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Cable-Arm Clamshell Bucket

IN THIS ISSUE

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AIMS & SCOPE OF THE JOURNAL

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

METHOD FOR ESTIMATING CLAMSHELL DREDGE PRODUCTION AND PROJECT COST

R. F. Adair[1] and R. E. Randall[2]

ABSTRACT

Clamshell dredges are used around the United States for both navigational and environmental dredging projects. These mechanical dredges are extremely mobile and can excavate sediment over a wide range of depths. The objective of this paper is to develop a methodology for production and cost estimation for clamshell dredge projects. There are current methods of predicting clamshell dredge production which rely on production curves and constant cycle times. This paper discusses calculating production by predicting cycle time, which is the time required to complete one dredge cycle. By varying the cycle time according to site characteristics, production can be predicted. A second important component to predicting clamshell dredge production is the bucket fill factor. This is the percent of the bucket that fills with sediment depending on the type of soil being excavated.

Using cycle time as the basis for production calculation, a spreadsheet has been created to simplify the calculation of production and project cost. The production calculation also factors in soil type and region of the United States. The spreadsheet is capable of operating with basic site characteristics, or with details about the dredge, bucket size, and region. Once the production is calculated, the project cost can be determined. First, the project length is found by dividing the total amount of sediment to be excavated by the production rate. Once the project length is calculated, then the remainder of the project cost can be found.

The methods discussed in this paper are used to calculate project cost for 5 different projects. The results are then compared to estimates by the government and the actual cost of the project. The government estimates are an average of 39% higher than the actual project cost, and the method discussed herein is only 6% higher than the actual cost.

INTRODUCTION

Purpose

The purpose of this paper is to describe a method for predicting production for mechanical clamshell dredges using cycle time. There are existing methods to predict production for cutter suction and hopper dredges. This paper focuses on developing a method for mechanical

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clamshell dredges. The emphasis is on using an adjustable cycle time factor and bucket fill factor to determine production. The cycle time is the period of time required to complete one dredging cycle. The method also allows for a variance in production due to the ability of the material being dredged to fill the total volume of the bucket (fill factor). Once the production is successfully estimated, the output is used to predict the total dredging cost and duration.

Background

The earliest dredges were mechanical dredges. A few thousand years ago, people began using "Spoon and Bag Dredge" (Huston, 1970). This simple device consisted of a barge with at least one pole extending from the side of the vessel. This pole had a bucket on the end that was used to remove sediment or debris from the bottom and placed inside the barge. Once the barge was full, it was emptied at the shore and the process continued. Until the advent of the steam engine, dredges were powered by wind, animals or humans. An example of a wind powered dredge is the Krabbelaar scraper (Herbich, 2000). This was a wind powered, wooden hulled, scraper dredge. Once the steam engine and then the diesel engine were invented, mechanical dredges began to resemble the ones used today.

There are several types of dredges used in the United States and around the world today. These include mechanical, dustpan, hopper, cutter head, and other special types of dredges. Mechanical dredges are clamshell, backhoe, and bucket type dredges. A dustpan dredge uses a suction line to excavate sediment. Hopper dredges use a suction line and transport the excavated sediment on board the dredge. Cutter head dredges, also called cutter suction or pipeline dredges, use a rotating cutter head to loosen the sediment before it is excavated through a suction line.

There are many classifications of mechanical dredges (Bray, 1997). A backhoe dredge is literally a backhoe used in a marine environment. It is either used off the shore, from a barge, or fixed to a vessel. A dipper dredge uses a rigid arm with a bucket on the end. It swings up as it cuts through the sediment. A bucket ladder dredge uses a chain of buckets on a belt to excavate sediment. The dragline dredge places its bucket away from the vessel in the sediment and then drags the bucket back towards the vessel. Finally, the clamshell dredge uses a bottom opening bucket at the end of a crane. The bucket is dropped or lowered directly down into the sediment, closed, and then raised to the surface. Mechanical dredges are used for building new channels, deepening existing waterways, and removing contaminated sediment.

An important characteristic of mechanical dredges is the bucket size. Figure 1 shows the distribution of bucket sizes for mechanical dredges for the United States in 2003 (IDR, 2003). It is apparent from Figure 1 that the majority of buckets are smaller than 11 m^3 (15 yd^3). There are several buckets between 11 and 23 m^3 (15 and 30 yd^3). The largest bucket reported is 38 m^3 (50 yd^3). This paper limits the range to 0-38 m^3 (0-50 yd^3) due to the availability of buckets in the United States.

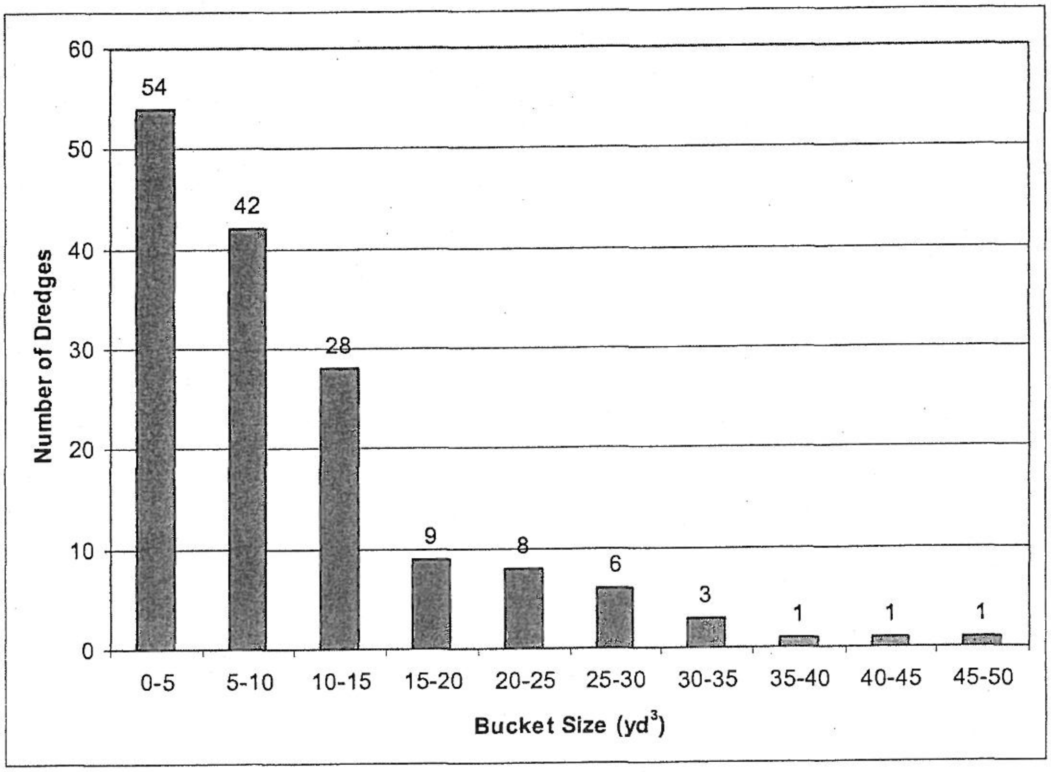

Figure 1. Distribution of Bucket Sizes in the United States (Multiply by 0.765 for m^3).

Figure 2 shows a mechanical clamshell dredge working just offshore on the west coast of Japan in the town of Sakata. The dredge is working near a public beach in late summer 2003. This picture shows the main components on a mechanical dredge. The dredge itself is the crane-like structure on the left side of the barge. The crane positions the bucket above a desired location and then lowers it to the bottom of the waterway. The bucket picks up the sediment as it closes. The closed bucket is raised out of the water and positioned over the barge. Finally the bucket is opened over the barge and the dredged material is placed in the barge. The cycle is then repeated for a new position until the desired depth is reached over the entire area. Figure 2 also shows a work boat and the barge that is supporting the dredge. The barge supports the weight of the dredging equipment and positions the clamshell bucket over the desired location.

Figure 2. Mechanical Dredge in Sakata, Yamagata, Japan

Figure 3 shows the different parts on a clamshell bucket. The hoist wire supports the weight of the clamshell and the sediment when it is full. The actual bucket pivots around the arm. During operation, the bucket is dropped or lowered into the sediment and then closed. The cutting edge penetrates and cuts the sediment. Once the bucket is closed, it is lifted and the sediment is then placed in a barge. The middle clamshell in Figure 3 is a simple open bucket. Some buckets are closed with gaskets to prevent water from escaping. There are level cut clamshells such as the ones described by Bergeron (2000). These buckets are frequently used for environmental dredging. There are also other special buckets that are used for harvesting clams (Gaspar et al., 2003); these are made of a mesh that allows sediment to escape. Randall (2004) indicates that clamshell dredges are best suited for soft sediments and where access is an issue. Since the dredge uses a mechanical cable to control the bucket, the clamshell is limited in depth of operation only by the length of its cable.

