected by DQM.

At the start of development, several checks were already in place to test for a limited set of behaviors. These included the reporting of null or zero values, egregious spike values, and violations of minimum or maximum value settings. In addition, a check for possible incorrect load number increments—an issue specific to dredging data—had previously been developed. The improved sensor health checks added several additional checks to the existing suite. The new checks examine short segments of data to look for relational patterns, such as static, disjointed, or erroneous values and specialized checks to verify the pump-out and hull status signals' likely accuracy. The sensor health checks are applied to incoming hopper and scow data, and the results are stored in the DQM database as unique flag values, which can be used to trigger alerts or generate reports as needed.

Some typical terminology used in the comments section of the weekly QC reports to identify the type of data quality issue observed include Disjointed (disconnected measurements observed in the signal which last over several points), Noisy (incoherent signal which bounces between values), Static (very little to no change observed to the signal), and Invalid Values (erroneous values outside the physical expectations observed in the signal) (Figure 4).

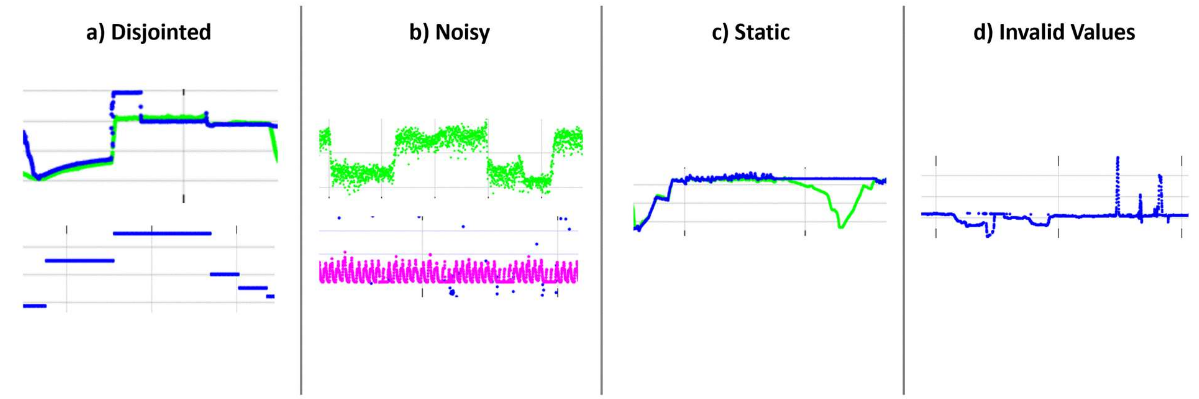
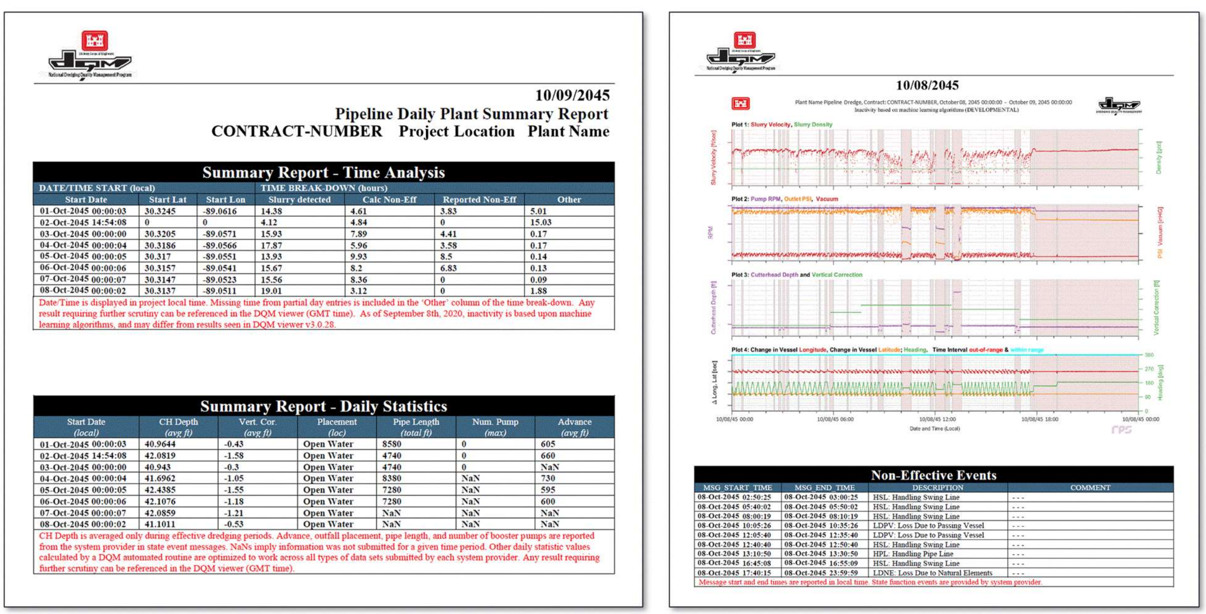


Figure 4. Signal descriptions used in data review: Disjointed, Noisy, Static, and Invalid Values.

Additionally, because much of the “state” data received from pipeline dredges is not available on the DQM Online Data Viewer, weekly summary reports of pipeline data are generated and sent out to the local USACE Districts to verify receipt of the information and to provide an easy way to view the data. This content and format of this report continue to be under development. It currently consists of three parts: daily summary report tables, a graphical display of work event data, and a list of reported non-work events (Figure 5).



10/09/2045
Pipeline Daily Plant Summary Report
CONTRACT-NUMBER Project Location Plant Name

Summary Report - Time Analysis

DATE/TIME START (local)			TIME BREAK-DOWN (hours)			
Start Date	Start Lat	Start Lon	Slurry detected	Calc Non-Eff	Reported Non-Eff	Other
01-Oct-2045 00:00:03	30.3245	-89.0616	14.38	4.61	3.83	5.01
02-Oct-2045 14:54:08	0	0	4.12	4.84	0	15.03
03-Oct-2045 00:00:00	30.3205	-89.0571	15.93	7.89	4.41	0.17
04-Oct-2045 00:00:04	30.3186	-89.0566	17.87	5.96	3.58	0.17
05-Oct-2045 00:00:05	30.317	-89.0551	13.93	9.93	8.5	0.14
06-Oct-2045 00:00:06	30.3157	-89.0541	15.67	8.2	6.83	0.13
07-Oct-2045 00:00:07	30.3147	-89.0523	15.56	8.36	0	0.09
08-Oct-2045 00:00:02	30.3137	-89.0511	19.01	3.12	0	1.88

Date/Time is displayed in project local time. Missing time from partial day entries is included in the ‘Other’ column of the time break-down. Any result requiring further scrutiny can be referenced in the DQM viewer (GMT time). As of September 8th, 2020, inactivity is based upon machine learning algorithms, and may differ from results seen in DQM viewer v3.0.28.

Summary Report - Daily Statistics

Start Date (local)	CH Depth (avg ft)	Vert. Cor. (avg ft)	Placement (loc)	Pipe Length (total ft)	Num. Pump (max)	Advance (avg ft)
01-Oct-2045 00:00:03	40.9644	-0.43	Open Water	8580	0	605
02-Oct-2045 14:54:08	42.0819	-1.58	Open Water	4740	0	660
03-Oct-2045 00:00:00	40.943	-0.3	Open Water	4740	0	NaN
04-Oct-2045 00:00:04	41.6962	-1.05	Open Water	8380	NaN	730
05-Oct-2045 00:00:05	42.4385	-1.55	Open Water	7280	NaN	595
06-Oct-2045 00:00:06	42.1076	-1.18	Open Water	7280	NaN	600
07-Oct-2045 00:00:07	42.0859	-1.21	Open Water	NaN	NaN	NaN
08-Oct-2045 00:00:02	41.1011	-0.53	Open Water	NaN	NaN	NaN

CH Depth is averaged only during effective dredging periods. Advance, outfall placement, pipe length, and number of booster pumps are reported from the system provider in state event messages. NaNs imply information was not submitted for a given time period. Other daily statistic values calculated by a DQM automated routine are optimized to work across all types of data sets submitted by each system provider. Any result requiring further scrutiny can be referenced in the DQM viewer (GMT time).

10/08/2045

Non-Effective Events

MSG_START_TIME	MSG_END_TIME	DESCRIPTION	COMMENT
08-Oct-2045 02:50:25	08-Oct-2045 03:00:25	HSL: Handling Swing Line	- - -
08-Oct-2045 05:40:02	08-Oct-2045 05:50:02	HSL: Handling Swing Line	- - -
08-Oct-2045 08:00:19	08-Oct-2045 08:10:19	HSL: Handling Swing Line	- - -
08-Oct-2045 10:05:26	08-Oct-2045 10:35:26	LDPV: Loss Due to Passing Vessel	- - -
08-Oct-2045 12:05:40	08-Oct-2045 12:35:40	LDPV: Loss Due to Passing Vessel	- - -
08-Oct-2045 12:40:40	08-Oct-2045 12:50:40	HSL: Handling Swing Line	- - -
08-Oct-2045 13:10:50	08-Oct-2045 13:30:50	HPL: Handling Pipe Line	- - -
08-Oct-2045 16:45:08	08-Oct-2045 16:55:09	HSL: Handling Swing Line	- - -
08-Oct-2045 17:40:15	08-Oct-2045 23:59:59	LDNE: Loss Due to Natural Elements	- - -

Message start and end times are reported in local time. State function events are provided by system provider.

Figure 5. Pipeline Daily Plant Summary Report.

The first page of the report includes two tables. The first summarizes the amount of non-effective working time (NEWT) and effective working time (EWT). "Reported Non-Eff" is a value reported by the contractor for NEWT while "Calc Non-Eff" is a calculated value for NEWT, defined here as the number of hours during the specified 24-hour dredging operation when the dredge is operational, but no material production is taking place, such as during times of minor operating repairs, repositioning of dredge, vessel traffic, and weather. This value is calculated using ML algorithms. Slurry detected is a calculated value for EWT, defined here as the number of hours during the specified 24-hour dredging operation when material production is taking place. This value is also calculated using ML algorithms. The second table summarizes daily statistics for variables such as cutterhead/suction depth, outfall placement, pipe length, and number of booster pumps. Advance is currently entered daily by the contractor. A recognized challenge is that Advance needs to be entered for the previous time period, with the timestamp down to the correct second. The DQM Center is working to calculate Advance using ArcGIS to measure distance.

The second part of the report is a graphical display of the work event data, plotted in 24-hour increments. The focus of the figure is to show effective and non-effective dredging time, as determined by an ML algorithm. Effective time is displayed in the white space, and non-effective time in pink. The third part of the report lists the downtime explanations that have been manually submitted by the contractor. Comments are optional. Detailed information about this report is available from the DQM Center.

COORDINATING DATA QUALITY ISSUES

After the weekly summary reports are generated, any potentially bad data discovered is communicated to the dredger or system provider. Modifications to the method of disseminating these concerns were initiated so that responses and action plans could be dealt with at the lowest level, ideally eliminating excess pressure on the dredgers and system providers by giving them more opportunity to communicate the status of a problem and proposed resolutions before escalating an issue to upper management. In the past, these communications led to an increased workload for the instrumentation repair personnel due to a lack of clear expectations. The new system provides more explicit expectations and limits the message distribution so that the on-site personnel have time to evaluate and often repair the issue before the response escalates.

Each week the DQM Center emails the dredging contractors/system providers a list of all data quality issues identified during a review of the previous weeks' data. Comments are classified as "Investigate Further" (issues the DQM Center would like to have resolved along with an explanation of the issue or a plan of action for resolving the issue), "Advisory Items" (items that have been noticed but that the DQM Center does not feel are significant enough to warrant immediate action, such as one-off incidents or minor issues with "lower importance" sensors that generally do not affect DQM's ability to make dredge state determinations or perform data analysis), and "Acknowledged" (issues that have been previously identified and for which the contractor has provided a plan of action or explanation). Any item marked "Investigate further" is also forwarded to the appropriate local USACE District for awareness, along with contractor comments clarifying their response to the issue.

The DQM Center realizes that it can take time to resolve sensor issues, particularly during the ongoing COVID-19 pandemic. To account for this, any identified issue for which the contractor has provided a plan of action or explanation is tagged "Acknowledged" until the issue is resolved or the planned timeframe for repair has elapsed. If the issue is not resolved at that point, it is moved back to "Investigate Further."

OPPORTUNITY TO EVALUATE HISTORICAL RECORDS

The DQM Center has used the "extra" time available from not having to conduct field visits to evaluate various aspects of how well DQM is doing as a program. One of the first tasks involved compiling a database of all the QA notifications sent out over the past two years. This data was then analyzed to see if any trends could be identified in the frequency of certain types of notifications, differences in plant type issues, and any changes in notifications due to the pandemic. Normalizing the data for the various plant types and including more recent data will involve additional analysis to some of the factors that are driving the observed trends can be determined.

Over the 14 years the DQM program and its predecessor, Silent Inspector, have been in existence, it has been observed that a portion of the dredging fleet checks and or recalibrates its instrumentation only in conjunction with a DQM field QA check visit. Although this is far from ideal, the pattern has been well established. Historically, some plant-specific trends in declining sensor performance were observed in the lead-up to an annual DQM check; however, this year, with no checks being performed, the dataset grew and allowed for further trend analysis. Across the fleet, an uptick in the number of sensor problems roughly corresponding to the elapsed time since the last DQM QA check was evident.

Figure 6 shows a plot of the total number of notifications sent out per month. Since these notifications were sent weekly, the totals may include more than one notification per plant. Also, the totals do not distinguish what level of concern was noted ("Data Gap," "Investigate Further," "Advisory," or "Acknowledged"), so that each notification may only reference one issue or multiple issues for that plant. Time series totals reflecting the number of instances for each level of concern are also graphed per month. Overall, the graphs show that the number of issues noted was reasonably steady until about June of this year when there was an increase in total notifications for "Advisory" items. This increase may reflect the additional pipeline dredges coming online as it lags the mandate to include DQM for pipelines by about six months. It may also result from the effects of the suspension of the annual and start-up on-site checks due to the COVID-19 travel restrictions.

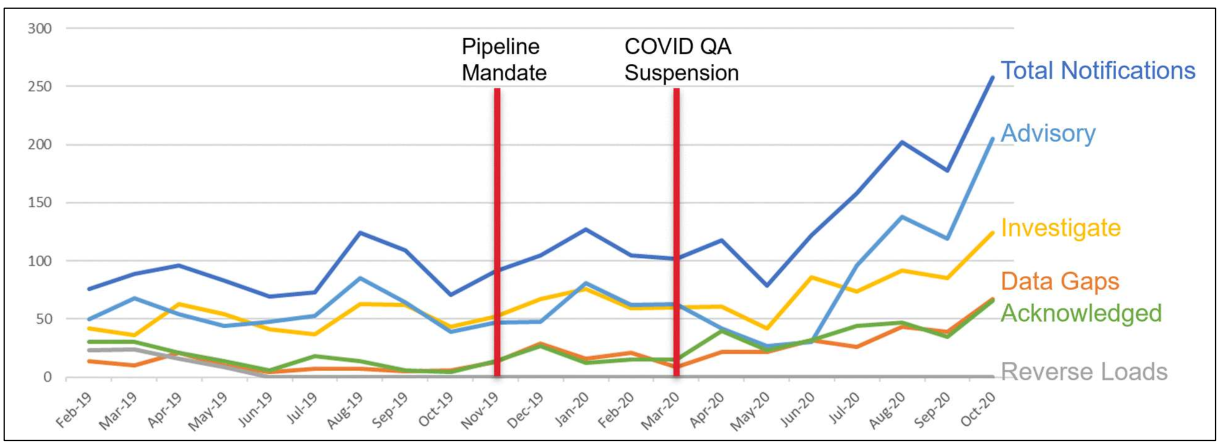


Figure 6. Time series graph showing the total number of QA notifications sent to contractors/ system providers per month from February 2019 to October 2020.