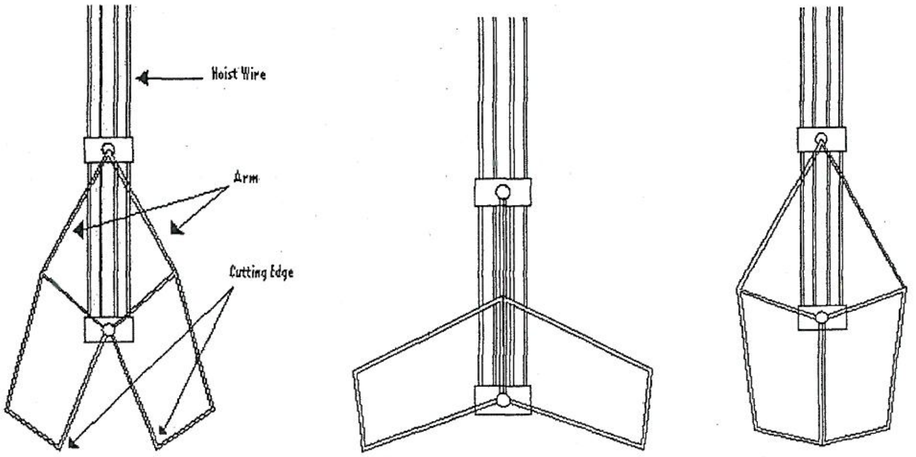

Figure 3. Operation of a Clamshell Bucket (Key Components, Open Position, Closed Position).

Literature Review of Clamshell Bucket Production and Cost Estimation

Dredge production can be determined in various ways depending on the type of dredge. There are several publicly available methods for estimating production for both hopper and cutter suction dredges (Miertschin, 1997; Miertschin and Randall, 1998; Belisimo, 2000). These methods use dredge pump and sediment characteristics to estimate production. The specific gravity that can be carried is determined and used with other dredge specific properties to determine the time required to dredge a given amount of sediment. Both of these methods then use their output to estimate project cost and duration.

Cycle time is the amount of time required for the dredge to complete one cycle and is usually expressed in units of time. Once cycle time is known, delay factors, such as the time to change hopper barges, can be applied and the total length of a project can be determined. Many cost estimation methods assume a constant value for cycle time. This constant value is usually about 60 seconds (Bergeron, 2000; Hayes, 2000).

Emmons (2001) used cycle time determined by water depth and swing angle. This is an improvement over using a constant cycle time, but did not allow for factors such as the rate a bucket is raised or lowered, swing rate, as well as bucket opening and closing time. It is important to be able to vary the individual components of the dredge cycle in mechanical clamshell dredging. In these projects it is common to limit the velocity that the clamshell is allowed to travel through the water column. Slowing the bucket velocity reduces re-suspension, and reduces the sediment from re-suspension when the bucket strikes the bottom. Besides bucket velocity in the water column, the other parameters in cycle time are swing angle, swing velocity, time to open the bucket, time to close the bucket, and water depth. The combined time to complete all of these tasks is the cycle time, which is combined with bucket volume to define production (m^3/h, yd^3/h).

An additional factor to be considered in evaluating production is the bucket fill factor. The fill factor is the percentage of the bucket that is filled with sediment during a given dredge cycle. Depending on the sediment type, bucket velocity, and fall velocity, this value can vary considerably. Dense or hard sediments make it difficult for the clamshell to close, and the sediment may contain large voids. Clays are difficult for a bucket to cut. Due to the increased difficulty of excavating the dense clays, the bucket does not always reach its maximum possible depth into the sediment. If the bucket does not reach its maximum depth, it cannot fill completely. Additional reasons a bucket may not be completely filled are due to voids between rocks and debris interfering with the complete closure of the bucket. A clamshell bucket uses its own weight and some mechanical advantage to cut the sediment and fill the bucket, so rocks can also keep the bucket from closing. A method of estimating the fill factor has been developed by Bray (1997). This method works well, but was developed for small buckets. It uses the bucket size and sediment type to provide a reduction factor. This reduction factor is multiplied by the size of the bucket and then is used to determine the estimated amount of sediment that is removed each cycle. However, it is necessary to determine the fill factor for buckets of any size. This is accomplished by fitting data from Bray (1997) and Emmons (2001) over the full range of bucket sizes.

Cycle time and fill factor are thus the dominant parameters in mechanical dredge production. The cycle time provides the time required for each dredge cycle, and the fill factor determines the amount of sediment removed each time. These factors are combined to estimate the maximum production rate for a clamshell dredge.

Clamshell Dredge Production Estimation Procedure

The procedure for estimating mechanical dredge production is divided into four stages. The first stage is developing a method for estimating cycle time. First, the parameters that determine cycle time must be determined. These parameters are water depth, bucket fall velocity, bucket close time, bucket open time, bucket lift velocity, presences of debris, hard or soft sediment, cut depth, swing angle, and swing velocity. Second, default or normal values for most of these parameters are determined. For example, for most projects the average swing angle is 120 degrees (Emmons, 2001). The method must also allow the user to alter each parameter to match a specific dredge, site conditions, or project requirements. This lets the method account for special cases such as environmental dredging, or special buckets. For an environmental project, a bucket may not be permitted to free fall, or drop, to the bottom, but it is lowered slowly to the bottom (e.g. one third of its normal rate). This increases the cycle time while decreasing the production rate. The goal is to obtain the average values from industry or the NDC (2003) for normal projects and to have a method to vary these parameters for a specific project or dredge. This provides a cycle time that works for both normal and special cases.

The second stage for the mechanical dredge production estimation method is to determine the bucket fill factor. The fill factor is the percentage of the total volume of the bucket that is filled with sediment. For certain materials the bucket is not completely full. Bray (1997) provides limited data for the fill factor for small dredges that are less than 8 m^3 (10 yd^3). The fill factor for this method comes from curve fitting these data points with limited data points for larger dredges (Adair, 2004). This provides the method for estimating production for a large range of mechanical clamshell dredges.

The third stage is to develop a cost estimating method that uses the output from the production calculations to determine project cost for dredging and placement. The cost of treatment of contaminated sediments and water treatment is not included. For this stage, it is necessary to obtain contract information from the U.S. Institute for Water Resources Navigational Data Center (NDC, 2003). Factors such as dredge cost, crew size, wage rates, mobilization and demobilization costs, and disposal costs are considered. These data are obtained from various regions to account for cost differences between the Pacific, Atlantic, and Gulf coasts. The NDC provides information about the total cost of all dredging contracts awarded by the United States Army Corps of Engineers (USACE). This information is used to find the relationships between project costs around the United States.

The final stage of the mechanical clamshell dredge program is to verify its results against known projects and to conduct a sensitivity analysis for the production estimation program. The sensitivity analysis is done to determine how production varies when either cycle time or fill factor are changed. The cost estimation is checked against actual projects from the NDC (2003). The projects used need to vary in both location and size to show the program is valid over a range of dredges. Once the production and cost estimation methods were verified, then the method was incorporated into an easy to use spreadsheet form that allows the user to quickly estimate production and cost for a clamshell dredging project.

It is beneficial to have a method for predicting production of mechanical dredges based on cycle time. By basing the calculations on cycle time, the production rates are accurate for a wide range of dredges and projects. The method is adjustable for the requirements of a specific project and still provides accurate results.