The vertical bar graph in Figure 7 illustrates the percentage of active plants displaying issues in FY 2020. This graph does not discriminate on the type of issue noted, but instead focuses on the percentage of active plants receiving a notification by month over the FY. It appears that more issues are noted as the complexity of the array increases. The percentage of pipelines displaying issues may be low due to the leniency extended by DQM as the plant type gets geared up and the bugs are worked out.

The horizontal bar graph in Figure 7 compares the frequency of "Investigate Further" issues for various commonly cited parameters. Not surprisingly, ullage sensors seem to give the most problems, either because of foam, sea conditions, or misalignment. Density issues follow, generally recording static values or drifting. Hull status may remain open during Transit Light, it may spike at unexpected times, or it may not indicate open when placement appears to be occurring based on the information from other sensors. The GPS sensor is not currently listed in the statistics due to its historic low rate of failure; however the GPS positions have more recently increased frequency of intermittently reporting zero (0) positions, which is now being tracked more closely and is under investigation. Latitude and longitude values reported as zero (0) are flagged in the DQM database.

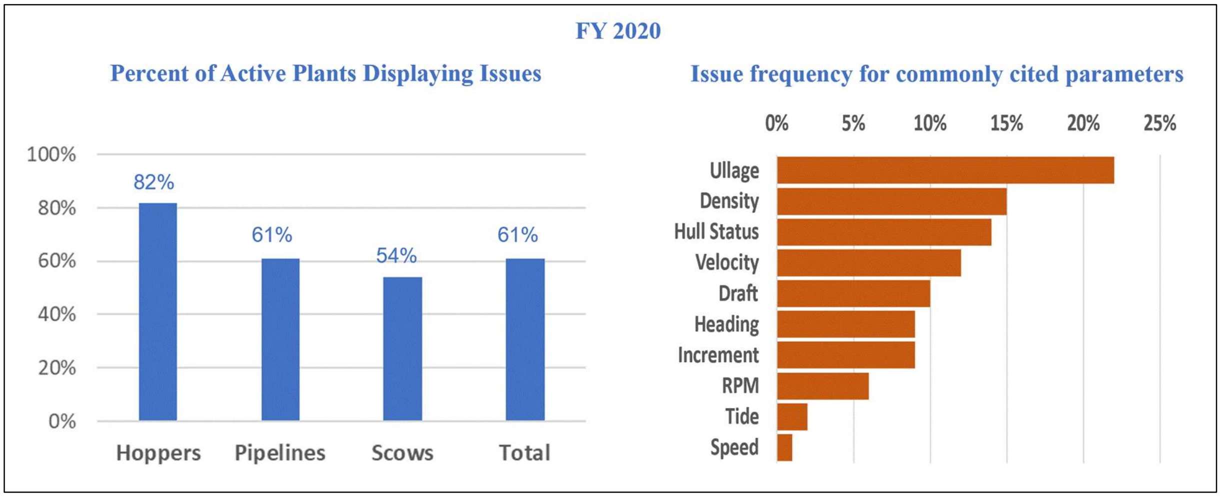


Figure 7. (L) The percentage of active plants, by dredge type, displaying issues in FY 2020; (R) The issue frequency for each sensor type inspected as part of the DQM system.

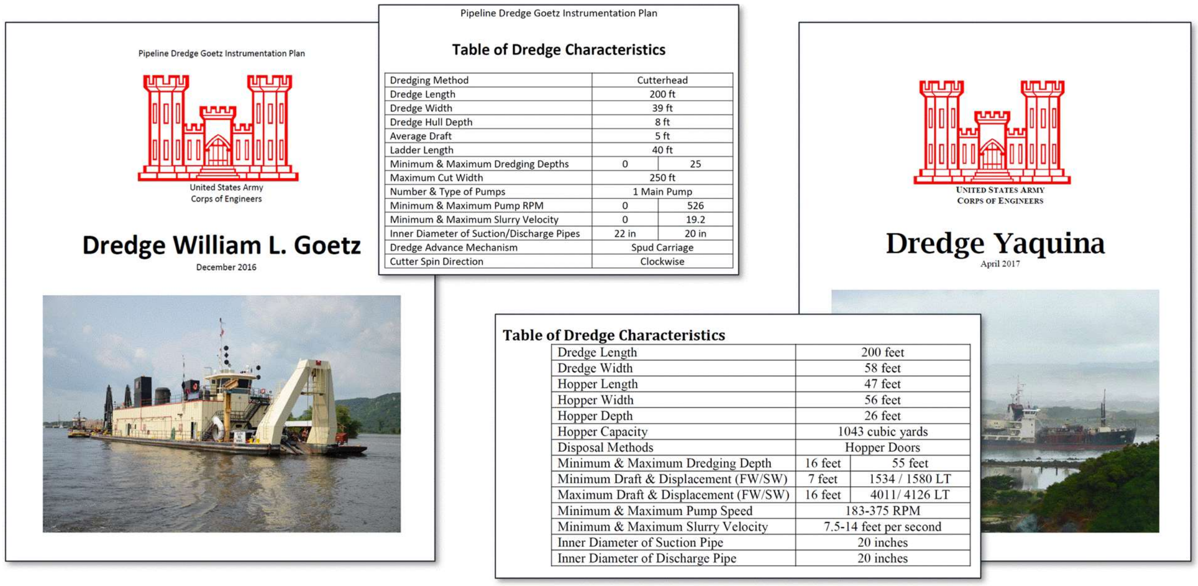
The actual percentages assigned to each parameter may vary from those shown here as they were not broken out by plant type or profile. For example, scows would not have issues with density or velocity, both of which have relatively high levels of incidents when looking at all plant types. Likewise, missing or unusual values for state data reported by pipeline dredges rank high on overall issues even though they are reported only for that plant type.

OPPORTUNITY TO CONSOLIDATE AND EVALUATE FIELD DATA

Another opportunity discovered from not having to conduct field visits was the potential to use the time to digitize DPIPs and past field data for analysis. It has been a longstanding goal of the program to study this data, but the DQM Center previously lacked the time and personnel to convert the data into a queryable format. Loading the information contained in the DPIP's Plant Characteristics table and other tabular values (Figure 8) into a spreadsheet format allows the information to be easily retrieved to answer questions on an individual plant, supports fleetwide analysis for plant characteristics and behaviors, and provides a ready reference for dredging estimators. This exercise reinforced the DQM Center's desire to reformat the entire DPIP to a digital webform in the future.

Also digitized was information from the previous year's trip reports from the annual QA checks (Figure 9). This prompted some questions on how best to organize this data for future use. Should it be based on the individual plant or trip regardless of how many dredge plants were checked? By including the timeline of the checks, it could be estimated how long it took to perform the different checks and determine the average amount of time to complete each as well as the overall length of time for each plant type.

The number of checks performed in 2019 and the percentage of those checks that uncovered issues that were either corrected on site or required a return visit are illustrated in Figure 10. As the data shows, only about 20% of the checks found no issues or recalibrations necessary. A more significant percentage of checks effectively performs calibrations while the team is on site and are thus in compliance when the checks are complete. This could be partly due to efforts to make the checks more efficient by simulating drafts; this procedure essentially eliminates whether the sensor was out of compliance before the checks were made. Again, about 20 % of the time, there were issues identified that kept the plant from passing the certification checks, some of which required an additional trip to become fully certified.



Dredging Method	Cutterhead	
Dredge Length	200 ft	
Dredge Width	39 ft	
Dredge Hull Depth	8 ft	
Average Draft	5 ft	
Ladder Length	40 ft	
Minimum & Maximum Dredging Depths	0	25
Maximum Cut Width	250 ft	
Number & Type of Pumps	1 Main Pump	
Minimum & Maximum Pump RPM	0	526
Minimum & Maximum Slurry Velocity	0	19.2
Inner Diameter of Suction/Discharge Pipes	22 in	20 in
Dredge Advance Mechanism	Spud Carriage	
Cutter Spin Direction	Clockwise	

Dredge Length	200 feet	
Dredge Width	58 feet	
Hopper Length	47 feet	
Hopper Width	56 feet	
Hopper Depth	26 feet	
Hopper Capacity	1043 cubic yards	
Disposal Methods	Hopper Doors	
Minimum & Maximum Dredging Depth	16 feet	55 feet
Minimum Draft & Displacement (FW/SW)	7 feet	1534 / 1580 LT
Maximum Draft & Displacement (FW/SW)	16 feet	4011/ 4126 LT
Minimum & Maximum Pump Speed	183-375 RPM	
Minimum & Maximum Slurry Velocity	7.5-14 feet per second	
Inner Diameter of Suction Pipe	20 inches	
Inner Diameter of Discharge Pipe	20 inches	

Figure 8. Digitization of DPIP information for more efficient plant evaluations and comparisons.

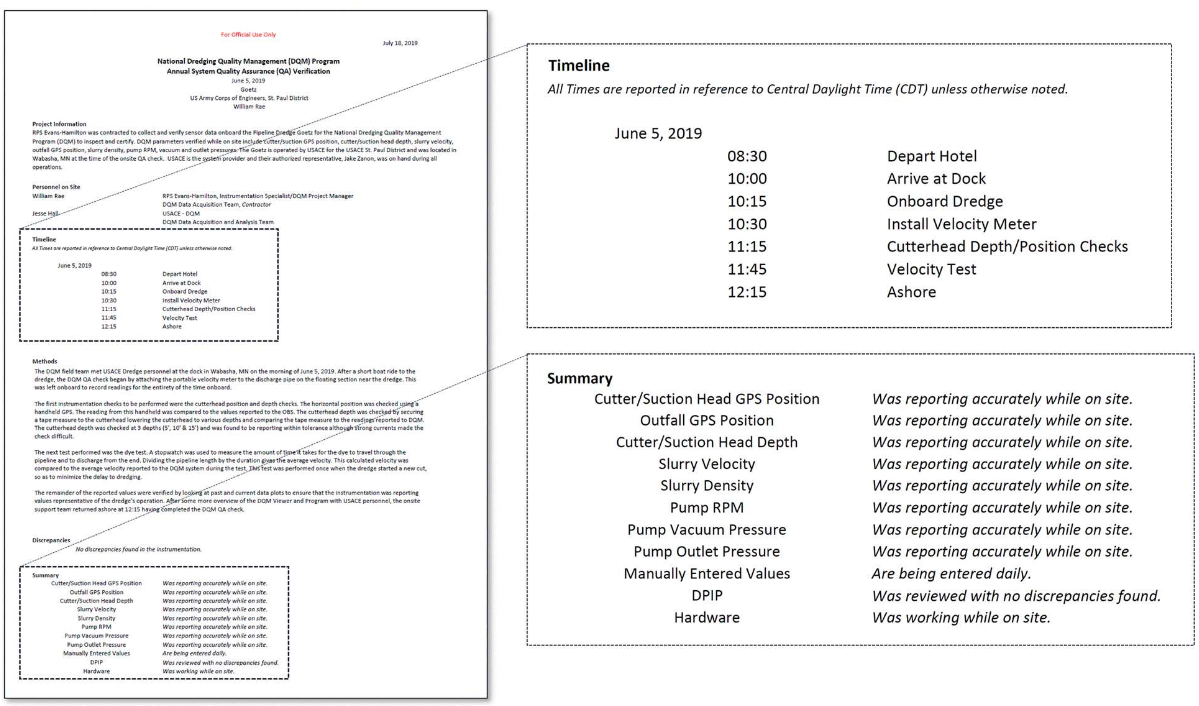


Figure 94. Digitization of timelines and Summary information for tracking of QA check durations and instrument issues.

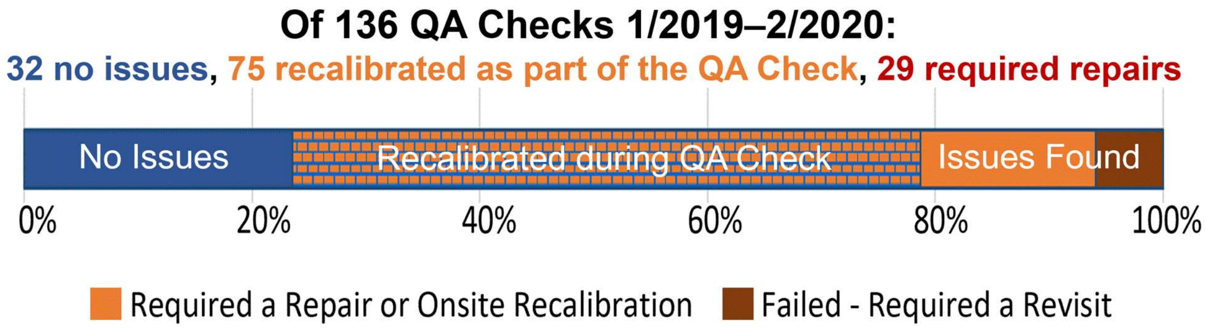


Figure 105. The number of checks performed in 2019 and the percentage of those checks that uncovered issues that either were corrected on site or required a return visit.

Based on a review of the duration of the QA checks for the different plant profiles, it can be argued that the longer DQM staff have been visiting a plant, the more accustomed the dredger is with what to expect and be prepared for the visit, thus seeing a reduction in the length of the procedure. Generally, the DQM team tries to work around the standard procedures of the dredging operation; however, with the consent of the contractor, accommodations may be agreed upon to take some downtime or otherwise modify a dredging cycle to minimize the time on site. New QA procedures, including replacing the traditional draft check on scows with a simulated check, appear to reduce the time on site required for scow checks. In many cases, this reduces the on-site time from days to hours for jobs with multiple scows. Pipeline dredges illustrated the broadest range of duration for QA checks, which could be associated with many new plants coming on line and their relative inexperience with what to expect during the visit.

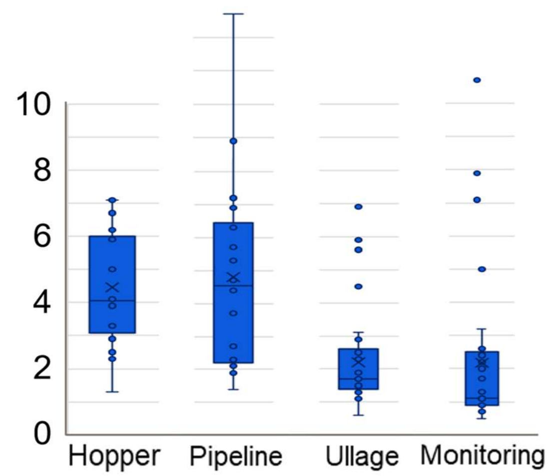


Figure 6. Durations of QA Checks by dredge plant type 1/2019-2/2020.

While some companies have done a great job of internally monitoring and maintaining their systems, and it must be acknowledged that field operations during the pandemic are not completely indicative of normal performance, there is still a significant industry-wide trend for an increase in problems that supports the continuation of a routine calibration requirement as seen when we have an on-site DQM QA presence. With the continued observation of trends in declining sensor performance in the lead-up to annual DQM checks, it appears that hoppers and plants with more sensors need frequent oversight. In contrast, others may have the potential to reduce field visits. The data supports further study, which may mean that some plant types could go to a biannual check or have the length of time between checks increased if they consistently perform with no major sensor QA issues.

RECOGNITION OF NEW CHALLENGES AND OPPORTUNITIES

One field opportunity that has presented itself from the fleetwide postponement of field QA checks is optimized scheduling when the program resumes field activities. The exact form this may take is still open to discussion, but there is strong potential now to visit multiple plants in a geographic region as part of the same trip, or in some regions where seasonal work is typical, the DQM team may try to perform all of the QA checks using simulation methods in the offseason to eliminate impact to dredging operations in season. DQM has been communicating with system providers and dredgers to make the most of this fleetwide reset on expiration dates in the hope that this is a chance to improve the process for all parties involved.

An additional item of interest to DQM was the COVID-19 inspection procedures implemented by the USACE Portland District as described in their 2020 Pacific WEDA presentation, "Remote Dredge Inspection." In that presentation, they describe the use of video inspection techniques. Although DQM has previously investigated including video transmission as part of its requirements, technology may now have advanced enough to take a second look and investigate the addition of remote video oversight into an optional DQM package. Bringing programs like this into DQM can help standardize contract requirements across the country, so dredgers are not required to change expensive equipment when they move a plant between USACE Districts.

CONCLUSIONS

Although it initially appeared that the COVID-19 pandemic would shut down a significant portion of the DQM Program, it has instead strengthened the program overall. The DQM Center was able to foster new connections with the dredging safety industry which, hopefully, will be continued and expanded. In addition, new techniques were developed to perform QA on incoming data more efficiently and distribute this information to field personnel more effectively. The challenges presented by the elimination of on-site inspections became opportunities to document and evaluate the effectiveness of existing field QA procedure, identify trends and issues in sensors and requirements and, potentially, incorporate new technologies in the program.

REFERENCES

National Dredging Quality Management Program, https://dqm.usace.army.mil/.

Smith, Thomas P. (November 12, 2019). *Update to the National Dredging Quality Management (DQM) Program for Pipeline Dredges* [Memorandum for Commanders, Major Subordinate Commands and District Commands, Chiefs of Operations], U.S. Army Corps of Engineers, Civil Works Directorate, Construction-Operations Division.

CITATION

Allen, B.P. and Rae, W.M. "Finding the Silver Lining in COVID-19 Impacts on National Dredging Quality Management Program (DQM) QA Practices," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual Conference, June 15-18, 2021*.

DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential. These data may be provided upon request with restrictions on republication and use.

IT'S ALL (SAFETY) DATA: HARNESSING MEANINGFUL, ACCESSIBLE LAGGING AND LEADING INDICATORS THAT DRIVE SAFETY CULTURE

M. Davis[1]

ABSTRACT

As modern workplaces evolve with advanced technology, tools, and ongoing improvements in whole-worker safety, it is essential that safety data systems capture meaningful, actionable data. Going beyond the adage of "*You get what you measure,*" this paper explores how to customize what you measure and how to engage all levels of your organization in analyzing and acting on what the data is telling you about where you can most improve.

Designing and distributing accessible safety data can help employees at all levels understand where their behaviors and company systems (or lack thereof) may be contributing to injuries.

There is no one magic set of numbers to measure for every organization. Balancing who is collecting what kinds of data is a powerful step to defining and sustaining improvements in your safety culture. Resetting expectations and elevating all parties to data generators and analysts creates organizations collectively focused on results-driven safety.

Extending past collecting meaningful safety data to *doing* something with it, this paper demonstrates that effective safety data systems go beyond care and concern and demand measurable results. Timely and digestible data can show where your efforts are bearing the most fruit and can similarly help you let go of traditional processes that may have gone stale.

This paper chronicles tested and true safety data collection and engagement strategies from best-in-class dredging, construction, and geotechnical companies and offers innovative and scalable solutions proven to send more people home safe every day.

Keywords: Dredging, safety, construction, lagging indicators, leading indicators, data, analysis, field engagement, safety leadership.

INTRODUCTION

We collect data every day in everything that we do. From the moment you wake up you are looking at the clock to gauge how on time (or late!) you are, you watch the morning news while you are getting ready to see how much traffic will affect your morning commute, and you may even have software included in your email that tracks productivity and collaboration in your company meetings. Each data set we collect throughout our day, no matter how formal or informal, provides us with valuable information that affects our decision making and behavior.

Safety data is no exception. While safety data has traditionally been relegated to reporting injuries and incidents for regulatory purposes, many companies have begun to understand the value of collecting, analyzing, and sharing their safety data at all levels to drive targeted action to improve their safety results.

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THE POWER OF MEASUREMENT

The adage of "*You get what you measure*." is certainly true in safety data collection. It is impossible to gauge the off gas of your safety system and culture if you are not measuring the right things. There are essentially two types of safety data indicators to consider measuring- lagging and leading.

Traditional safety data collection avenues such as numbers and types of incidents, man hours, body parts affected, etc. continue to be valid data points to track and are categorized as lagging indicators- measured in the form of past injury statistics, or simply put, things that have already happened.

Increasingly, companies additionally track significant leading indicators to help understand the true state of their safety systems and cultures. Leading indicators signal the increased possibility of a future event and are used to drive activities towards the prevention of incidents.

Without a combination of tracking, analyzing, and communicating lagging and leading safety indicators in your organization, it is impossible to get a true picture of what your current safety environment is. All three factors are needed to point you in the right direction of how to improve your safety results and send more people home safe every day.

It is important to remember that quality safety data may not always be measured in numbers. The raw numbers are important, but you should consider additional metrics like employee satisfaction with current safety programs, field and leadership engagement in safety programs and processes, gut feelings of safety accomplishment, and beyond.

QUALITATIVE VS. QUANTITATIVE SAFETY DATA

In considering what safety data is best to measure for your organization, it is essential to find the balance between the lagging and leading indicators and explore ways to present the data at all levels of your organization. The best way to approach customizing what you measure is to first consider the difference between what quantitative and qualitative data your system is capable of and interested in consistently producing.

Quantitative Safety Data

Quantitative safety data is easy(er) to track and consists of information collected that is numerically represented. When we first think about safety data (quantitative), people will generally talk about incident rates, days away, etc. These numbers help find which areas need immediate focus and urgent attention.

For example, quantitative metrics can help you look at incident rate trends to figure out what training program you implemented had measurable impact. Alternately, you could compile worker's compensation costs to find out how much money you are spending/could save by meeting stricter safety targets. Quantitative metrics like percentages of body parts injured or ages/job titles of workers injured can easily make safety issues concrete. These can be important numbers to share with management and frontline employees to help drive corrective action, but they generally do not show you what is beneath the surface of your safety culture.

Qualitative Safety Data

Qualitative safety data is much harder to track, analyze, and communicate. It consists of information collected that is not numerically represented and, while not readily talked about or characterized in company safety dashboards, it makes up the bulk of safety-related data.

Meaningful qualitative safety data includes employee morale, root causes behind injuries/incidents, sequence of events leading up to injuries/incidents, etc. While it may be more difficult to measure, it can tell you invaluable details about employee stress, production pressure, and overall system-wide contributing factors to incidents and injuries. Qualitative safety data is where you will find useful feedback from the employees actually doing the work on how to improve safety in your workplace.

Qualitative safety data can help you move more toward affecting worker behavior than outcomes. Think safety *performance* data (quantitative) vs. safety *culture* data (qualitative). In a mature safety culture, the goal is to have your incident and injury rates so low that the only data you are able to consistently capture is qualitative. However, understanding that "zero injuries doesn't necessarily mean safe," we will further explore how to find the right mix of data to capture for your organization.

CONSIDER CUSTOMIZING WHAT SAFETY DATA YOU MEASURE

If customizing what you measure regarding safety data were easy, this paper (and the myriad of others out there on similar topics) quite frankly would not exist. The simple answer is: *There is no magic set of data to track for your company.* It is a complex equation that must be routinely evaluated as your organization evolves and your safety culture matures.

The bottom line is that you should engage in collaborative discussion between your Safety Department, leadership, and front-line workers to determine what data they are interested in receiving, capable of contributing to, and think will drive meaningful action at all levels. One attribute everyone is sure to agree on is that more safety data is not necessarily a good thing, and it just makes good sense to narrow your focus on a few types of lagging and leading indicators that everyone will use on a regular basis.

Picking the Right Lagging Indicators

In considering what lagging indicators to track, it is recommended you start with what data is already being captured in your system. For regulatory purposes, most companies are likely already tracking the traditional indicators which include, but are not limited to, injury numbers, types, severity, and location. These can be important numbers to keep your eye on for alarming trends that point you in the direction of where energy should be focused. For example, if you notice your hand injuries are trending significantly higher than past years, it might be time for some intensive hand injury mitigation interventions with your crews.

Traditional lagging indicators like Total Recordable Injuries (TRIR) or Days Away/Restricted/Transfer (DART) rates can provide a consistent number to communicate across your entire company and are also useful to benchmark how your company stacks up to others in industry.

Picking the Right Leading Indicators

Leading indicators can be both quantitative and qualitative. Quantitative might include percentage of employees regularly attending safety meetings and numbers of Good Catches and Near Misses submitted monthly.

Qualitative leading indicators are a little more difficult to capture, and it is recommended that you first define objectives for key safety activities and desired outcomes that will contribute to your positive safety culture. Some ideas of key elements of a successful safety program to help get you started (Bongarde Media 2015):

- Management and leadership commitment to safety
- Employee attitudes and motivation to work safely
- Employee ownership and involvement in safety program/processes
- Communication and feedback effectiveness
- The effectiveness of your current safety programs and initiatives, including incentive and recognition programs, incident investigations, audits and inspections, safety meetings, etc.

Additionally, the following tips may be helpful to companies looking to hone their leading indicator tracking (Davis 2019):

- ✓ **Measure the positive**: what people are doing versus failing to do
- ✓ Have a **short list** to be implemented at the corporate, business unit, and site level
- ✓ Create **vigilant observers at every level**
- ✓ Consider **not publishing scores from site audits**
- ✓ **Incident Analysis:** to predict the future, look at the present
- ✓ Track/provide **data on open/closed Corrective Actions**
- ✓ Focus on **impact versus intention**
- ✓ **Adjust your requests** for info from the system based on the types of injuries you see and the kinds of risks that are out there

Other non-traditional leading indicators, like time it takes to answer a safety question and how your senior leadership responds to incidents and injuries, can also tell you about the status of your safety culture.

Again, these data points might not be easy to capture on the surface, so collaborative discussion with company stakeholders is key to making sure what you decide to track is meaningful and not just busy work.

STRATEGIES FOR COLLECTING, ANALYZING, COMMUNICATING, AND ACTING ON SAFETY DATA

If there was one magic piece of advice to offer about safety data, it might be that it is not just about collecting it, but doing something with it! The quickest way to kill a budding safety data system is to request a bunch of data from the system, but the results never get back to the people being asked to collect it.

When you make a data ask of your teams, be sure you are prepared with a way to compile and share that data back to them on a regular basis. The frequency will vary depending on what kinds of data you are collecting. Certain types of data will be communicated weekly, others monthly, some quarterly, and a few annually.

How Feedback Motivates Behavior

Most typically observed in relation to Good Catch and Near Miss programs, if results are not communicated to the field, employees will not see value in continuing to provide the information to you. This is the single quickest way to impede a data collection effort. If the field does not get feedback on the data they are submitting, they will simply stop submitting. They have too many other responsibilities to maintain in their day-to-day jobs to spend their time actively contributing to safety data systems if they see no value.

Conversely, if employees get regular feedback on the quantity *and* quality of safety data they are submitting, they are sure to continue submitting it! This is another key area where it is important to find the right balance between quantitative and qualitative data for your system. For example, if you solely focus on the number of Good Catches and Near Misses submitted (*quantitative*) and never offer employees feedback on whether or not the ones they are submitting are valuable (*qualitative*) then you will likely continue to receive reports that are not particularly helpful in advancing your safety culture. By offering constructive feedback on submitted reports, you will aid those who are engaged through expanded hazard awareness and quality report writing.

Accessible and meaningful safety data can help employees at all levels understand where their behaviors may be contributing to injuries. There is no way for your system to know whether or not the safety data they are providing is meaningful if you're not giving them regular feedback. The feedback might come in the form of daily toolbox talks, updates at weekly safety meetings, quarterly company newsletters, or even via company intra-net sites. The only wrong way to give safety data feedback is to not give it at all.

Innovative and Scalable Solutions

As you consider possible overhauls to your company's safety data systems, it is important to remember to walk before you run. There are TONS of software programs out there claiming they can help you predict where your next injury might come from, and they all have seemingly infinite ways to present the information to your teams. But remember they all rely on the data you are importing, which is only as good as the people importing it and what they understand about its significance. This includes the consistency with which people enter the information. When you set expectations for what data people will input and how often, ensure you "design with the end in mind" so the expectations are reasonable in relation to their regular workloads and that they will see the results of their data entry in a timely manner.

As with any successful program within your organization, the foundation for change needs to occur in the intersection between where people, processes, and technology come together. No one person, process, or software will be the lynch pin that makes or breaks your safety data system. It is recommended you start small, perhaps using Microsoft Office software likely already in place in your company to collect and share your safety data. Figures 1 and 2 below show simple, yet meaningful examples of how Microsoft Word and Excel can help you paint meaningful pictures of how to communicate your safety data to your company.

In terms of next steps, begin with data that is available to you. Take a hard look at what data is already being collected and start there. Then review and adjust to understand priorities and changes, and do not forget to poll your leadership and front-line employees to determine what data they are most interested in seeing and contributing to. And, most importantly, get out in the field to talk with managers and employees to learn about how they are (or are not) using data in their daily, weekly, and monthly practices and what ideas they have about how they could up their data use games.

SAFETY DATA CASE STUDIES

In the following Case Studies, leaders from best-in-class dredging, marine construction, and geotechnical companies were interviewed to learn more about out how they customize, collect, analyze, communicate, and act on their safety data.

Case Study #1- Vice President from International Dredging Company

A tenured Vice President at an international dredging company shared that the evolution of his company's safety data has moved from paper and spreadsheets to dashboards and things that are much more easily

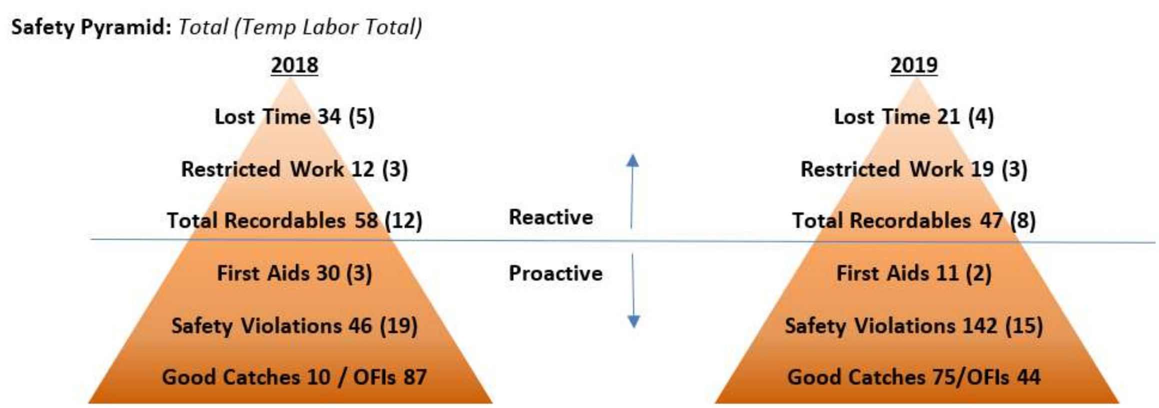
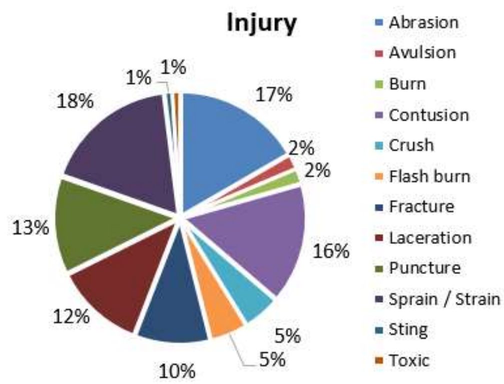


Figure 1. Raw Data Across Organization Example.