CLAMSHELL BUCKET PRODUCTION THEORY

Cycle Time

The cycle time (T_{cycle}) is the total time required for the dredge to empty, move to the desired location, fill the bucket and empty it. As the cycle time increases, so does the project length and cost. The cycle time is a function of swing angle (θ_{sw}), swing angular velocity (ω_{sw}), bucket fall velocity (u_f), time to open and close the bucket (t_g), bucket lift velocity (u_l), time to empty the bucket (t_e), water depth (d), and freeboard height of the barge (h_b), and the equation is

$$T_{cycle} = 2\left(\frac{\theta_{sw}}{\omega_{sw}}\right) + t_g + t_e + \frac{(d + h_b)}{u_f} + \frac{(d + h_b)}{u_f} \qquad (1)$$

The swing angle (θ_{sw}) is the difference between the location where sediment is dropped into the hopper barge and the location where the sediment is excavated. Swing angle is expressed in degrees, and an average value is 120 degrees. This value is doubled when the total cycle time is calculated to account for swinging to and from the excavation site. Swing speed (ω_{sw}) is the rate that the mechanical clamshell dredge swings between the excavation site and the barge. This is consistent with the swing speed of large cranes, and a default value is 21 degrees per second. The rate or speed at which the bucket is lowered to the bottom is the fall velocity (u_f). The bucket can be dropped in freefall, or lowered at a controlled rate. The grab time (t_g) is the time in seconds required to close the clamshell on the sediment. A common grab time value is one second, and it can be adjusted for buckets of various sizes. The velocity that the bucket is raised through the water column is the lift velocity (u_l). During environmental dredging the fall velocity is decreased to control re-suspension. Re-suspension occurs when sediment enters the water column due to flow over the top of the bucket, leaks out of the bucket, clamshell impacting the bottom, and when the bucket is partially closed due to debris. This is a problem in environmental dredging where contaminated sediments are being excavated. A common value for lift velocity is about 0.3 m/s (1 ft/s) during environmental dredging or 1 m/s (3.3 ft/s) during normal dredging. The empty time (t_e) is the time required for the sediment to leave the bucket after opening, and an average value is 2.6 seconds, which is the suggested default value. The average excavation depth (d) plus the barge freeboard height (h_b) is divided by the lift and fall velocity to determine the time to lower and raise the bucket. The freeboard height includes the height of the side of the barge above the free surface plus any additional height necessary to clear the deck of the barge and any sediment.

Bucket Fill Factor

The bucket fill factor is calculated by combining data from Emmons (2001) and Bray (1997). These data sets are fit to an exponential curve and forced to stay below 1 for values up to 50 m^3 (65 yd^3). If the fill factor value becomes greater than 1, then the program calculates that the bucket is picking up a volume of sediment greater than its capacity. For the remainder of the paper the dredged sediment is classified into 6 categories that are used to calculate bucket fill factor and bulking factor. The classifications are mud, loose sand, compact sand, sand and clay, stones, and broken rock. Mud consists of sediments such as loose silts, clays, and other fine grained sediment. Loose sand is sand that is not compacted. Compacted sand is dense sand that has been loaded or compacted. Sand and clay is a mixture of sands and clays. Stones consist of small rocks from gravel to cobbles. Broken rock is any sediment larger than cobbles. Figure 4 is the fill factor curve for loose sand, and Equation 2 is the bucket fill factor curve for loose sand,

$$f_m = 0.0614 \ln(C) + 0.6607 \tag{2}$$

where C is the bucket volume (m^3) and "ln" is the natural log. The curve begins at 0.65 and reaches 0.9 for 50 m^3 (65 yd^3) buckets. One point is used at 50 m^3 (65 yd^3) to keep the function below 1. It follows the same trend as the fill factor for mud with a very steep slope in the range of small buckets. The bucket fill factors allow the amount of sediment removed during each dredge cycle to be determined. These equations are integrated into the production and cost estimation spreadsheet and function in the background.

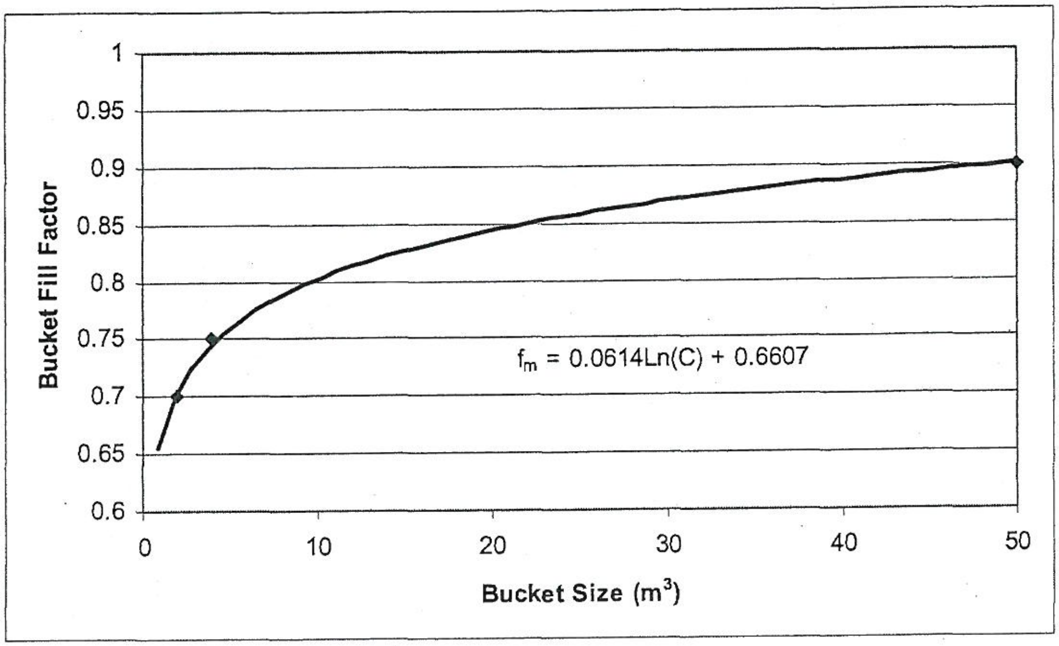

Figure 4. Fill factor for Loose Sand (Multiply by 1.3 to convert to yd^3).

Comparison of methods for estimating bucket fill factor

Three methods of determining bucket fill factor are compared in this paper. Method 1 uses data provided by Bray (1997). These data provide two values for the fill factor for each sediment type. These values are for relatively small buckets (<10 m^3, <13 yd^3). The fill factors are found by linearly interpolating between the two given values. Method 2 utilizes equations developed by Emmons (2001). Bucket size and sediment type are input into the equation, and it provides a fill factor value. The third method (method 3) uses the equations discussed in the previous section. Though methods 1 and 3 use the same sediment classifications, method 2 uses slightly different classifications. All three methods included sand, and therefore the direct comparison is performed using sand.

Figure 5 is a comparison between different curve fit equations for estimating bucket fill factors as a function of bucket size. The bucket size range is from 0 to 50 m^3 (65 yd^3). Realistically, bucket fill factors must not exceed a value of 1.0. Method 1 uses a linear curve fit of data from Bray (1997) to predict bucket fill factor values and is effective for small buckets (<10 m^3) (<13 yd^3), but it is not designed to work beyond a bucket size of 5 m^3 (6.5 yd^3). Method 2 is based on a curve fit reported by Emmons (2001) that predicts a bucket fill factor near 1.0 at approximately 5 m^3 (6.5 yd^3). The curve stays near 1 until 40 m^3 (52 yd^3), and then at 40 m^3 (52 yd^3) the curve begins to decrease. Method 2 predicted bucket fill factor values are unrealistic for bucket sizes smaller than 5 m^3 (6.5 yd^3). Adair (2004) developed the curve fit for method 3, and it predicts a bucket fill factor of 0.72 for a bucket size of 1 m^3 (1.3 yd^3) and gradually increases to 0.9 for a bucket size of 50 m^3 (65 yd^3).

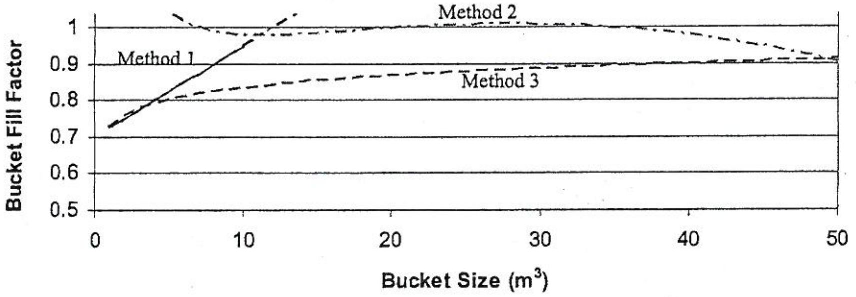

Figure 5. Comparison of Bucket Fill Factors (Multiply by 1.3 to convert to yd^3).

Figure 6 compares the three fill factor methods. The purpose of the graph is to show the relationship between the bucket size and the predicted amount of sediment excavated. The graph is over a full range of bucket sizes from 0 to 50 m^3 (65 yd^3). The predicted amount of sediment excavated (P_e) is the fill factor (f_m) for a specific method multiplied by the actual size (C). Equation 3 is the relationship between the predicted amount of sediment excavated and the fill factor.

$$P_e = (C)(f_m) \tag{3}$$

Whenever the curve for a method is less than the actual size curve the fill factor is less than 1, and when the curve for a fill factor is greater than the actual size the fill factor is greater than 1. From 0 to 20 m^3 (26 yd^3) all three methods appear to be linear. At about 20 m^3 (26 yd^3) method 1 begins to diverge from the actual bucket size, and it becomes unusable because the predicted amount of sediment excavated becomes larger than the actual size of the bucket. The other two methods function well to 50 m^3 (65 yd^3).

Figure 7 displays the relationships between the three methods and the actual size for buckets from 0 to 10 m^3 (13 yd^3). Method 2 is nearly linear with the actual size between 6 m^3 (8 yd^3) and 10 m^3 (13 yd^3). Between 0 and 6 m^3 (8 yd^3) method 2 predicts the size to be greater than the actual size. From 0 to 5 m^3 (7 yd^3) method 1 and method 3 are similar. Both methods stay well below the actual size in this range. At 5 m^3 (7 yd^3), method 1 begins to approach the actual size curve. Method 3 stays significantly less than the actual size curve until after 10 m^3 (13 yd^3). Method 3, developed in this paper, provides the best results for both large and small buckets.

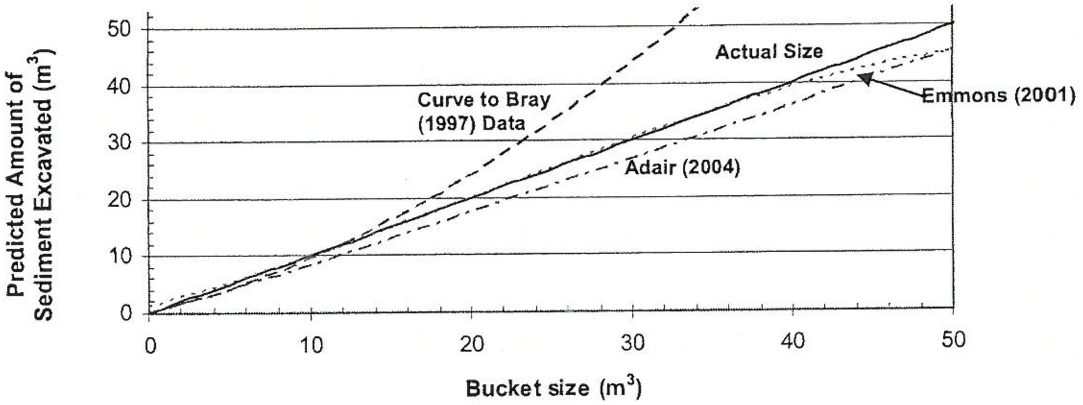

Figure 6. Comparison of Predicted Amount of Sediment Excavated as Predicted Using the Different Bucket Fill Factor Methods.

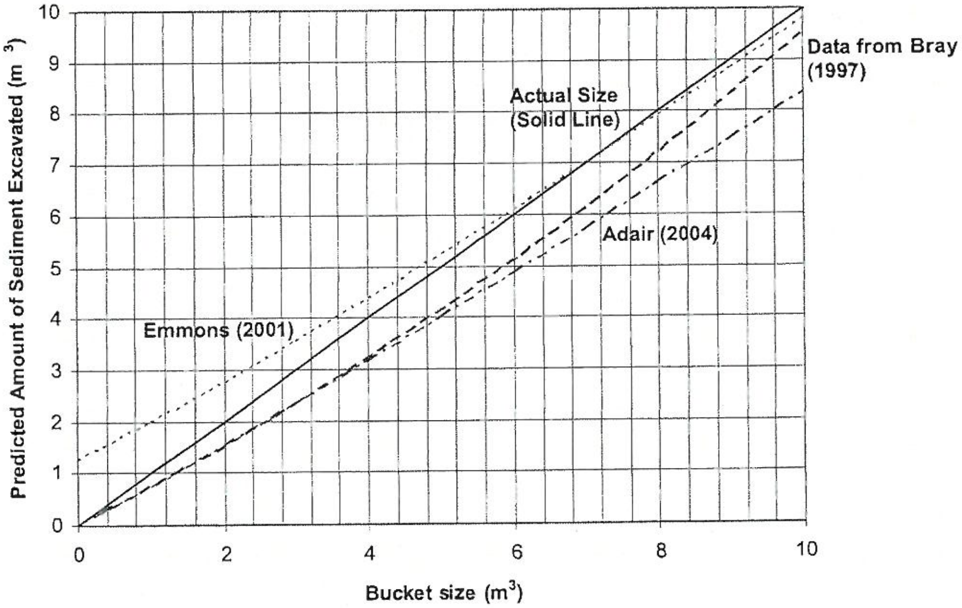

Figure 7. Fill Factor Comparison for Small Buckets (Multiply by 1.3 to convert to yd^3).

CLAMSHELL COST ESTIMATION

Introduction to Clamshell Cost Estimation

Once the production rate is determined the project cost for dredge excavation and material placement can be estimated. First, all of the individual costs must be calculated. Secondly, the length of the project must be calculated. The project length is determined by dividing the total sediment to be excavated by the maximum production rate. This value is used to determine the length of time equipment is rented, and how long workers are paid. The cost data has been taken from three sources. Means (2004) provides cost data on labor and some rental equipment and also provides methods to convert cost data from past years to current year values. The second source of cost data is the Institute of Water Resources Navigational Data Center's Report (NDC, 2003). These data provide the overall project costs for around the United States and are used to create regional cost factors. These factors adjust project costs for various regions in the country. The final source of cost data is from Emmons (2001).

Regional Cost Factors

The estimated cost for the project comes from average cost data for the United States. There is a difference between project costs in different regions of the country. This is due to labor rates, equipment costs, and other regional cost differences. For this reason, it is necessary to adjust the total project cost depending on the geographic location of the project. The cost estimation portion of the program is based on a national average. Therefore, it is necessary to modify the results to find the project cost for the specific regions. The main regions in the United States are Alaska/Hawaii, Pacific Coast, Gulf Coast, Atlantic Coast, and the Great Lakes. The NDC provides the total cost of all contracts awarded. The first step in determining a cost factor is to sort all of the contracts by region. All of the projects are then plotted based on cost per m^3 (yd^3). Next, the plots are visually inspected so that outliers can be removed. These outliers are projects that have a considerable larger average cost per volume than the rest of the data set. After all of the outliers have been removed, the average cost per volume for that region is calculated. The cost per volume for a specific region is then divided by the average cost per volume for the entire country. The ratio that results is the regional cost factor. This factor is then multiplied by the total cost of the project from the program. Figure 8 displays the range in project costs for the Atlantic coast. The data used came from the NDC (2003) report and include all mechanical clamshell dredging projects between 1990 and 2002. The data have been adjusted to 2004 dollars by using inflation factors from (Means, 2004). The cost per volume is determined from the actual total project cost divided by the total amount of sediment removed.

Figure 9 shows the majority of the projects are below the \$26 per m^3 (\$20 per yd^3) mark. The most expensive case had a cost of almost \$130 per m^3 (\$100 per yd^3), but all projects above \$52 per m^3 (\$40 per yd^3) were removed to find the average. With the outliers removed there were 88 projects in Figure 9, and 18 projects having a cost of over \$13 per m^3 (\$10 per yd^3). The average for the Atlantic coast is \$9.15 per m^3 (\$7.04 per yd^3) that is the lowest in the United States. This is slightly less than the Pacific coast and \$0.10 per m^3 (\$0.08 per yd^3) lower than the Gulf coast cost.

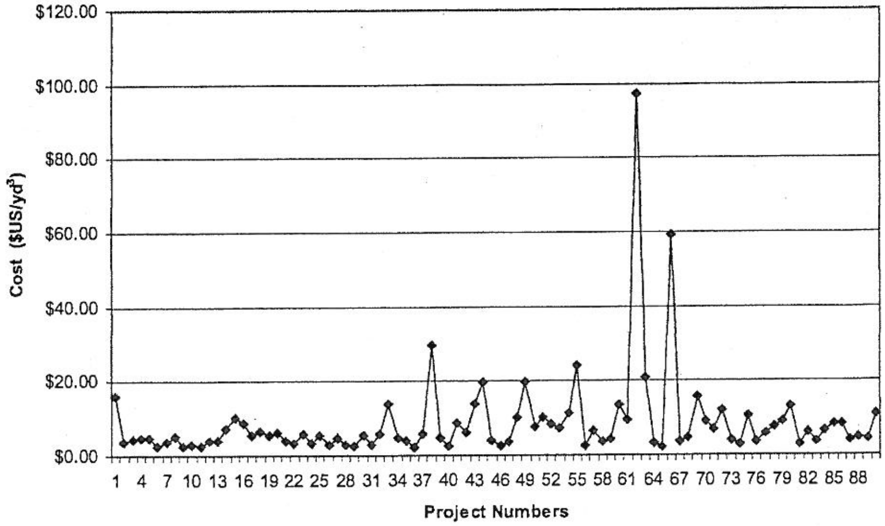

Figure 8. All Atlantic Coast Clamshell Dredging Projects (1990-2002) (Multiply by 1.3 to convert Cost to Dollars/m^3).