Injury	2017	2018	YTD 2019	Cumulative
Abrasion	9 (24%)	8 (14%)	2 (11%)	19 (17%)
Avulsion	2 (5%)	0	0	2 (2%)
Burn	1 (3%)	1 (2%)	0	2 (2%)
Contusion	4 (11%)	10 (17%)	4 (21%)	18 (16%)
Crush	3 (8%)	2 (3%)	0	5 (5%)
Flash Burn	3 (8%)	3 (5%)	0	6 (5%)
Fracture	0	7 (12%)	4 (21%)	11 (10%)
Laceration	3 (8%)	11 (19%)	0	14 (12%)
Puncture	0	15 (26%)	0	15 (13%)
Sprain / Strain	12 (32%)	0	9 (47%)	21 (18%)
Sting	0	1 (2%)	0	1 (1%)
Toxic	1 (3%)	0	0	1 (1%)

Figure 2. Body Part Trends Over Time Example.

communicated in pictures. They have always tracked lots of data, but the focus in recent years has led them to things they can share with their domestic and international fleets and easily create talking points about. Their safety stats are distributed weekly on the project level and then monthly and quarterly from corporate. *"Before it was just a bunch of numbers, now we have easy ways to share them with crews and have real conversations about what's going on in the fleet, and that has been really helpful."*

Leading Indicators were a pet project several years ago once their incident rates were becoming so low that they simply did not have much lagging data to interpret. (They have not had a recordable injury since 2017.) They now have a daily format to collect overall company leading indicator numbers, thereby enabling managers to have perspective of what is happening on their projects in almost real time. *"Who knew that we could create 1200-1500 Leading Indicators daily?! There was an incredible patch of data that was out there that we weren't previously tapping into."* Daily reporting of leading indicators from the project level in the field creates a lot of opportunity to drill down and actively monitor trends.

On a leading indicator basis, they are very consistent about reporting and reviewing. They are doing everything they want to be doing and tracking and are looking to normalize leading indicator rates much like they previously normalized review and trend analysis for Total Recordable Injury Rates (TRIR). They are looking to establish what is a "normal" rate for a Good Catch. Then, if they see the rate going down, they will talk about it, to figure out what they are doing, what is happening, and what they are going to do about it. *"The data is out there. I think we are still learning how to best use it in terms of trend analysis. That's where we need to go next."*

Early in his career before he really learned how the data could be so useful, the Vice President acknowledges being guilty of throwing the data on the desk in front of his crews and asking them to review. Since he has become a data hound, seeing firsthand how it can drive sustainable safety results, he has adopted his approach to be more face to face, explaining to his crews why it is important, how he uses it, and how he expects them to also use it in their daily, weekly, and monthly practices. He has taken personal responsibility for setting expectations and creating a leading culture of what he wants his group to be.

One poignant action that has recently come from consistent data review is represented in the example of an anchor barge that was routinely being tied up next to a cutter dredge. Near Miss reports showed numerous times where crews were reporting damage on the anchor barge from where a storm blew up and knocked it against the dredge. They noticed it was consistently happening and knew the wind was going to consistently keep coming up. Since the barge has its own anchor, the crews suggested they should just anchor it away from the dredge where it could not bang up. *"That was $100,000-$200,000 we didn't have to fix last year because the crews were engaged in reporting and acting on the data!"*

"When you put in a leading indicators system, you're going to find low hanging fruit. It is easy to detect and fix, but if you are not tracking it, you don't know what you don't know. As soon as you find out about it, it gives you opportunities for targeted improvement. If it gets measured it gets improved. When we first started tracking leading indicators, we focused on the ones that we thought were most impactful to performance and were easily measurable. We wanted it to be an easy yes/no fill in the blank type thing, so our early ones were Job Safety Analysis (JSA) and pre-shift related— the ones you can normalize and turn into rates instead of just counts. It can be daunting, but the benefit is immediate and so worth it."

Case Study #2- Division Manager from Nation-wide Geotechnical Engineering Firm

A Division Manager for a nation-wide Geotechnical Engineering firm looks at his company's Safety Matrix every Wednesday. The Safety Matrix is a custom-built Excel Spreadsheet that tracks just about every lagging and leading indicator the company has been able to think of since the document was created, including recordable injuries, Site Safety Check-ins (similar to audits), positive safety feedback, documented safety coaching, Near Misses, safety violations, and First Aids. While the Matrix has always been available to him, he just last year made it a common practice to review it on a weekly basis.

In addition to checking for recent updates to data in his Division, he also looks to make sure new employees have completed their New Hire Safety Orientation. If there is someone who has not taken it, he notes who and personally engages with one of his Trainers to schedule it.

Following a fatality in his region involving a motor vehicle last year, he has really stepped up his safety data review game and has challenged his Division to do the same. Losing a co-worker really challenged the Division to look at who they were safety-wise, especially when it comes to their safe practices and mindsets. They know if it is not getting the weekly attention and the weekly challenge, then it is not going to change. The Division Manager acknowledges that he does not think he was doing anything wrong before by not engaging more closely with the data, but he certainly did not make it a point to keep score. *"It's not all in the numbers, it's all in the mindset. But, if you're not tracking the numbers, you're not tracking the mindset."*

He also uses the data to drill down into different offices and departments in his Division to see how they are doing. He explicitly made it a point to set expectations that the offices in his Division will be better than company rates. If he sees they are lacking, he has direct conversations with his Office Managers to see how he can help them come up with a game plan to improve. This has helped the make the importance of safety data and its implications a lot clearer today than it was a year ago for all the leadership in his Division. Office Managers now also look at the data for their offices on a weekly basis. From a Department standpoint, it is pretty normal business now to have their weekly engagement in safety meetings.

The Division Manager's boss for the Operations Group develops a monthly agenda where the Division Managers meet with him, and then they use that same agenda to cascade to all the individual office meetings. The data helps inform one or two monthly topics to focus on, and then checking their driving scores is always next. These scores are tracked company-wide since there are so many fleet vehicles in service. Then, standing agenda items include a review of bi-weekly leadership letters, monthly/annual inspections, and any further data review deemed necessary in addition to what they are doing on a weekly basis. They also take the opportunity of all being together to share notable Near Misses and Lessons Learned from them in the previous month.

This time last year and in 2018 Preventable Motor Vehicle Incidents (PMVIs) in his Division were much worse than the company average. Through careful review of the data, they identified that drivers with two years' experience and drivers 30-years-old and less were having the majority of their vehicle incidents. The Division got the high-risk drivers together and had a detailed discussion presenting the numbers to make sure they were fully aware that they were the group that were having the wrecks/incidents. The drivers were asked peer to peer to break into groups to come up with solutions to help fix the problem.

It was key for these discussions to happen without their boss telling them how to fix it. The drivers then presented back to their managers what their solutions were. The Division has had follow up meetings through the year to keep both the drivers and management accountable for continued improvement. This approach brought a more heightened sense of emergency, resulting in better Pre-Task Plans to look at driver routes and plan them out before they ever leave the office. They now concentrate on truly being in the truck and just driving and taking their time to get to job sites. The entire Division is now committed to making sure their schedules are completed in advance to keep people from bouncing from job to job, never putting someone in a situation where they feel rushed. They have also made it a priority to intentionally use safety cones to help them physically make a 360 degree walk around of their vehicles every time before they drive away. They have since cut their PMVI rate in half and it is continually on a downward trend.

Since the Division has been more closely focusing on regularly reviewing and acting on their safety data, documented coaching has also gotten much better. Whether it is a violation or just a new employee orientation, they are intentional about having the tough safety conversations and *documenting* when they occur. They were always pretty good about having the conversations but were not in the practice of documenting them. The whole company has changed their mindset to realize that having a coaching session is not a bad thing. It helps both parties be in better mindsets. If it is just a hallway chat, it is not as meaningful. *"We thought we were doing the right thing before by talking about it, and we were, but we're doing the <u>better thing</u> now by documenting it."*

"It is important to me and it has made a difference in the last year that the offices, departments, and employees know that we're doing everything we can as a company to keep everyone safe. But, even with that, there's something to keeping score and watching. When you keep score, people play the game differently than when you don't. In addition to care and concern, it's also about friendly competition. We really didn't have that in the past."

Case Study #3- Senior EHS Manager from Nation-wide Dredging and Marine Construction Company

A Senior EHS Manager for a dredging and marine construction company has seen their safety data reporting, analysis, and communication system change for the better in recent years with the adoption of a web-based software tracking system for reporting. Any authorized user in the system can go in to report Near Misses, equipment issues, injuries, environmental concerns, etc. The software seamlessly tracks people involved, equipment being used, project name, time, date, tenure at company and industry, location, etc. It also can track and log what incidents are still open and which have been closed, and gives options to assign investigations and Corrective Actions.

It is up to each project to set up who can access. Some Project Managers like to input the data themselves and some try to not limit their crews on how they want to report things. At the end of the day, some crew members do not like to write reports, and the autonomy the company practices in letting the projects decide who will and will not create the reports has been beneficial.

The Sr. EHS Manager acknowledged that you can lose the data if people cannot easily capture it immediately. *"The easier you make the stuff to report, the more information you're going to get."* He also noted that following up when crews submit quality data is a key component to the company's continuing to collect quality data. *"Simply contacting a crew member and saying 'thank you for reporting' makes a big deal. When possible, we have Vice Presidents call people and acknowledge them for submitting quality data, too. You would be amazed at how many reports come in after one of those phone calls."*

Project level data is presented at weekly safety meetings where they review any incidents then ask crews for anything else that might be going on that did not make it into the system. Additionally, a weekly incident summary is sent out company wide. Compiled by the Safety Department, it consists of a summary of all incidents and Near Misses that they think are worthy of sharing system wide. The report also includes the Year-to-Date Total Recordable Injury Rate (TRIR) and Days Away/Restricted/Transfer (DART), and days since their last Recordable injury. The company summary is typically reviewed during project weekly safety meetings, and it is up to project management's discretion which of the incidents they cover. Since they do not have weekly safety meetings in the corporate office, it is up to office people to read and review themselves. The Safety Department and Executive Teams all review during their respective weekly calls.

When they notice trends in the system, particularly around Near Misses, it causes them to ask and wonder "why," prompting them to then go back and study the data. *"People are intrigued by trends and analysis. Once you start talking to them about it, it's eye opening. It triggers things like 'Oh that does happen here, I just hadn't thought to report it.'"* For example, they recently identified a large number of Near Misses related to falling objects. They ran some reports to see just how many, and the number was staggering. Some crews just thought falling objects were a normal occurrence and not worthy of reporting. The next week's safety meetings focused on falling objects and engaged crews in active discussion to think through how they could mitigate the hazards of falling objects. They concluded you cannot always predict what is going to fall, but you *can* predict where you are going to stand! In the following weeks, they actually saw an increase in falling object Near Misses being reported because people were paying better attention. *"These Near Misses were always happening; people are just reporting them more regularly now. The data is a gift to our system."*

CONCLUSION

In Hile Group's experience, and as detailed in the above Case Studies, the most important thing a safety culture can do regarding their safety data is continually monitor how they are collecting, analyzing, communicating, and acting on it. Safety data is a living, breathing animal that needs nurturing as an organization evolves to stay relevant and continually protect the men and women in its ranks from harm.

As you go forward with your company's unique safety data collection, analysis, and communication, please keep in mind the following:

- Set expectations. This applies to all levels for how they will report and consume data. Remember this will look different for an Executive and a Front-Line crew member in terms of what data they contribute, what frequency and format they see it in, and how they act on it. It is imperative people at all levels in your organization are clear on how you want them to engage with your safety data.
- Be consistent. Pick a handful of metrics and stick with them for at least three years. If you continually switch what you are tracking and sharing, you will never gain any useful information to accurately trend.
- Provide education. "Data literacy" is key. Employees need to understand what they are seeing and how it applies to their daily work. *What does the TRIR mean? How should/could TRIR influence the choices I make when working?* A straightforward way to get up the curve is to build upon data skills your people have in other areas like production and port them over to safety.
- Benchmark your data. *How do you compare to other projects/offices/divisions within the organization? How do you compare to other organizations in industry?*

- Ask leading questions. Don't just email the data out and say "*What do you think?*"
- Go slow and steady. Remember data can be scary for some people, but once they begin to gain fluency an confidence, you'll be amazed at what your system is capable of!

REFERENCES

Bongarde Media. "Building a Safety Culture by Measuring Results," *Safety & HCM Blog Post*, October 20, 2015.

Davis, M. "Harnessing Leading Indicator Data for Sustainable Safety Excellence," *Proceedings of the Western Dredging Association Dredging Summit & Expo '19, Chicago, IL, USA*, June 6, 2019.

CITATION

Davis, M. "It's All (Safety) Data: Harnessing Meaningful, Accessible Lagging and Leading Indicators That Drive Safety Culture," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Virtual, USA*, June 15-17, 2021.

DATA AVAILABILITY

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A 3D ANALYTICAL MODEL FOR LINEAR ROCK CUTTING PROCESS

X. Chen[1], T. Rutten[2], G. Liu[3], G. Hong[4] and S.A. Miedema[5]

ABSTRACT

In dredging, rock cutting is an often encountered engineering process. It is of great importance to be able to calculate the rock cutting forces, because they influence the energy consumption and the wear on the tool to a very large extent. Currently several existing models are capable of calculating the rock cutting forces in a two-dimensional (2D) domain where a sharp cutter is used. In this research an experimental study is conducted by using a pick-point cutter to linearly cut the rock to check which existing model fits the best with the measurements. It is found that the existing models cannot well predict the cutting forces due to the assumptions of the 2D process and the sharpness. Thus extra modules are derived and added for the 3D and the bluntness effects. Results from the expanded model agree well with the lab measurements within the allowable error margins.

Keywords: Experimental study, rock cutting, pick-point, analytical model.

INTRODUCTION

The world has witnessed a dramatic increase in dredging activities during the past 20 years, which is to meet the infrastructure demands for the increasing population. In dredging, the underwater excavation process is one of the most important engineering processes. The objects to excavate, by their mechanical characteristics, can be categorized as sand, clay and rock. Sand is considered to be non-cohesive and destructive, where "destructive" means that the structure of the sand pile changes during failure in an irreversible way. Clay's mechanical behavior is cohesive and non-destructive, and here "non-destructive" indicates that the change of solid skeleton during failure is reversible. Rock, on the other hand, is cohesive while destructive.

Among these three materials, cutting rock is the most energy consuming job. When cutting rock with various cutting angle and cutting depth, the specific cutting energy (SE) varies a lot. Here SE is defined as the energy consumed to remove one cubic meter of rock. It is thus quite important for the dredging industry

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to fully understand the physical phenomenon in rock cutting process, so that cutting forces and cutting energy can be calculated and predicted.

The rock cutting process is described in earlier research by (Chen et al. 2015), which was focused on modelling the cutting process of sand, clay and rock. In other relevant publications by Helmons (2017), (Li et al. 2012) and (Goktan et al. 2005) the influencing factors in cutting force calculations are studied, while the absence of some important physical phenomena within the prediction models is mentioned.

In those previous models, the cutting tools are considered perfectly sharp, while the force calculation is conducted in a two dimensional (2D) domain. However in practice, the cutting tool usually contains wear flat, and the cutting itself is a three dimensional (3D) process. In this research project, a series of linear cutting tests are carried out on sandstone samples. This research project utilizes the observations from experiments to improve the calculation model of rock cutting forces, by adding the modules representing wear flat effect and 3D effect.

DETERMINATION ON MECHANICAL PROPERTIES OF ROCK

No matter which calculation method to use, some key mechanical properties are always required for calculating the rock cutting forces. Usually, small cylindrical samples are obtained from the rock material and subjected to a Uniaxial Compression Test and a Brazilian Split Test to determine the Unconfined Compressive Strength (UCS) and Brazilian Tensile Strength (BTS). Then, by using the Hoek-Brown failure criterion, the cohesion (c) and internal friction angle (ϕ) of the rock sample can be calculated. The external friction angle (δ) is approximated by using $\delta=2/3\cdot\phi$.

The ratio between the UCS and the BTS gives the brittleness index (or the ductility number) of the rock, which partially determines the mode of failure. According to (Hucka et al. 1974), samples with higher brittleness tend to have: low values of elongation, fracture failure, formation of fines, low resilience, high angle of internal friction and formation of cracks in indentation.

With known UCS, BTS and brittleness index, the Hoek-Brown failure criterion can be used to calculate the internal friction angle (ϕ) and cohesion (c). This is done by applying the generalized equations by (Hoek et al. 2002). In equation 1, σ_1 and σ_3 are the major and minor effective principal stresses at failure, σ_{ci} is the UCS value of the intact rock.

$$\sigma'_1 = \sigma'_3 + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^{a} \tag{1}$$

Variables m_b, s and a are material constants. Variable m_b is a reduced value of a material constant determined by the brittleness (m_i). The brittleness can easily be calculated by dividing the UCS by the BTS, as described earlier. The expression to calculate m_b is given by equation 2. The Geology Strength Index (GSI) is based on the discontinuities in the sample. For intact rock $GSI = 100$.

$$m_b = m_i \cdot e^{\frac{GSI-100}{28-14}} \tag{2}$$

For the determination of variable s equation 3 is applied, with $s=1$ for intact rock. Finally, variable a is empirically composed to approximate the shape of the Mohr-Coulomb failure envelope (equation 4).

$$s = e^{\frac{GSI-100}{9-3D}} \tag{3}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{\frac{-GS}{15}} - e^{\frac{-20}{3}}\right) \tag{4}$$

The final expressions for the effective cohesion (c') and internal friction angle (ϕ') of the studied rock sample become as follows, where $\sigma_{3n}=\sigma_{(3,max)}/\sigma_{ci}$. The value of $\sigma_{(3,max)}$ is the upper limit of the confining stress.

$$\phi' = \sin^{-1}\left(\frac{6am_b(s+m_b\sigma_{3n})^{\,a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{\,a-1}}\right) \tag{5}$$

$$c' = \frac{\sigma_{ci}((a+2a)s+(1-a)m_b\sigma_{3n})(s+m_b\sigma_{3n})^{\,a-1}}{(1+a)(2+a)\sqrt{\frac{a+(6am_b(s+m_b\sigma_{3n})^{\,a-1}}{(1+a)(2+a)}}} \tag{6}$$

These formulae are implemented into the 'RocLab' software, where the rock parameters can be filled in, after which the program calculates the outcome of the above described equations. The general relationship in equation 7 was used to calculate the external friction angle (δ). Table 1 contains the results of the small scale laboratory experiments, as well as the calculated rock properties by 'RocLab'.

$$\delta' = \frac{2}{3}\phi' \tag{7}$$

ROCK CUTTING EXPERIMENT

In total of 5 sandstone samples were supplied from a quarry in the Yunnan province of China by the Yunnan Shihui Stone Co., Ltd.. To determine the relevant rock characteristics, small scale laboratory tests were conducted at the geotechnical department of the Tongji University in Shanghai. Here below Table 1 indicates the obtained mechanical properties of the rock samples. The *UCS*, *BTS* and m_i values are measured with small scale laboratory experiments. With the use of 'RocLab' software, the values for c' and ϕ' are determined. The value for δ' is calculated with the above described approximation (equation 7). Every sample was cut in half for the experiments. In this research both halves of sample 3 were used. Whenever the second half of sample 3 is used, it is marked as 3_2.

Table 1. The obtained mechanical properties of the rock samples to be cut in the experiments.

Sample	UCS [MPa]	BTS [MPa]	m_i [-]	c' [Mpa]	ϕ' [°]	δ' [°]
1	18.9	1.7	11	3.7	44	29
2	26.6	1.1	24	4.7	52	35
3	20.4	1.7	12	4.0	45	30
4	17.6	1.3	14	3.3	46	31
5	18.7	1.6	12	3.6	45	30

From Miedema (2014) it is learned that a brittleness (or ductility) index below 9 implies ductile failure, while above 15 would lead to brittle failure. Most samples from table 1 are in an intermediate range in terms of brittleness. The distinction between brittle and ductile failure is however an important criterion in deciding the most suitable calculation model and therefore necessary to predict the forces accurately. Since the brittleness calculations does not provide an irrefutable choice of failure mode, the observations on - and analysis of the cutting experiments have to give a conclusion.

The rock cutting experiments were conducted at a test facility of the National Engineer Research Center for Dredging Technology and Equipment Co., Ltd. in Shanghai and consisted of linear cutting tests with a single pickpoint. Several cutting angles and depths were incorporated to cover the range of most commonly used values. A range of 40º-60º is typical for dredging purposes, while angles up to 70º are used for the scraping of soil in the oil and gas industry. For applicability, this whole spectrum is covered, with the increments set to 5º.

The cutting velocity was set to 0.05m/s, which was determined by trial and error. Larger velocities increased the peak force at the moment of impact. Since the bottleneck was the capacity of the pressure sensor, the velocity was reduced to keep this peak force below the maximum allowed value. The cutting depths were again limited by the capacity of the pressure sensor. Increments of 0.5cm were used until the maximum force of the sensor was reached, which was around 1.5cm.

Although it seems contradictory for the purpose of dredging, the experiments were conducted without water. Since the cutting was carried out at a limited velocity and in a linear direction, no forming of voids will occur. Therefore cavitation would not play a role. Secondly, a limited water depth does not cause hyperbaric conditions. So the addition of water will not yield extra data, but would increase the difficulty of the experiments tremendously. The effects of hyperbaric conditions on the cutting of rock are covered in detail by (Chen et al. 2014). By sieving the produced material after testing, the particle size distributions were composed as well. These are later used for the determination of the mode of failure.

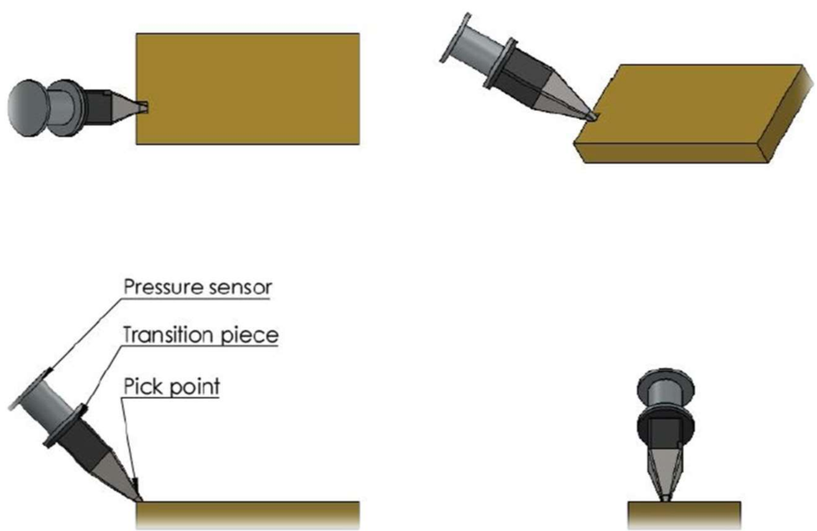

Figure 1. The cutting setup consisted of a pickpoint, which was mounted to a pressure sensor by a transition piece. This all was connected to an adjustable arm on a movable platform.

In figure 1, the cutting geometry is visualized. The pickpoint blade is mounted onto a transition piece, which is connected directly on a pressure sensor. The pickpoint has a total length of 30cm, with a tip angle of 26º. This setup is mounted onto an adjustable arm so the height and cutting angle could be set accordingly. By pulling the arm through, the pickpoint was pulled through the sample, while measuring the forces in x-, y-, and z-direction.

Figure 2 contains the results of the linear cutting experiments. For convenience, the data points are represented with linear approximations, similar to the assumptions made by the analytical model (as described in the next section). The maximum total cutting forces ($F_{t,char}$), horizontal cutting forces ($F_{h,char}$)

and vertical cutting forces ($F_{v,char}$) are made dimensionless according to the Buckingham-π theorem (Lyons et. al., 2011) and plotted over the depth.

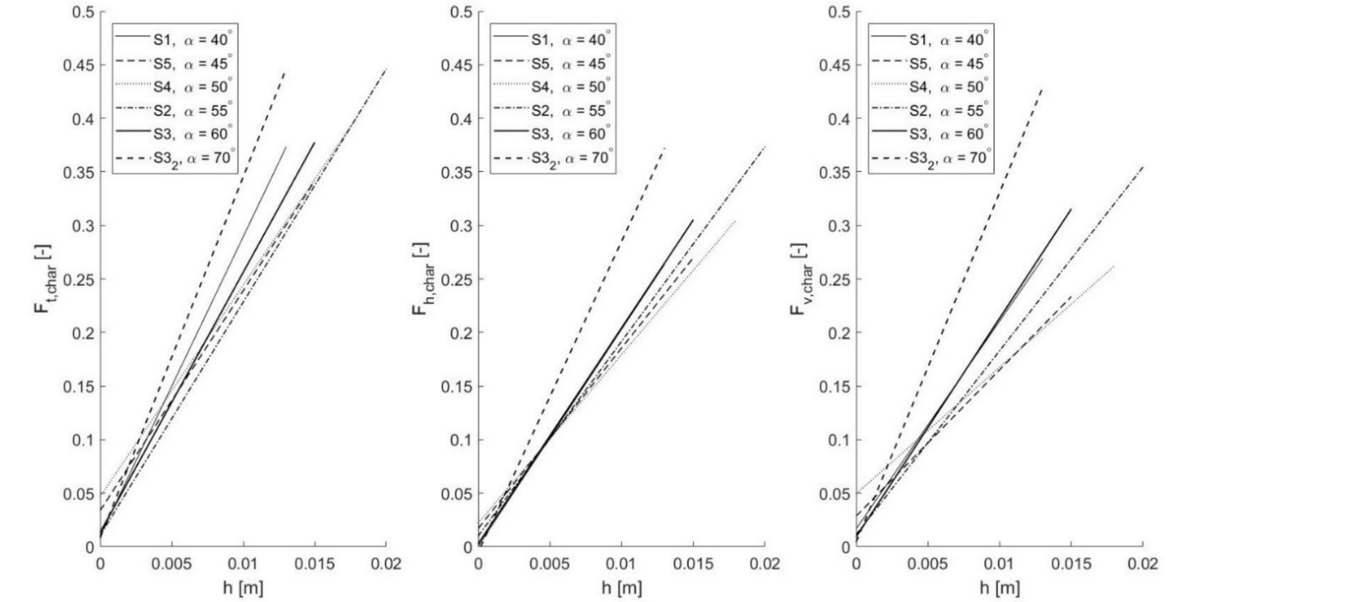

Figure 2. Results of the linear cutting experiments: the measured characteristic maximum total cutting forces, maximum horizontal cutting forces and maximum vertical cutting forces plotted over the cutting depth.

The cut out granular material was collected after every experiment and sieve analysis was applied to assess the particle size distribution. By using sieves with meshes of 2mm, 5mm, 10mm and 20mm, the distributions of the rock fragments is composed. The average depth ($h_{average}$) of the whole cut is used to distinguish the different experiment per cutting angle.

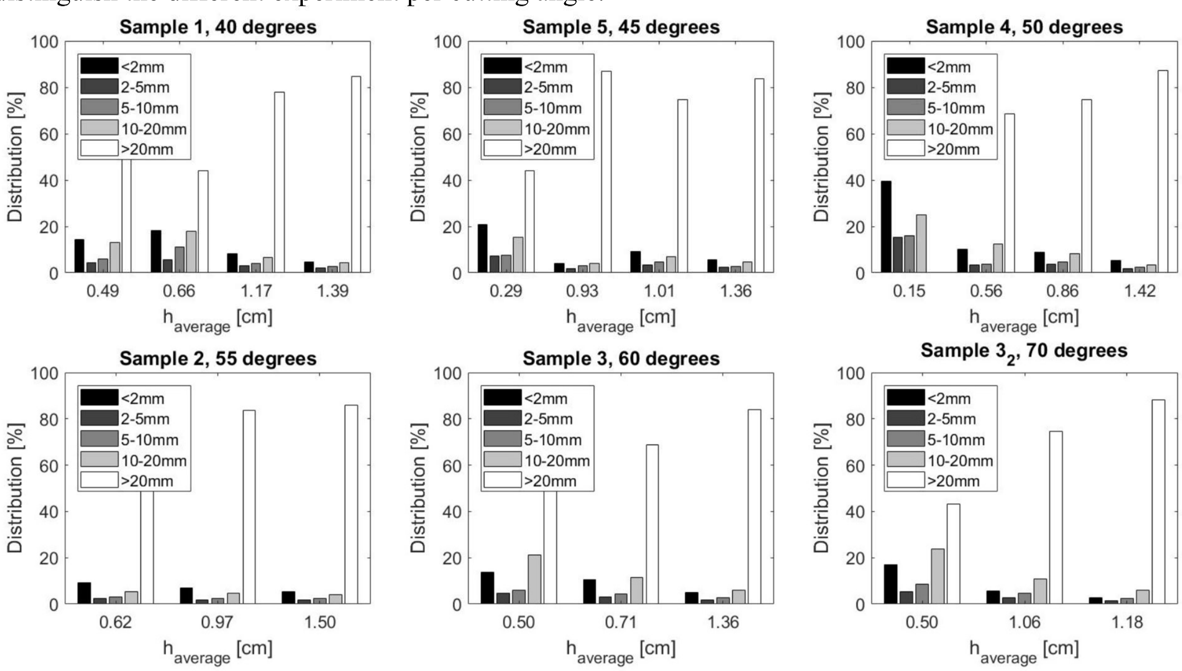

Figure 3. Results of the linear cutting experiments: the particle size distributions plotted over the depth and separated per cutting angle.

VALIDATION WITH ANALYTICAL MODEL

The failure of rock can occur in several manners depending on the rock properties, confining pressure and cutting depth. Cutting force prediction models have been developed for each type of failure. Rock failure occurs either in a brittle (brittleness $m_i > 15$), a brittle-ductile (brittleness $9 < m_i < 15$) or a ductile manner (*brittleness* $9 < m_i$). Brittle failure occurs at relatively low confining pressure and deviatoric stresses. Pure tensile failure, axial tensile failure and (discrete) shear plane failure are all considered types of brittle failure.

In brittle failure the force builds up until a certain limit is exceeded after which the failure occurs. At higher confining pressures during the cutting process, the failure shifts to a more brittle-ductile (or semi brittle) failure with either a shear belt or a shear zone. Even higher confining pressures can lead to a ductile failure mode. The brittleness indexes of the samples used during the experimental stage are all in the intermediate brittle-ductile range, except for sample number 2. Therefore, the brittleness index alone does not provide a decisive answer on the failure mode.

To determine the exact failure mode, the experimental settings and observations are analysed. Since the experiments are conducted without the presence of water, the maximum possible confining pressure is atmospheric. A ductile failure mode is therefore not likely to happen while cutting rock. The major brittle failure modes are the brittle tensile type and the brittle shear type. For the brittle tensile type sufficient depth is required for the development of a tensile crack. Since the maximum cutting depths during the experiments are approximately 1.5cm, the brittle shear type seems more likely.