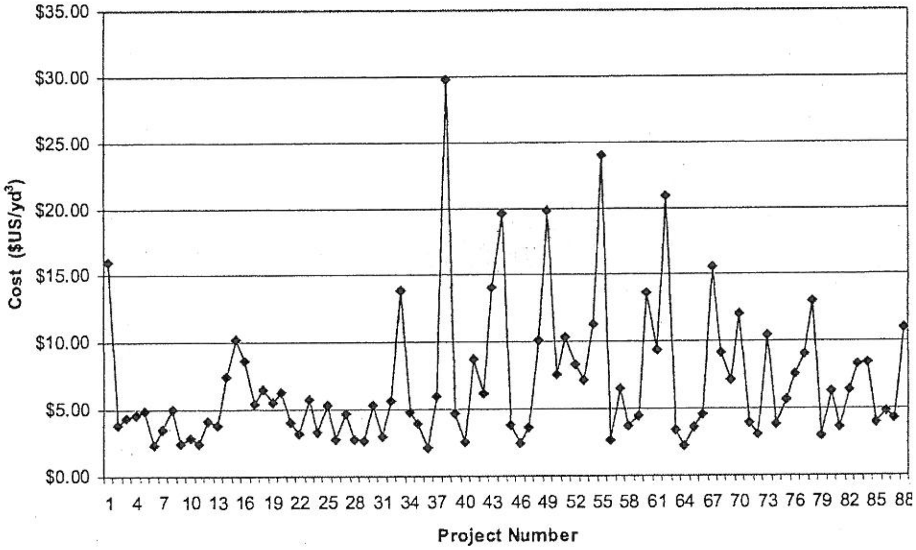

Figure 9. Atlantic Projects without Outliers (1990-2002) (Multiply by 1.3 to convert Cost to Dollars/m^3).

Table 1 shows the average cost per volume for each region and the overall average cost per volume at the bottom. The regional cost factor is the ratio of the regional average divided by the overall average. The Alaska/Hawaii region has the largest average cost per volume and almost doubles the overall average cost per volume. The Atlantic Coast region has the lowest regional cost factor. The ratio between the national averages matches the expected values that show Alaska/Hawaii being the highest and the Gulf and Atlantic coasts being the lowest. Once the total cost of a project is calculated, it is multiplied by the regional cost factor to determine the total project cost. For example, a project with all of the same inputs is almost twice as much in Anchorage, Alaska, as it would be in Boston Harbor.

Table 1. Average Project Unit Costs and Regional Cost Factor.

Region	Average Cost/yd^3	Average Cost/m^3	Regional Cost Factor
Alaska/Hawaii	$13.84	$18.10	1.71
Atlantic	$7.04	$9.21	0.87
Gulf	$7.12	$9.31	0.88
Great Lakes	$8.04	$10.52	0.99
Pacific	$7.76	$10.15	0.96
Overall Average	$8.11	$13.28	

The regional cost factor is necessary to provide accurate cost estimation. Though production rates should be consistent anywhere in the United States given the same sediment and ocean conditions, project cost vary significantly between the Alaska/Hawaii region and the rest of the United States. The other four regions are within 10% of each other.

Project Cost Comparison

The second step in confirming the validity of the production and cost estimation program is to compare it to actual results. The cost estimation method developed in this paper is compared with the government (NDC, 2003) estimate, the Emmons (2001) estimate, and the winning bid (NDC, 2003) and the actual project cost (NDC, 2003) for five different projects. The winning bid is the amount the winning contractor bid for the project, and the actual cost is the amount the project finally cost the sponsor. The comparisons of project costs for the 5 projects are shown in Figure 10. Table 2 displays the relationship between the numbers on the graph and each project. It also shows the values for each bar in Figure 10.

The first project comparison is the Erie, PA project. The calculated project cost is 32% higher than the actual cost. Emmons (2001) predicts a project cost that is 15% above the actual cost while the government estimate (NDC, 2003) is 1% below the actual cost. The second project in Figure 10 is from Coos Bay, OR in 1995. The cost estimate developed in this paper provided better results being only 22% above the final project cost while the government estimate (NDC, 2003) is 24% above the final project cost.

The third comparison is Coos Bay, OR in 1997, which is the first project that this paper predicted a cost under the actual cost. Also, this is the largest project compared in this paper with an actual cost of 2.5 million US dollars. The Fernandina, FL project is the fourth project compared in Figure 10. In this comparison the cost estimating procedure developed in this paper is 6% below the actual cost and within $110,000. The other estimates are within 20% of the actual cost with the exception of the government estimate that is 48% above actual cost. The fifth comparison is for Wando, NC harbor. In this comparison the estimates broke into two groups. The winning bid, this paper and the actual cost were within $400,000. The government and Emmons (2001) method were over $1,600,000 above the actual cost. Figure 10 gives a graphical representation of the relationship between the different estimation methods and the actual cost for each project.

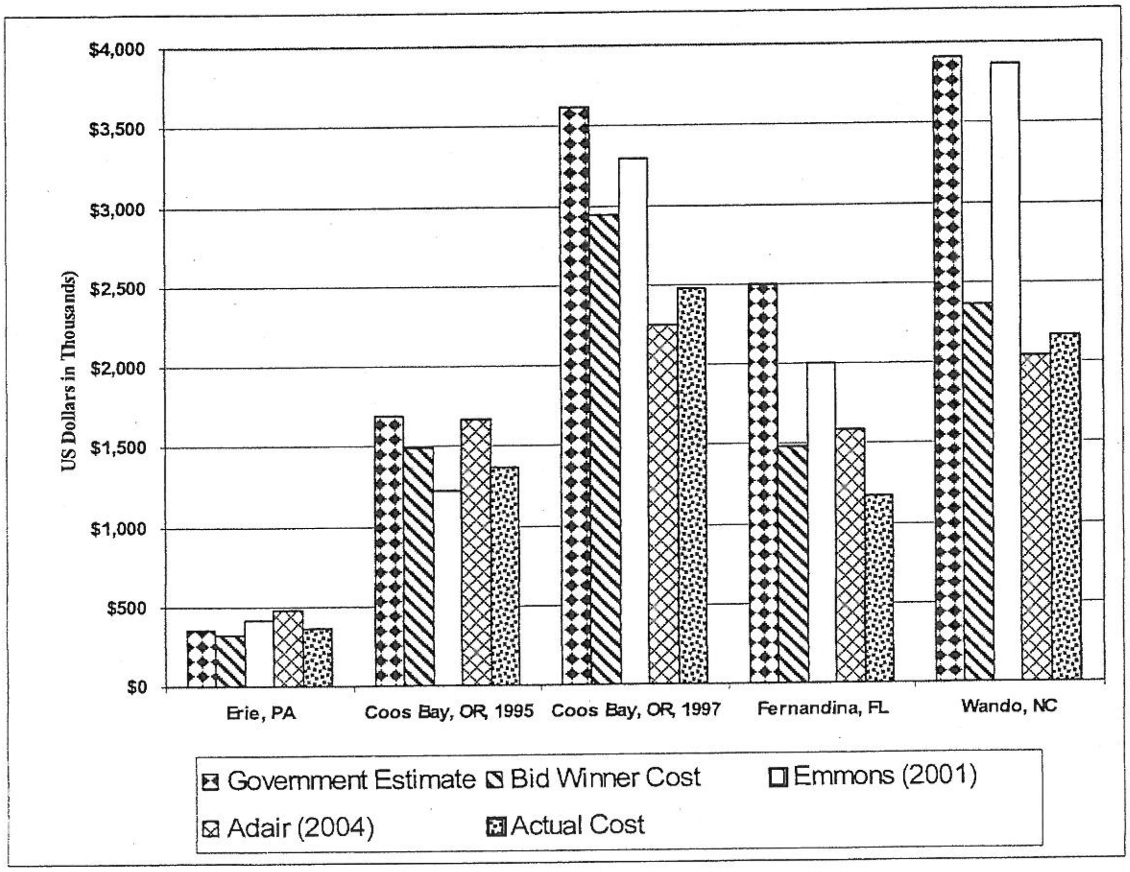

Figure 10. Five Project Cost Comparisons for Government Estimate, Bid Winner, Actual, Emmons (2001) and Adair (2004).