From the particle size distributions, the presence of crushed material (< 2mm diameter) is established. On average this crushed material makes up for 10-20% of the total distribution, with an outlier up to 40% for the shallowest cut on sample number 4. Since pure tensile failure does not produce crushed material in these quantities, this increases the likelihood of the brittle shear type failure mode. So even though the possibility of the existence of a tensile crack at the top part of the rock cannot be refuted, based on physical interpretations and observations the dominant failure type is assumed to be brittle shear.

Several models have been developed in the past to predict the cutting forces under the assumption of brittle shear failure. In the Delft Sand Clay and Rock Cutting Model[9] several calculation models are described and derived, including the model by Nishimatsu[10]. The Nishimatsu model assumes the use of a sharp cutting tool and a 2D cutting process. It also assumes a linear relationship between the maximum cutting forces and the cutting depth. Since cohesion delivers the resistance force to shear failure, it is used as the dominant rock characteristic in the force calculation model. The expressions for the horizontal, vertical and total force component are stated below. If the stress distribution factor $n = 0$, a calculation model for the ductile failure arises: the Flow Model.

$$F_h = \frac{1}{n+1} \cdot \frac{c\, h_i w \cos(\phi) \sin(\alpha+\delta)}{\sin(\beta) \sin(\alpha+\beta+\delta+\phi)} \tag{8}$$

$$F_v = \frac{1}{n+1} \cdot \frac{c\, h_i w \operatorname{co}\ (\phi) \cos(\alpha+\delta)}{\sin(\beta) \sin(\alpha+\beta+\delta+\phi)} \tag{9}$$

$$F_t = \sqrt{F_h^2 + F_v^2} \tag{10}$$

After substituting the rock parameters in the Nishimatsu model the characteristic maximum force predictions are plotted over the cutting depth (figure 4).

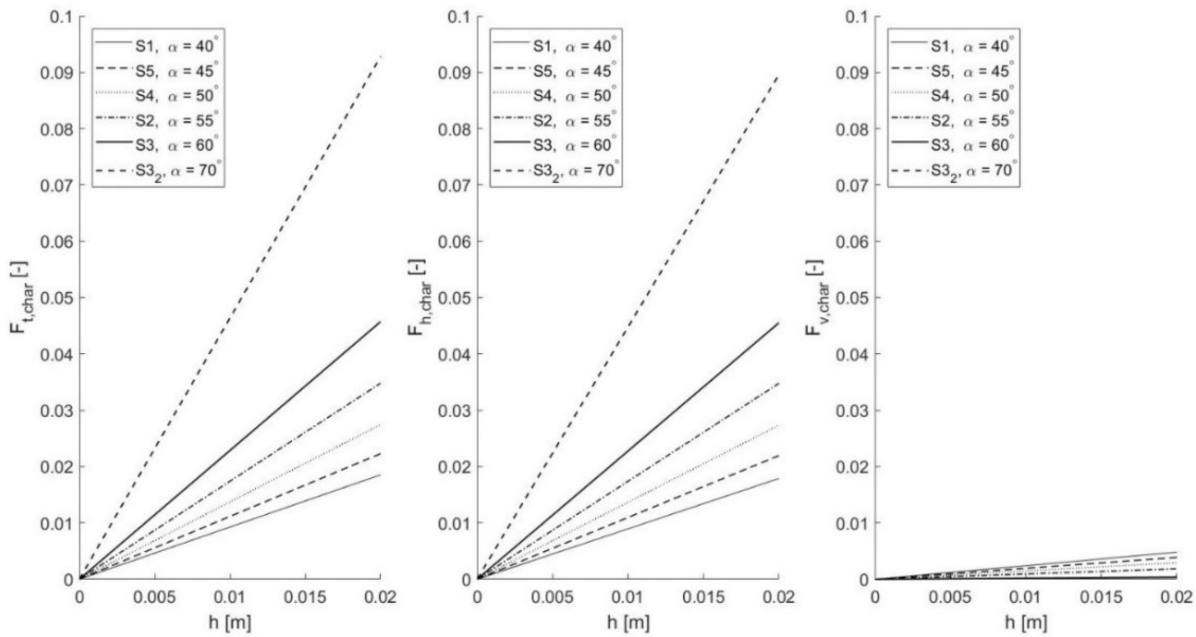

Figure 2. Results of the cutting force calculation models: the predictions of the maximum total cutting forces, maximum horizontal forces and maximum vertical forces according to the Nishimatsu model

Figure 5 shows the comparison of the total, horizontal and vertical cutting forces from the calculation of Nishimatsu model and the experimental measurements. In Figure 5, $F_{calcuated}$ indicates the forces from the Nishimatsu model, while $F_{measured}$ indicates the experimental measurement. A linear relation of $F_{calcuated}=F_{measured}$ has been plotted out together with the 20% variation boundaries. When the dots fall in the region above the $F_{calcuated}=F_{measured}$ line, it means the calculated values (Nishimatsu model) are larger than the measured values. When the dots fall in the region below the $F_{calcuated}=F_{measured}$ line, it means the measured values are larger than calculated values (Nishimatsu model). As shown by Figure 5, it is learned that the predictions ($F_{calculated}$) only make up for a small percentage of the actual measured cutting forces. Even the ductile model with $n = 0$ does not accurately predict the forces.

EXPANSION OF NISHIMATSU MODEL

To increase the accuracy of the force predictions, the assumptions under which the Nishimatsu model operates are investigated in detail. In particular the sharp tool assumption and the 2D cutting process assumption. In the proposed component model by Rutten (2019), the measured cutting force (F_c) is decomposed and the magnitudes of each component is explained, derived and calculated. The cutting force calculated by the Nishimatsu model (F_1) is assumed to be the force to initiate the 2D cut. The additional components (F_2 and F_3) are added to include physical processes observed during the experimental stage of this research (equation 11). Further research will be aimed at achieving force prediction models which include all physical processes to produce accurate force predictions.

$$F_c = F_1 + F_2 + F_3 \tag{11}$$

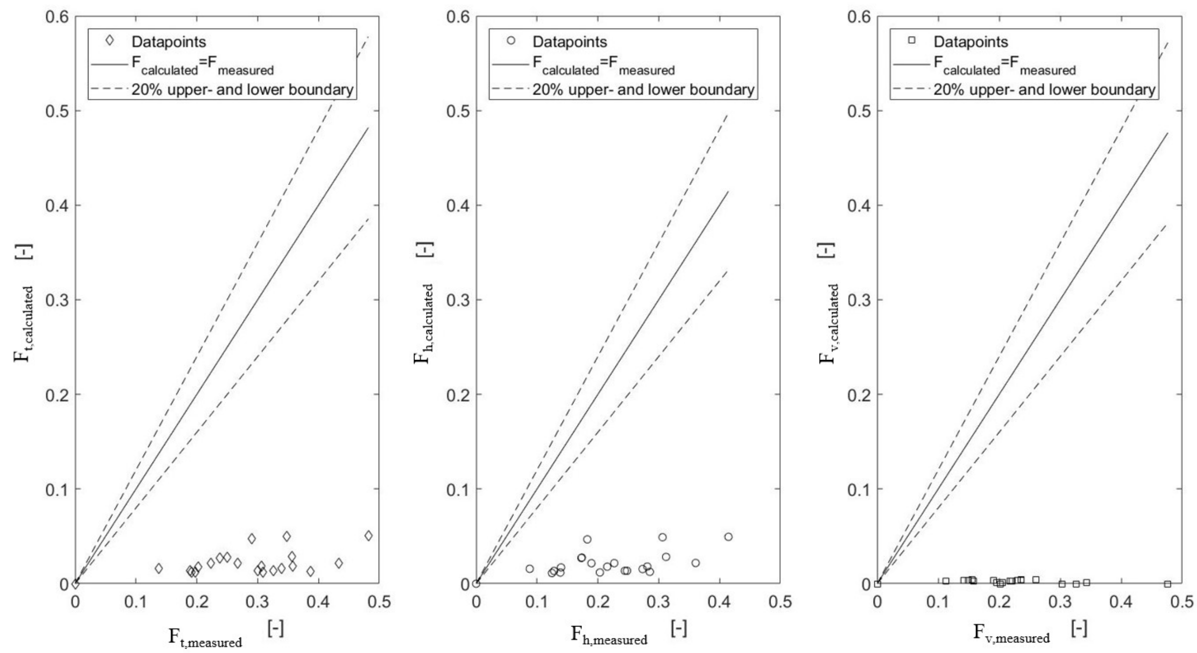

Figure 3. Comparison of the calculated forces by using the Nishimatsu model (*$F_{calculated}$*) with the measured forces (*$F_{measured}$*) during the linear cutting experiments

The wear flat effect

The assumption of the usage of a sharp tool raises a practical question: does the tool stay sharp during the entire cut? Wear and tear make the tool less sharp and, depending on the criterion of sharpness, the tool might be considered blunt after cutting a certain distance. From this point on, the sharp tool assumption is not valid and the calculation model does not account for the effects of cutting with a blunt tool. Therefore it seems more appropriate to assume a blunt tool instead of a sharp tool and include the effects in the calculation model.

According to the research conducted by (Li et al. 2012), cutting with a blunt tool lead to the development of a secondary crushed zone. The removal of this secondary crushed zone requires an additional force: the indentation force. Figure 6a visualises the cutting mechanism for cutting with a blunt tool. The same research indicates that the horizontal part of the indentation force (P_2) is approximately equal to the dynamic friction between the cutting tool and the rock sample. By using figure 7 creatively, the magnitude of the dynamic friction (and thus P_2) can be determined.

In Figure 7, an object with weight W is resting on a surface with dynamic friction coefficient μ, which delivers a normal force F_n to keep the object from moving vertically. To move the object in the direction of cutting velocity v_c, the frictional force F_{fric} has to be overcome. Now the object is substituted with the pick point and instead of the weight, the vertical cutting force (measured during the experiment) is used. Under the assumption that the pick point only moves in horizontal direction, the normal force F_n is equal to the vertical cutting force F_v for vertical force equilibrium. In order to move the pickpoint in cutting direction, the friction force F_{fric} has to be overcome by the cutting force. Since the vertical cutting force is known from the experiments and the dynamic friction coefficient between sandstone and steel is determined by Gaffney (1976), the following dynamic friction laws can be applied. Under the assumption that the indentation direction is perpendicular to the shear plane of the rock (β), the values for the vertical part of indentation force Q_2 and the total indentation force F_2 are known.

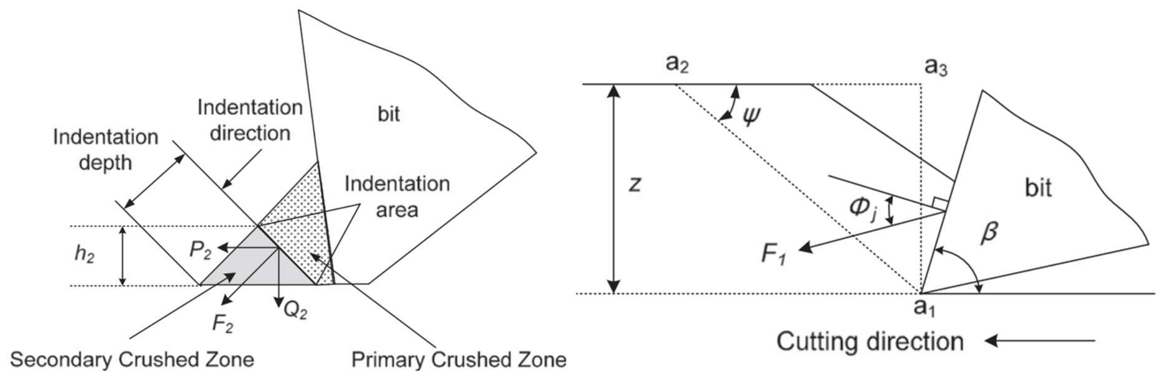

Figure 4. a: (left) Cutting mechanism for cutting with a blunt tool. In contrast to cutting with a sharp tool (b, right). With a blunt tool a secondary crushed zone develops in front of the primary crushed zone. The cutting direction is from right to left in both graphs (Li et al. 2012).

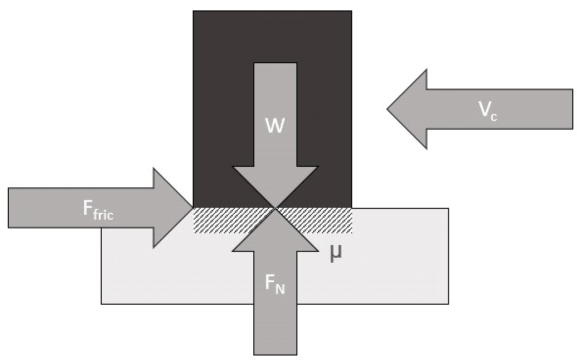

Figure 7: Concept of dynamic friction for approximating the horizontal part of the indentation force *P₂*

$$P_2 \sim F_{fric} = \mu F_n = \mu F_v = 0.39 F_v \tag{12}$$

$$Q_2 = \frac{P_2}{\tan\beta} = \frac{0.39\,F_v}{\tan\,\beta} \tag{13}$$

$$F_2 = \sqrt{P_2^2 + Q_2^2} \tag{14}$$

After substituting the measured vertical forces F_v into equations 12, 13 and 14, the indentation forces are plotted over the depth in figure 8, separated again per cutting angle. Apparently, the indentation force increases with a root of the depth until a certain limit is reached. A physical interpretation of this behaviour indicates that this effect is due to the development of the secondary crushed zone. When a certain cutting depth is reached, the secondary crushed zone is fully developed, so the indentation force required to remove it converges to a constant value. So increasing the cutting depth even further would not increase the indentation force.

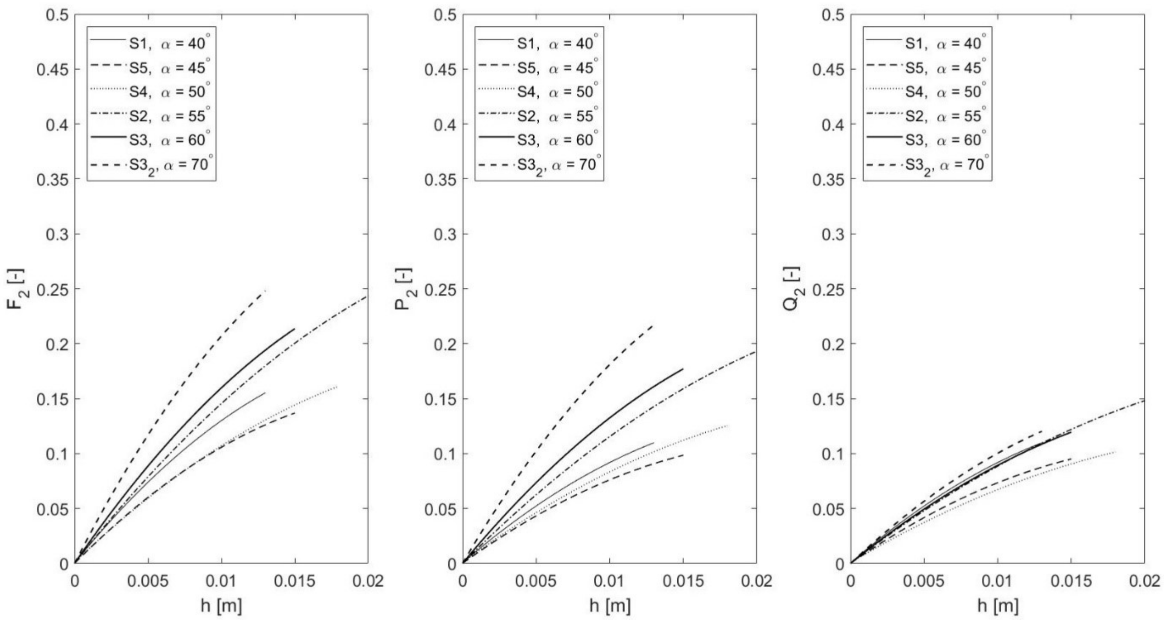

Figure 8. The total indentation force as well as the horizontal and vertical component of the indentation force increase with a root of the depth until it converges to a constant value

The 3D effect

The 2D assumption used by many calculation models raise another problem, which is clearly visible in the rock sample after the experiments. Sideways outbreaking of rock is observed throughout every experiment (figure 9a). This sideways outbreaking increases the area of the shear plane (shear area (A)) which requires an additional force.

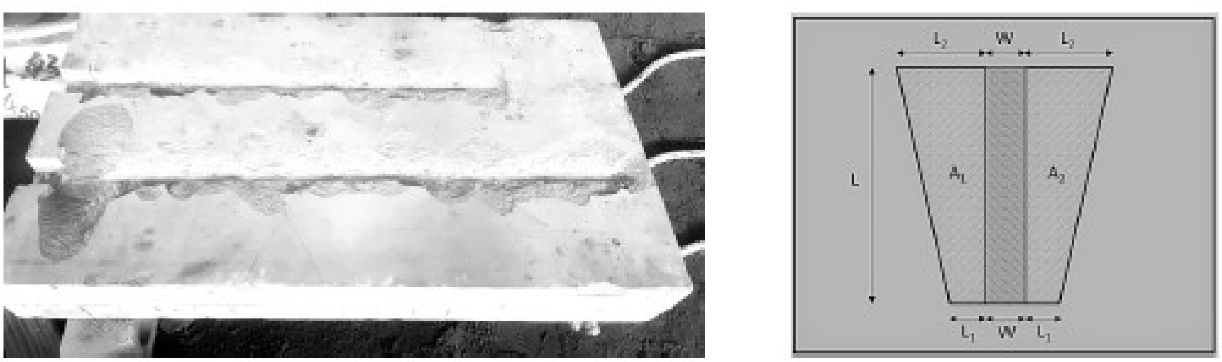

Figure 9. Rock sample after a linear cutting test. a: (left) The sideways outbreaking is clearly visible. b: (right) The calculation template to determine the additional shear area due to sideways outbreaking

Since the position where the maximum force occurred could be calculated by using the timestep, measuring frequency and velocity, the additional shear area was known by applying the geometry from figure 8b. After plotting these calculated areas over the cutting depth, Figure 10 is constructed.

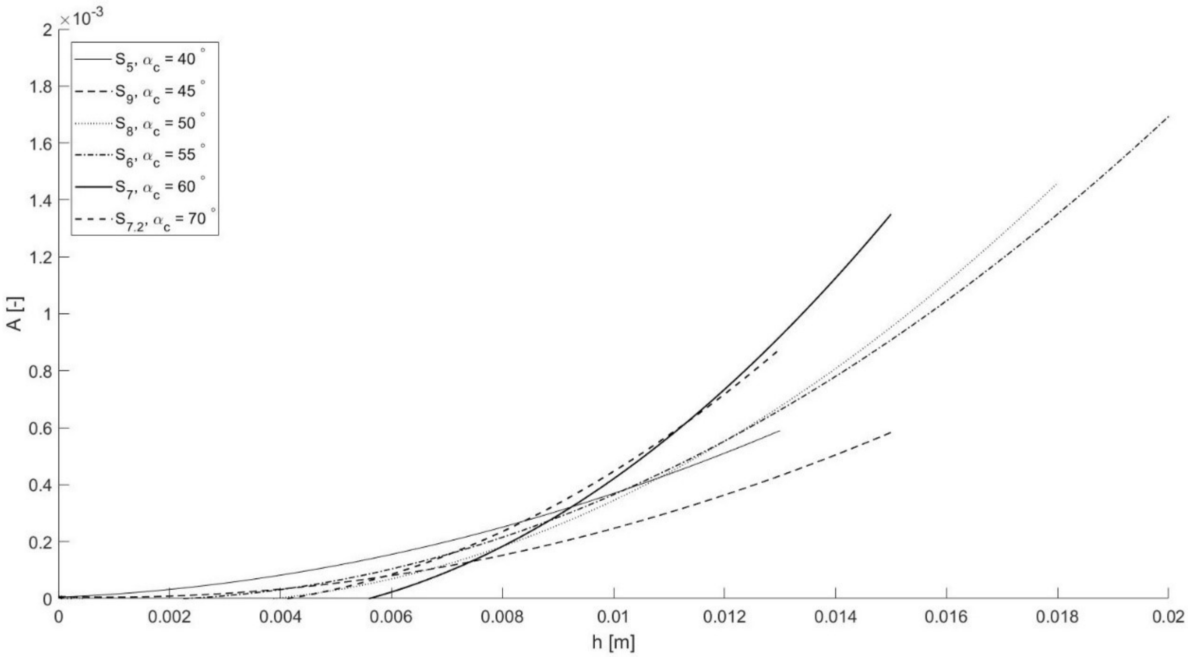

Figure 10. The characteristic shear area plotted over the cutting depth

Since the failure mode is assumed to be brittle shear, the rock characteristic that delivers the resistance force is the cohesion. So the additional force to remove a rock piece with the size of the additional shear area can easily be calculated by multiplying the area with the cohesion of the rock sample (equation 15). Even though the cohesion of the rock samples differ slightly, from figure 9 it is already observed that the additional force for shearing a rock piece over the area increases quadratically with the depth.

$$F_3 = A \cdot c \tag{15}$$

Calculation of the Shear area

After adding the Nishimatsu model (or the initiation force component), the indentation force component and the shear force component, the calculations are compared with the measured results in figure 11. The accuracy of the forces increased tremendously compared with the accuracy in figure 5. This endorses the hypothesis that the assumptions limit the force predictions in terms of accuracy. Although the proposed component model still underestimates the vertical cutting forces, the total - and horizontal cutting force predictions are almost within a 20% error margin.

Further analysis of the force predictions is done by decomposing the total cutting force and check the contributions of each component (figure 12). Interestingly, the contribution of the calculation model ($F_{t,1}$) makes up for only 10% of the total force. For the smaller cutting depths used during this experimental study, the cutting forces were mostly dominated by the indentation force ($F_{t,2}$). Since the indentation forces increase with a root of the depth, the contribution of this component will decrease when the cutting depth, and therefore the cutting forces increase.

Analysing the contribution of the shear force component ($F_{t,3}$) reveal that cutting with angles in the range of 0º- 60 º is more dominant compared with the other cutting angles. Since the indentation force increases quadratically with the depth, the influence becomes more and more significant. During shallower cuts this effect is countered by the indentation part of the force, which increased with a root of the depth, but for larger cutting depths it might lead to a quadratically increasing cutting force when the cutting depths increase.

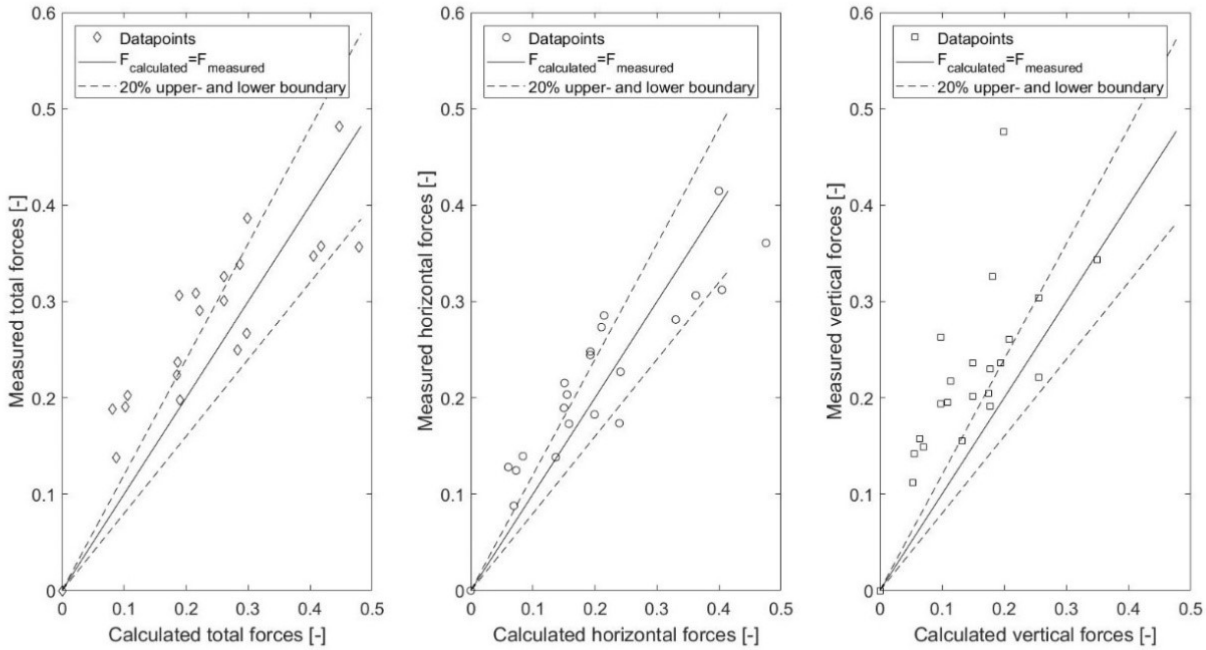

Figure 51. Comparison of the measured forces with the force prediction by the component model

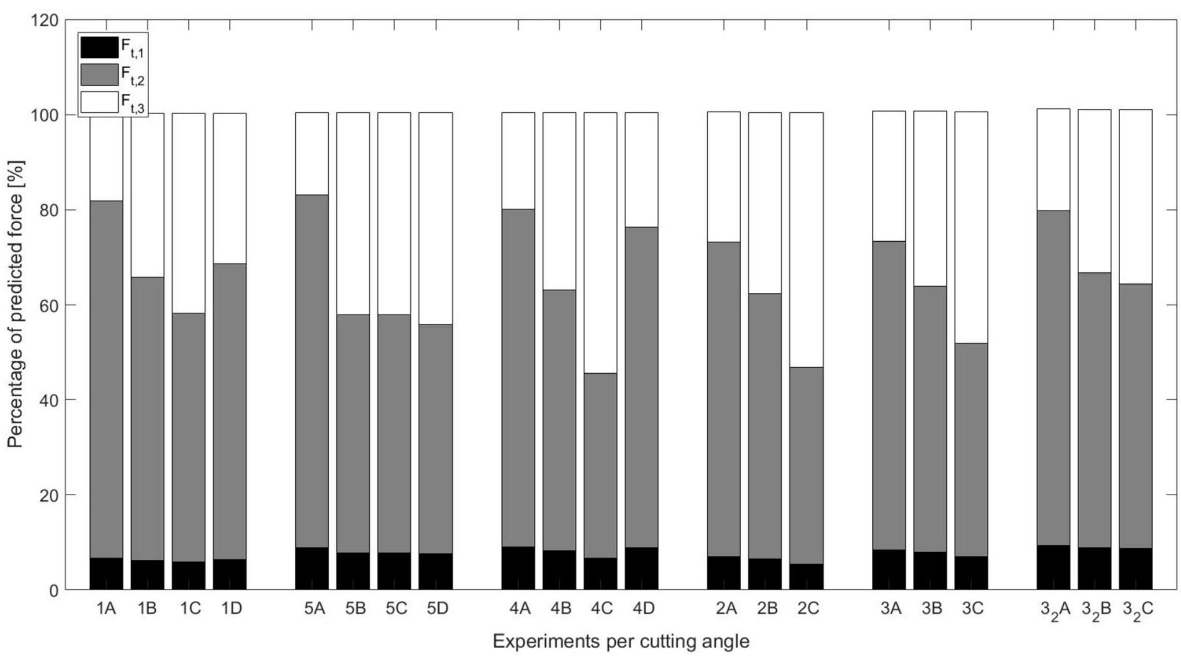

Figure 12. Contributions of the components on the total predicted cutting force, separated by cutting angle

CONCLUSIONS AND RECOMMENDATIONS

Experimental results have revealed that the Nishimatsu model significantly underestimates the cutting forces when using a pickpoint cutting into sandstone in a linear motion. It is believed that the applicability of the Nishimatsu models is limited by its two assumptions. The perfectly sharp tool assumption and the 2D process assumption. The assumption of a sharp tool neglects the fact that a wear flat maybe present during the cutting process and causing a secondary crushed zone which develops in front of the primary crushed zone. The removal of this secondary crushed zone requires additional vertical and horizontal forces. The 2D cutting assumption neglects the fact that rock cutting is a 3D dynamic process, while observations during experiments clearly indicate the sideways outbreaking of the rock. Thus extra force is required to break out these rock pieces,.

Additions to implement the development of a secondary crushed zone and the sideways outbreaking of rock pieces not only increase the accuracy of the force predictions, but also include the physical phenomena that occurred during the cutting process. The assumption of a linearly increasing cutting force seems to be accurate for the smaller depths. However, the contributions of the shear force component (especially when cutting in the 50º -60º angle range) increase quadratically with the depth. If this trend continues when the cutting depth increases, the total cutting force will increase quadratically as well. The indentation forces, due to the bluntness of the tool, increases with a root of the depth until it converges to a certain constant value. Therefore, the contributions decrease with an increasing cutting depth.

It is recommended to conduct further investigations into these hypotheses in the near future, and more experiments should be carried out with rock samples of different ranges of strengths. Furthermore, prediction models for the additional force components should be composed when more data is available.

REFERENCES

Chen X., Miedema S.A. & van Rhee C. (2014). "Numerical Methods for Modelling the Rock Cutting Process in Deep Sea Mining". *33rd International Conference on Ocean, Offshore and Arctic Engineering, Volume 3: Offshore Geotechnics*, San Francisco, California, USA, June 2014

Chen X., Miedema S.A. & van Rhee C. (2015). "Numerical Modelling of Excavation Process in Dredging Engineering". *Procedia Engineering* Vol. 102, 804-814.

Gaffney E.S. (1976). "Measurements of dynamic friction between steel and rock". *Defence Nuclear Agency*

Goktan R.M., Gunes N. (2005). "A semi-empirical approach to cutting force prediction for point-attack picks". *The Journal of The South African Institute of Mining and Metallurgy*, Vol. 105.

Helmons R.L.J. (2017). *Excavation of hard deposits and rock: on the cutting of saturated rock.* Delft University of Technology.

Hoek E., Carranza-Torres C. & Corkum B. (2002) *Hoek-Brown failure criterion – 2002 edition*

Hucka V., Das B. (1974). "Brittleness determination of rocks by different methods". *Int. J. Rock. Mech. Min. Sci. & Geomech*, Vol. 11.

Li Z., Itakura K. (2012). "An analytical drilling model of drag bits for evaluation of rock strength". *Soils and Foundations*, Vol. 52, 216-227.

Miedema S.A. (2014). *The Delft Sand, Clay & Rock Cutting Model.* Delft University of Technology, ISBN 978-1-61499-453-4 (print), ISBN 978-1-61499454-1 (online), DOI 10.3233/978-1-61499-454-1-I, IOS Press BV.

Nishimatsu Y. (1971). "The mechanics of rock cutting". *International Journal of Rock Mechanics and Mining Sciences*, Vol. 9.

Rutten T. (2019). *Cutting forces in the linear rock cutting process: Validating and expanding cutting force calculation models,* Delft University of Technology.

Lyons, W. C., & Plisga, G. J. (2011). *Standard handbook of petroleum and natural gas engineering*. Elsevier.

CITATION

Chen, X., Rutten, T., Liu, G., Hong, G. and Miedema, S.A. "A 3D analytical model for linear rock cutting process," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Dredging: The Impact of Climate Change, virtual meeting, USA*, June 15-17, 2021.