Table 2. Cost Comparison (Thousands of dollars US)

Project Number	Region	Government Estimate	Bid Winner Cost	Emmons (2001)	Adair (2004)	Actual Cost
1	Erie, PA	$357	$324	$416	$476	$360
2	Coos Bay, OR, 1995	$1,692	$1,490	$1,226	$1,667	$1,366
3	Coos Bay, OR, 1997	$3,615	$2,939	$3,296	$2,244	$2,480
4	Fernandina, FL	$2,502	$1,480	$2,003	$1,590	$1,169
5	Wando, NC	$3,908	$2,360	$3,870	$2,038	$2,169

The project comparisons show that the method developed in this paper is useful for estimating costs for mechanical dredge projects and is more accurate in estimating large projects. There are some discrepancies in smaller projects. These are most likely due to assumptions being made in the cost calculation about crew size and other project costs. Also, the production rate is more sensitive for small projects using smaller buckets than it is for large projects. From Table 2, the mean difference and standard deviation between each method and the actual cost have been calculated for these 5 projects and tabulated in Table 3.

Table 3. Percent Difference between Estimation Methods and Actual Project Cost.

Project	Adair (2004)	Government Estimate	Emmons (2001)	Winning Bid
1-Erie	+32 %	-1 %	+15 %	-10 %
2-Coos 95	+22 %	+24 %	-10 %	+9 %
3-Coos 97	-10 %	+46 %	+33 %	+19 %
4-Fernandina	-6 %	+48 %	+18 %	-13 %
5-Wando	-6 %	+80 %	+78 %	+9 %
Mean	+6 %	+39 %	+27 %	+3 %
Standard Deviation	+19 %	+30 %	+33 %	+14 %

The government estimate (NDC, 2003) is an average of 39% higher than actual cost with a standard deviation of 30%. The results from Emmons (2001) are an average of 27% higher than actual cost with a standard deviation of 33%. The results using the cost estimating method developed in this paper are 6% higher than the actual cost with a standard deviation of 19%. The only prediction method with better results for these five projects is the bid from the winning contractor. The winning bids were an average of 3% higher than the actual cost with a standard deviation of 14%.

CONCLUSION AND RECOMMENDATIONS

It is possible to effectively estimate production and project cost for mechanical clamshell dredges. Two important components in estimating the production rate are the cycle time and the bucket fill factor. Traditionally the cycle time has been assumed to be about 60 seconds. In water depth greater than 10 m (33 ft) the cycle time is greater than 60 seconds. As the cycle time increases, the project cost increases as well. Therefore, it is necessary to adjust the cycle time for specific projects.

The second important parameter in production rate and project cost is the bucket fill factor. It is necessary to determine how much of the bucket fills to estimate the production rate. The fill factor changes rapidly for bucket sizes between 0 to 20 m^3 (26 yd^3). Once the predicted amount of sediment excavated is known, then the production can be estimated.

There are several things that would be beneficial in predicting production for mechanical clamshell dredges. First, the crew size is fixed unless the user knows details of a project. It would be beneficial to develop a way to automatically adjust the crew size depending on the size of the project. This would provide more accurate estimates of project costs. Since the labor rates are recurring costs, a small change over a long period is a major influence on project cost. Fuel costs are another major factor affecting dredging project costs.

A second area for improvement is the bucket fill factor. The factors used in the spreadsheet follow the expected trends and are extrapolated from actual data. Experiments would help to verify the behavior of the large buckets. It could also explain the rapid change in fill factors for small buckets. Though the bucket fill factors behave as expected, it would help to refine them using experimental testing.

Delay factors for changing the hopper and advancing the dredge need to be improved. The actual delay factor for changing hopper barges does not include the number of hoppers, or the distance they have to travel between the disposal sites and the dredge. This assumes that there is always a hopper barge waiting, which may not be true. Finally, delay factors for estimating downtime and delays due to the presence of debris need to be developed. The spreadsheet currently does a good job estimating production and project costs, but these improvements would allow for better estimates with less site specific information.

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APPENDIX 1: NOMENCLATURE

A	Average area dredged at one location
B	Bulking factor
C	Capacity of the bucket
d	Water depth
f_a	Delay factor to advance the dredge
f_h	Delay factor to change hopper barges
f_m	Bucket fill factor
H	Hopper capacity
h_b	Freeboard height of the barge
P_{nom}	Nominal production rate
P_{act}	Actual production rate
T_{cycle}	Cycle time
t_a	Time to advance the dredge
t_e	Time to empty bucket

t_g	Time to close bucket during filling
t_h	Time to change hopper barges
u_f	Bucket fall velocity
u_l	Bucket lift velocity
z	Average thickness of material to be excavated
θ_{sw}	Bucket swing angle
ω_{sw}	Bucket swing rate

HABITAT VALUE CONSIDERATIONS FOR SEDIMENT CAPS

D. Ludwig[1], C. Barnes[2], S. Garbaciak, Jr.[3], T. Iannuzzi[4], and R. Mohan[5]

ABSTRACT

Among the most compelling issues in aquatic environments are habitat losses and chemical pollution. In general, management tools for pollution abatement and ecosystem restoration within waterways are quite different. An exception to this pattern is active sediment remediation where benthic substrate is frequently altered by removal (dredging) or emplacement (capping) of materials. This paper presents one conceptual approach to integrated pollution/habitat management design for sediment environments, develops some specifics regarding the implementation of such designs and the associated benefits, and discusses some project examples that take advantage of integrated design principles. The basic premise is that an upper module (EpiCap), based on specific habitat considerations, can be laid over an engineered subcap designed to control contaminant migration. Conceptual designs of four potential EpiCap modules (emergent wetland, submerged aquatic vegetation, hard bottom, and soft bottom) are discussed. The value of the habitat modules is presented in terms of one potential measure of restoration "success"-fish production. Other measurable benefits include food web support, shelter, foraging substrate, and cover for a great variety of resources, ranging from invertebrates to forage fish, amphibians and reptiles, through birds and mammals. Costs can vary significantly reflecting the degree to which the habitat modules can be effectively integrated into the overall cap design. Where more intense intervention is required, such as active planting of wetland vegetation or submerged aquatic vegetation, costs can rise precipitously. A successful example of habitat integration into a sediment capping project is the St. Paul Waterway in Washington State, USA, constructed a decade ago. This illustrated that restoration of sediment environments can be designed into sediment management projects. The habitat components enhance biological recovery from intrusive effects of dredging or capping and, if carefully designed, contribute to the control of contaminant transport or exposure as an integral component of the project.

INTRODUCTION

Waterways around the world have been impacted in many ways as humans have appropriated an increasing proportion of the biosphere and its products (McNeill 2000). The fundamental importance of surface waters to the health of global economies and ecologies (Peterson and Lubchenko 1997, Postel and Carpenter 1997) makes their effective management and restoration critical. The U.S. National Research Council (NRC 1992) stated starkly:

> "Restoration [of waterways] is essential if per capita ecosystem services are to remain constant while the global human population increases."

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Among the most compelling issues in aquatic environments of all kinds are habitat losses and chemical pollution (Iannuzzi et al. 2002). The NRC characterizes these sources of impact as requiring comprehensive response (NRC 1992):

> "...restoring [waterways is] ...at least as urgent as protecting water quality through abatement of pollution from point and nonpoint sources. Indeed these two activities are not dissociated, but rather are part of a continuum that includes both protection from pollution, and restoration and management."

While acknowledging the complementary nature of pollution and habitat impacts, we might well inquire whether this has any practical effect. After all, with the exception of wetlands (generally acknowledged to provide pollution control services systematically as an artifact of the patterns and processes characteristic of the habitat itself), are not the management tools for pollution abatement and ecosystem restoration quite different? In many cases this may be true. However, when considering sediment contamination, it is not. Indeed, habitat effects are inherent in any sediment management action—the benthic ecosystem is altered when substrates are manipulated by removal or emplacement, by active or passive means. And chemicals in sediments, at least those in the upper strata of the sediment column, are potentially accessible to the many organisms that occupy benthic habitats.

Along with the easily recognized problems, the intimate linkage between pollution and habitat in sediment environments provides promise and opportunity. Restoration, replacement, and reconstruction of sediment environments can be designed into sediment management projects as an integral component of the program. The habitat components can be developed to enhance biological recovery from intrusive effects of dredging or capping, or they can be designed to contribute directly to the role of contaminant transport or exposure. The objectives of this paper are to present one conceptual approach to integrated pollution/habitat management design for sediment environments, develop some specifics regarding the implementation of such designs and the associated benefits that can be realized, and discuss some project examples (both existing and planned) that take advantage of integrated design principles for sediment management programs.

INTEGRATED SEDIMENT MANAGEMENT DESIGN CONCEPT

The fundamental concept is that contaminated sediments amenable to management by capping can be managed simultaneously for habitat enhancement. To make this concept practical, engineering and ecology need to be forged into a unified set of tools that can be applied flexibly to management problems covering a broad range of chemical, physical, and biological conditions. One way to build the integrated technology needed to meet both engineering and ecology needs is to accommodate each category of design objective in a different component of a single structure. In both engineering and biology, analogies might be drawn to integrated films or coatings with dual purposes. For example, the inner layer of an automobile paint must adhere rigorously to the substrate, while the outer must endure a variety of chemical and physical stresses without noticeable alteration. In biology, the inner surface of gastrointestinal wall systems maximize absorption of water and nutrients while the outer surface isolates the organ and protects both the internal and external environments.

For isolating contaminants in sediments, an engineered substructure (subcap) laid directly on the substrate can control chemical transfers and constrain exposure. An outer layer (EpiCap), laid over the substructure, can be configured for habitat enhancement. Such a structure is shown schematically in Figure 1. Note that this figure is a generic illustration—the subcap can be engineered with layers of differing content to control contaminant transfer by resuspension, advection and diffusion as appropriate (Mohan et al. 2000, Palermo et al. 1998), and the EpiCap can be designed for a variety of habitat types.

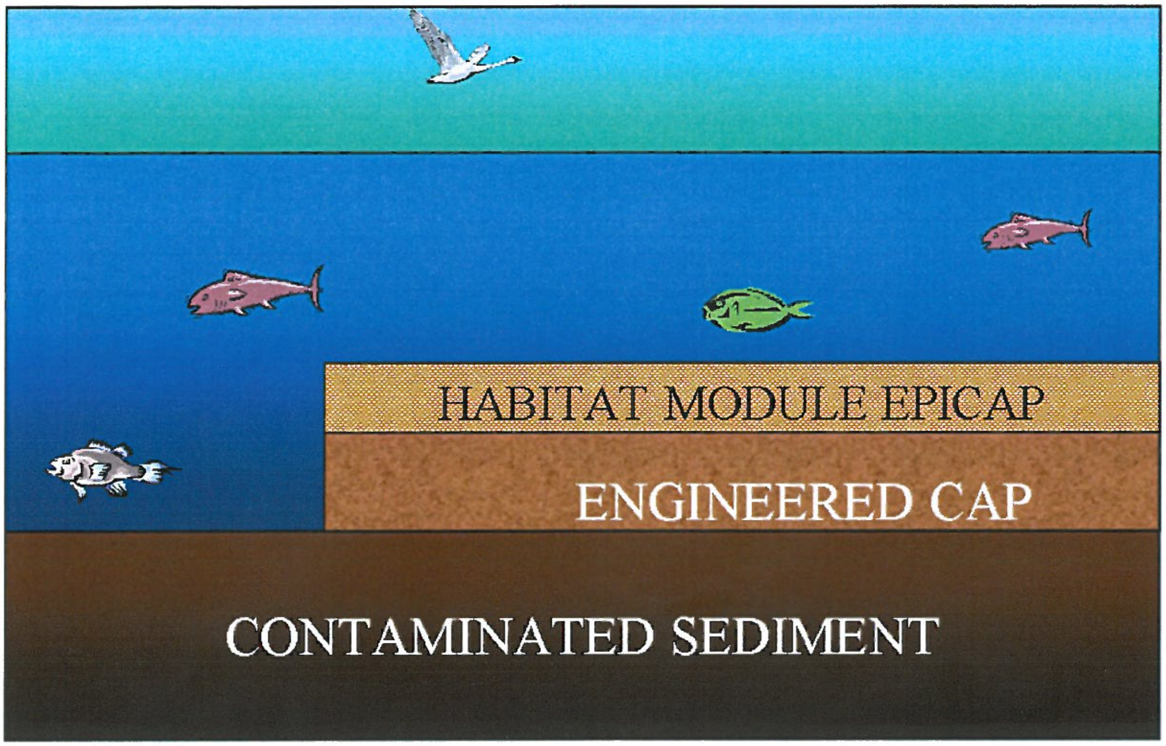

Figure 1. Conceptual Illustration of an "EpiCap"

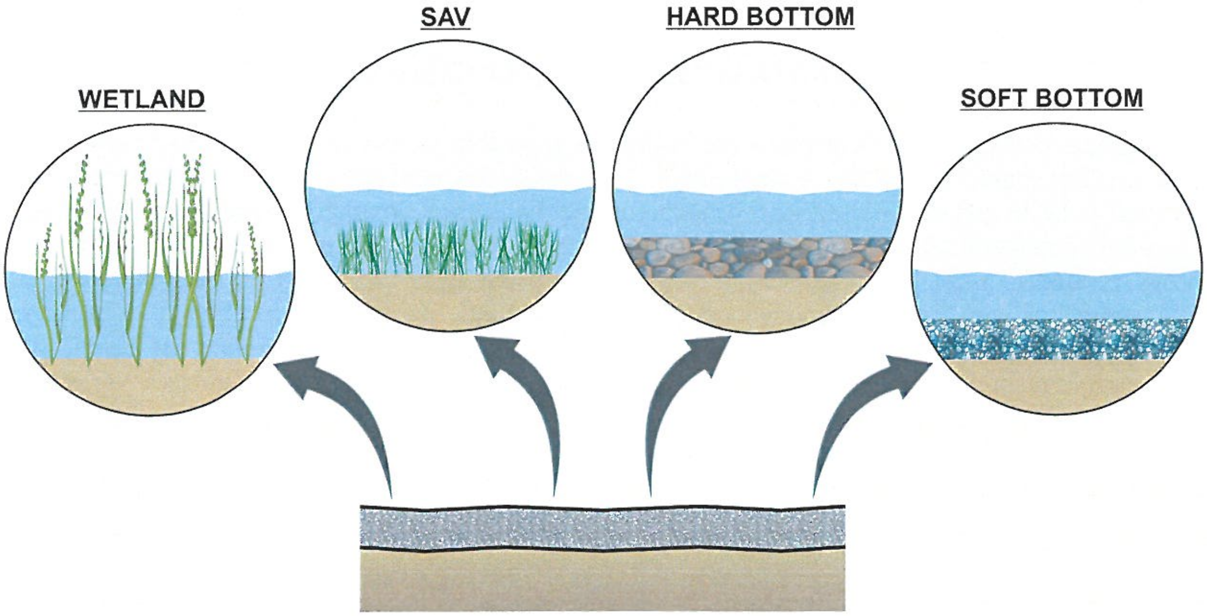

Figure 2. Types of Habitat Modules in Aquatic Environments

The habitat layer can be developed in modular form to encompass a range of ecological conditions that might be desired in the post-capping environment. Figure 2 shows four possible habitat modules—emergent wetland, submerged aquatic vegetation (SAV), hard bottom, and soft bottom, relative to a cap like that illustrated in Figure 1.

In most natural waterways, there is a mix of habitat types present. Applying the modular concept (as in Figure 2) allows the manager to provide habitat enhancements by improving the quality of the system in particular locations, while offering the flexibility to enhance the particular habitat mix present in the management area.

HABITAT MODULE DESIGN CONSIDERATIONS

Each of the habitat modules conceptualized here (other modules can be developed for this flexible system as well) has its own design requirements. These will vary depending on the particular application to which the module is applied—as an example, consider how different the design parameters would be for an emergent wetland in an alpine lake environment vs. a high-salinity tidal estuary. However, there are certain universal environmental features that can be applied at a preliminary or conceptual level when considering the design of these module types. While it is impossible to characterize these in detail in this paper, it is at least worthwhile to identify them and touch briefly on their significance.