DATA AVAILABILITY

All data and models generated or used during the study are included in the manuscript. The data can be found in the graphs, the models in the equations.

NOMENCLATURE

Abbreviations

BTS	Brazilian Tensile Strength	*MPa*
GSI	Geology Strength Index	-
UCS	Unconfined Compressive Strength	*MPa*

Roman

A	Shear area	m^2
a	Material constant to approximate Mohr failure envelope	-
c	Cohesion	*MPa*
F_1	Initiation force	*kN*
F_2	Indentation force	*kN*
F_3	Shear force	*kN*
F_c	Cutting force	*kN*
F_h	Horizontal force	*kN*
$F_{h,char}$	Horizontal characteristic force	*kN*
F_t	Total force	*kN*
$F_{t,char}$	Total characteristic force	*kN*
F_v	Vertical force	*kN*
$F_{v,char}$	Vertical characteristic force	*kN*
$h_{average}$	Average cutting depth	*m*
h_i	Cutting depth	*m*
m_b	Reduced brittleness	-
m_i	Brittleness (or ductility number)	-
n	Stress distribution factor	-
P_2	Horizontal part of indentation force	*kN*
Q_2	Vertical part of indentation force	*kN*
s	Material constant	-

w	Width of pick point blade	m

Greek

α	Cutting angle	º
β	Shear angle	º
δ	External friction angle	º
μ	Dynamic friction coefficient	-
σ_1'	Major effective principal stress	*MPa*
σ_1	Major principal stress	*MPa*
σ_3'	Minor effective principal stress	*MPa*
σ_3	Minor principal stress	*MPa*
σ_{c_i}	Unconfined Compressive Strength	*MPa*
ϕ	Internal friction angle	º

INNOVATIVE SCOW BOARDING SYSTEM

Aiden Horan[1], Norman Bourque[2] and Nathaniel T. Tipton[3]

ABSTRACT

The introduction of a new type of scow boarding system on several dredges in the Cashman fleet has drastically improved the safety for the crews, increased productivity, and boosted morale. These safety innovations were developed in part to solve the industrywide problem of safe access and egress to a dump scow from a dredge throughout the entire draft range which scows are likely to experience from empty to fully loaded. Before the introduction of this new system, the traditional solution for access to the scows was either using a hinged ladder attached to the deck of a dredge which is swung into position when needed or via the pigeonholes on the side of the scow. This hinged ladder system is adequate for a lite scow when the ladder is used within normal ladder parameters, but the more a scow is loaded the shallower the angle becomes for the hinged ladder until it can no longer safely perform the function for which it is intended. Cashman Dredging developed a new scow boarding system that can be safely used for the entire draft range for dump scows and in almost all-weather conditions. Since the introduction of the new method, the traditional hinged access ladder approach has been discontinued on most of our dredges. Since the scow boarding systems were introduced in late 2018, their use has been widespread with positive feedback from the field on their success and utility. This safety innovation has also been well received by our clients and industry partners as a positive step towards a safer culture and workplace. It also reinforces our commitment to continually create a safer working space for our personnel and to push the industry forward.

Keywords: Dredging, safety, innovation, gangway, walkway, scow

INTRODUCTION

A typical split hull dump scow has an air draft ranging from roughly 20ft (to the scow walkway surface) when empty to around 4ft when loaded. This large range of vertical movement in a working environment has made safe access to the scow troublesome at times. The use of the hinged ladder mentioned at the outset may sometimes be unsafe or difficult to use depending on the type of material in the dump scow, the weather conditions, the sea state or how much load the scow has onboard.

Cashman Dredging & Marine Construction Ltd. pursued a novel solution to this decades old industry problem in late 2018 and devised an innovative approach which allows for safe and constant access to a scow at any draft through a series of custom-built elevated platforms and variable angle gangways. These platforms are permanently mounted to the structure of a dredge and are primarily used for scow access but can also be used for dock access when in port.

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The introduction of this new scow boarding system has drastically increased the safety of our personnel when travelling between the dredge and scow and it has proven to remain effective in all seasons as well as in adverse weather conditions. There has also been additional knock-on benefits in terms of improved productivity for the entire dredging operation as well as a noticeable increase in morale.

BACKGROUND

Cashman Dredging & Marine Construction Ltd. Recently completed the Phase 2 capital improvement work in Boston Harbor by removing approximately 12,000,000 yd^3 of material over a roughly 2.5 year period. At the outset of the project, an internal challenge was set to find operational improvements and innovations that would pay off in the long run given the longevity of the project and the repetitiveness of the work. The initial main areas of focus were safety, efficiency and quality. A program was initiated whereby all the important repetitive day to day operations were identified and examined, we then asked if there was a better way to perform these tasks. The introduction of the gangway system is just one of the successful outcomes from this program.

PROBLEM STATEMENT

In order to fully understand the problem at hand, we first needed to define it. As with most problems, this particular one had an upper and a lower bound condition. With reference to Figure 1 a & b, we can see both boundaries. Figure 1a shows the upper boundary condition whereby we have an empty scow alongside a dredge. The traditional way to board a scow in this condition is either by using the hinged ladder attached to the deck of a dredge or by climbing the pigeonholes on the side of the scow. An empty scow such as the one shown in Figure 1a has the greatest air draft meaning that its height above water is at or close to its maximum. In this instance, a traditional boarding ladder can be used as intended as the angle that the ladder makes with the horizontal is usually within tolerance for what is considered safe.

Figure 1B shows the lower boundary condition where we have a loaded scow meaning that the scows air draft is at or near its minimum. The angle the boarding ladder now makes with the horizontal is much shallower and not very practical or safe. At this point, the boarding ladder no longer functions as a ladder but more of a floor with large holes in it. A ladder in this position would never be used on a land-based construction site. It is possible that in the loaded scow position, a light gangway can be launched from the dredge to the scow as an alternative access solution, however, this may not always be practical or safe and it introduces an extra piece of deck hardware and an additional work procedure for the crew.

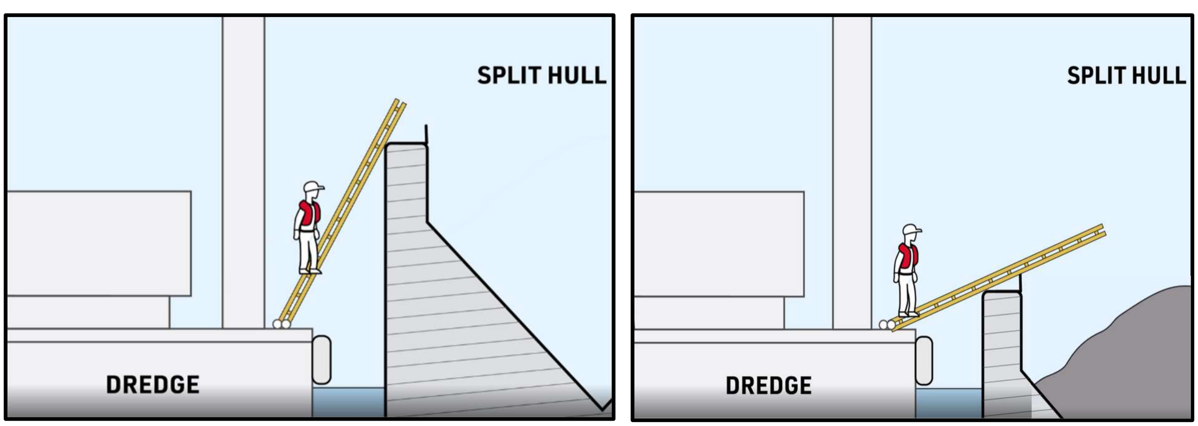

Figure 1. Boundary Conditions for Scow Boarding (a) upper boundary on left and (b) lower boundary on right

Crews have been "*making do*" with this ladder system for decades but as part of the review program outlined in the Background section, the team at Cashman decided to see if there was another way that this access problem could be solved. The problem statement which drove the follow-on process was defined as: -

"*to develop a boarding system that can provide safe and continual access when required to scows at various drafts when alongside a dredge*"

APPROACH

The first stage in our approach was to reexamine the issue from first principles and try not to let any misconceptions or opinions affect our future direction on the process. We then wanted to see if there were any existing solutions because it would make it easier if someone has already solved the problem or if a good solution already exists. Several potential solutions did already exist, but most were for a ship to shore scenario, were too complicated for a dredge environment, required too much deck space or some combination of all of these. The greatest challenge was finding a compact solution that could deal with the large range of vertical movement from the lite to loaded condition.

After an exhaustive reexamination process, it was determined that no existing solution would work for the conditions at hand, therefore, we began creating new proposals. Several boarding system candidates were then developed from scratch. We knew that not all of these would be practical or viable but we wanted a thorough vetting and review process to arrive at a well thought out conclusion as each proposal may offer some positive contribution to the overall solution.

We then shortlisted a select number of the best proposals and reviewed them with an internal discussion group to figure out their advantages and disadvantages. This group consisted of personnel at all levels within Cashman and it was at this stage that a lot of the finer details emerged that ultimately made the program a success.

Throughout the discussion and refinement process, some clear ideas of what was needed began to emerge. As the less practical ideas were removed from the group and the better ideas advanced and were further discussed, a solution similar to Figure 2 was proposed.

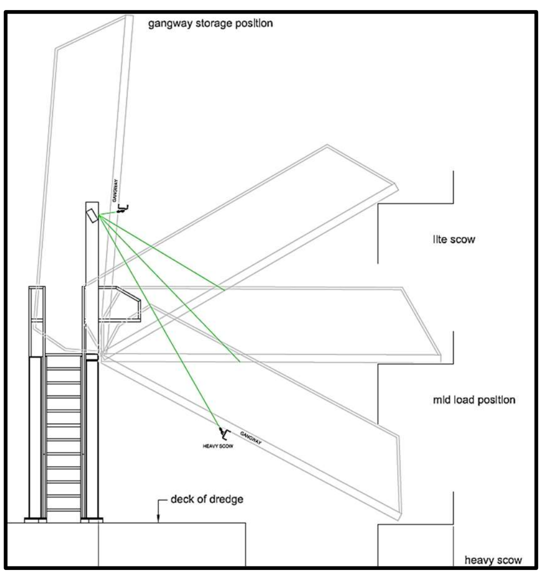

Figure 2. Tower & Gangway Scow Access Solution

Figure 2 shows that there are essentially two main parts to the system: 1) the tower structure which is attached to the deck of the dredge and 2) the gangway itself which is attached to the tower. Figure 2 shows that the gangway system proposed will work with the Cashman fleet of scows in all draft positions ranging from both extremities and also at an interim "mid-load" position. The review and discussion phase identified that the gangway had its longest horizontal dimension at this mid-load state and the concern was that the scow would impact the gangway given the potential horizontal differential movements between both vessels, however, we were able to design around this consideration. Also shown in Figure 2 is the likely position of the winch cable that attaches to the underside of the gangway which would be used to lower and raise the gangway.

The positioning of the tower and gangway on the deck of the dredge is a very important consideration to the success of the system. Figure 3 shows a plan on one of our dredges outlining the location of the system, in the deployed or down position.

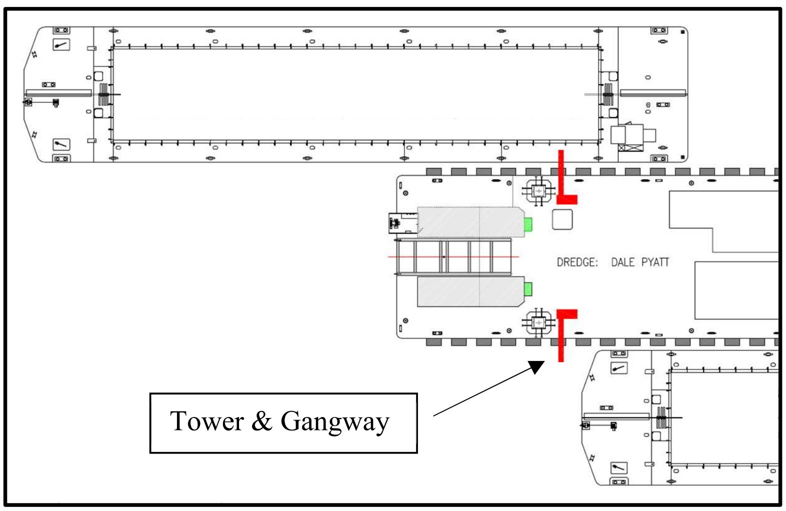

Figure 3. Layout of Gangways on Deck of Dredge (Dredge: Dale Pyatt)

For this dredge, the *Dale Pyatt*, we were able to install the platforms adjacent to the spuds. This helped satisfy one of the requirements that we didn't interfere with normal dredging operations by introducing any additional aerial hazards. With reference to Figure 2, the gangways in the storage position have a height of around 26ft from the tip of the gangway to the deck of the dredge. This could have posed a problem to swinging the bucket on deck if placed in the wrong location. By keeping the gangways close to a tall structure, we were able to limit the effect of their install on normal operations. In total, each tower takes up roughly 25ft^2 deck space in the stored position meaning that with the correct positioning the system should have a minimal impact if any on day-to-day operations.

Figure 4 shows the completed boarding system installed on another Cashman dredge, the FJ Belesimo. Both gangways are shown in the stored position and again we kept these gangways adjacent to the spuds so they don't create any additional hazard to the day to day operation of the dredge. From this angle, an additional safety feature is shown whereby access to the tower is blocked by the gangway when the gangway is stored. The gangway folds up into the landing area of the tower as a space saving and safety feature. Figure 4 also shows the relative amount of deck space needed for the complete system.

The winch that lowers and raises the gangways is hard wired into the dredges power supply via a control box located under the tower. The lower/raise motion of the gangway is controlled by a pendant with a simple up & down button.

Figure 4. Completed Tower & Gangway System (Dredge: FJ Belesimo)

Figure 5. Completed Tower & Gangway System

Figure 5 shows a completed tower system attached to the dredge located beside the old ladder system that it has replaced on the right of the Figure. The electric control box can be seen underneath the tower and on the left upright, the winch which lowers and raises the gangway. An interesting feature of the system is how the tower is attached to the deck. By looking carefully at the bottom of the tower legs in Figure 5, the tower actually sits on flanged legs rather than being connected directly to the deck. If there was ever a need to remove the gangway system quickly, these flanged connection points are unbolted and the tower can be removed within an hour or so. This was another feature which arose from the discussion and review phase.

CONCLUSIONS

As with every new piece of equipment, we had to implement a safe work system on how to correctly use the gangways. This system covered how to use them, when to use them, when not to use them and how to maintain them.

There were some initial teething problems at the beginning which included reinforcing some high stress locations and strengthening some parts of the gangways and towers after initial use but in general, the system worked well once installed.

A good early indicator that the gangways were working well is that they were very successfully adopted in the field from the moment they were installed. Although the gangways were installed for crew safety, there was also a notable and unexpected improvement in productivity. It was very satisfying to see that something we did for safety also had an unintended positive knock-on effect on dredge output.

Perhaps the best feedback received from the field was in spring 2019 shortly after the gangways were installed when the mate on the dredge Dale Pyatt told us that these gangways had extended his dredging career because he now didn't have to climb a precarious ladder as part of his job. This was a great success story that was even more justification that we had done the right thing.

Since installing the system on our first dredge in early 2019, we have subsequently installed the same system on all of our mechanical dredges. The standardized design means the same tower, same gangway, same winch and controls are on each of our dredges and the use of the old scow boarding ladders have been discontinued.

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CITATION

Aiden Horan, A., Bourque, N., and Tipton, N.T., "Innovative Scow Boarding System," *Proceedings of the Western Dredging Association Dredging Summit & Expo '21, Dredging: The Impact of Climate Change, virtual meeting, USA*, June 15-17, 2021.