For emergent wetland modules, a relatively fine-grained substrate is appropriate for a broad range of vegetation that might be planted or allowed to colonize naturally on the EpiCap. Such a substrate might range from muds and silts to sands in grain size, with amendments of organic matter, fertilizers, or microbial inocula as appropriate. Minimum thickness of the EpiCap (or EpiCap plus outer subcap elements if rooting would be acceptable) in many applications will range between 20 and 50 cm. Under many circumstances, careful planning will allow colonization from existing nearby wetlands to do much of the work of "planting" by natural engineering processes. Where possible, a natural colonization approach is almost always ecologically preferable because it assures that the conformation of the biological community is determined by the site and not by a propagule mix application. Where invasive species colonization is likely to precede development of a desired plant community, chemical preparation of the EpiCap and/or prophylactic application of specific growth enhancers or inhibitors might be considered.

For SAV modules, a similar range of fine- to medium-grained substrate types is appropriate. In open water bottoms where currents are constant, bottoms will tend to naturally sort to coarser particles, sometimes with a substructure of finer material. In such circumstances, the design may require one or more elements specifically intended to stabilize the substrate and prevent shifting or transport loss. Amendments and colonization considerations are similar to those for emergent wetland modules, understanding that the plant species involved are very different with quite different growth requirements.

Hard bottom modules comprise a range of substrates from gravels and cobbles to boulders and rubble, or combinations of these with or without soft substrate additions. Key ecological values of hard bottoms are clean and stable surfaces of varying topography, and deep interstices. In some areas, natural processes will retain these conditions. Where possible, the substrate comprising the hard bottom can be sized to promote self-maintenance based on analysis of hydraulic conditions (Milhous 1998). Under other circumstances where finer material will tend to deposit on, coat, and cover hard bottoms, increasing embeddedness, and active maintenance for fines control may be required.

Soft bottom substrates are fine materials lacking macrophyte vegetation—often in deeper water where light penetration is insufficient for plant growth or in locations (such as seasonal and tidal waterways) where inundation and drying cycles are too stressful. Ecologically healthy soft bottoms often develop stabilizing conditions in the upper layers of the sediment column through particle aggregation via invertebrate gut processing, production of extracellular binding materials by microbes, and a network of living and nonliving organisms that combine to create a substantial structure from otherwise fine particles that might be subject to easy physical transport. In exposed conditions, it may be necessary to engineer substrate stability to allow the development of the biological conditions necessary for long-term self-maintenance.

HABITAT MODULE VALUE CONSIDERATIONS

The natural world is essentially infinitely diverse, because detailed examination at one scale of space and time reveals patterns and processes at larger and smaller scales *ad infinitum*. This presents more than a mere academic paradox, because it means that a habitat yields patterns and processes at many scales simultaneously, and that monitoring and measurement parameters (such as criteria to demonstrate successful completion of a restoration project) must be selected from a large universe of potentially applicable parameters. Where habitat restoration, replacement, or reconstruction is undertaken to meet the requirements of regulations or enforcement programs, some parameters are usually measured to demonstrate quantitative progress, others may be characterized or catalogued to show that a range of values is accruing from the enhancements.

For this paper, we will illustrate these points with examples of specific resources from a particular geographic area. Often in aquatic ecosystem management, fish and fisheries are a primary concern. For projecting and measuring the benefits of habitat restoration, fish production may be a measure of restoration "success." While it is not trivial to adequately project or measure such production, it can be done. At the same time, a number of other production parameters might be measured, or at least identified qualitatively as clear contributions from the restoration effort. In cold fresh waters of the northern U.S. and southern Canada, a valued suite of sport and commercial fishes includes:

- Walleye (*Stizostedion vitreum*), a large carnivorous perch
- Smallmouth bass (*Micropterus dolemieu*), a large sunfish
- Northern pike (*Esox lucius*), an abundant large predator
- Muskellunge (*Esox masquinongy*), a large and much less common pike
- Yellow perch (*Perca flavescens*), a smaller species of enormous recreational and commercial importance in many areas.

For habitat restoration planning, the potential for production of these species may be taken as one way to estimate quantitative habitat value. For walleye, the hard bottom module provides appropriate spawning substrate, and such habitat can produce on the order of 1.6×10^6 eggs and 100 harvestable adults per hectare each year. Smallmouth bass is also a hard bottom spawner, and such habitat can yield 1.5×10^5 eggs and 200 harvestable adults per hectare annually. The northern pike would be produced in both emergent wetland and SAV modules at a rate of 3×10^5 eggs and on the order of 500 harvestable adults per hectare per year. Muskellunge spawns in emergent wetlands, such systems can yield about 100 harvestable adults per year. Yellow perch requires SAV for spawning, under favorable conditions such habitat can yield 1×10^5 larvae and on the order of 1,000 adults per hectare per year.

These examples provide some idea of the enormous quantitative value that can accrue from properly configured habitat value modules. In addition, habitat enhancements of any kind provide food web support, shelter, foraging substrate, and cover for a great variety of resources, ranging from invertebrates to forage fish, amphibians and reptiles, through birds and mammals. In addition, natural systems yield human uses and aesthetic values. Any or all of these can be quantified in the context of a particular sediment management/habitat enhancement program, depending on available resources of time, expertise, and money.

Another category of value that can be realized from habitat enhancement is control of undesirable species. Proper design and plant management can help assure that desired vegetation grows in place of weedy species. In addition, habitat conditions can help constrain animal pests. In North America, the common carp (*Cyprinus carpio*) is in many places a devastating invasive species that builds to enormous biomass levels. Carp abundance can increase turbidity and sediment transport, alter plant diversity and abundance, and interfere with the production of more desirable recreational and commercial fishes. Carp breed and feed in shallow, soft-substrate habitats, with or without dense plant growth. For control, provision of a hard bottom habitat module with cobble sized substrate at least 10 to 50 cm depth can, if maintained in clean condition, suppress carp spawning with concomitant return in production of desirable species and other benefits.

In general, for a sediment management project, it will be most effective to project quantitative values for a limited range of parameters (these may be identified by stakeholders or by technical team consensus) and identify a broader suite of values that is not estimated (or monitored) quantitatively.

HABITAT MODULE COST CONSIDERATIONS

Costs will vary greatly depending on job-specifics. However, the relative significance of various components of total cost can be characterized for the different habitat modules. Such a characterization is useful for planning purposes, as a relatively small additional investment in conceptual design may yield a large return in overall project value if other costs are known to be modest.

The most critical cost factor is what would be called "installation" in a hard engineering context. For habitat, installation means the costs involved in direct provision of the habitat condition. Under many circumstances, effective design of the sediment cap can integrate an appropriate substrate as an outer layer with little or no additional expense. Ideally, construction sequencing can be designed to coordinate with other activities at the location to minimize additional mobilization and heavy equipment costs for such installation. If the waterway provides ready sources of plants and animals for colonization, and such colonization occurs appropriately, there may be little or no additional cost (beyond that necessary for the sediment capping itself) to provide the habitat value enhancements.

Conversely, if active planting of wetland vegetation or SAV is required, habitat installation costs can rise precipitously—but not always. Careful attention to site preparation, conformation, and topography, effective use of natural engineering, and inexpensive prophylaxis can yield disproportionately successful habitat enhancement value. In our experience, high-quality wetlands and SAV habitat modules can be actively installed for as little as a few thousand dollars (U.S.) per hectare, but we are also aware of cases that have involved costs of $50,000 (U.S.) or more.

Other cost categories include design, permitting, monitoring, and operations and maintenance. The latter can often be managed most efficiently by designing a program of adaptive management, tailoring operation and maintenance activities to specific thresholds and using natural engineering as much as possible (Haney and Power 1996, Weinstein et al. 1997).

PROJECT EXAMPLES

There is an existing, long-term habitat value sediment capping success story-implemented under the direction of the Washington State Department of Natural Resources in the St. Paul Waterway in Washington State, USA. This was the first estuarine Superfund site to be cleaned up in Washington, USA. The aquatic ecosystem had been affected by pulp mill effluent and associated woody and organic debris, with chemical and physical impacts on the environment. Phenols, polyaromatic hydrocarbons, and copper were of particular concern in sediments.

Remediation of contaminated sediments included the installation of a cap in nearshore and intertidal environments. The cap was designed in several layers for chemical and physical stability, and varied from about 1 to 7 meters in thickness. Over the engineered subcap designed for controlling exposure to contaminated sediments, an EpiCap was provided, along with additional areas of nearshore habitat. This is primarily the equivalent of a soft bottom module. The EpiCap has persisted for more than a decade with a relatively low level of required maintenance, and has been successfully colonized by a healthy community of benthic organisms. The habitat value enhancement of this sediment management project is widely acknowledged.

To leave the reader with some ideas for the future, we close this paper with a project example that has not yet been implemented. Figure 3 shows the conceptual design of a sediment management project combining control of exposure to contamination with a wetlands module value cap and specific human use enhancements associated with the project.

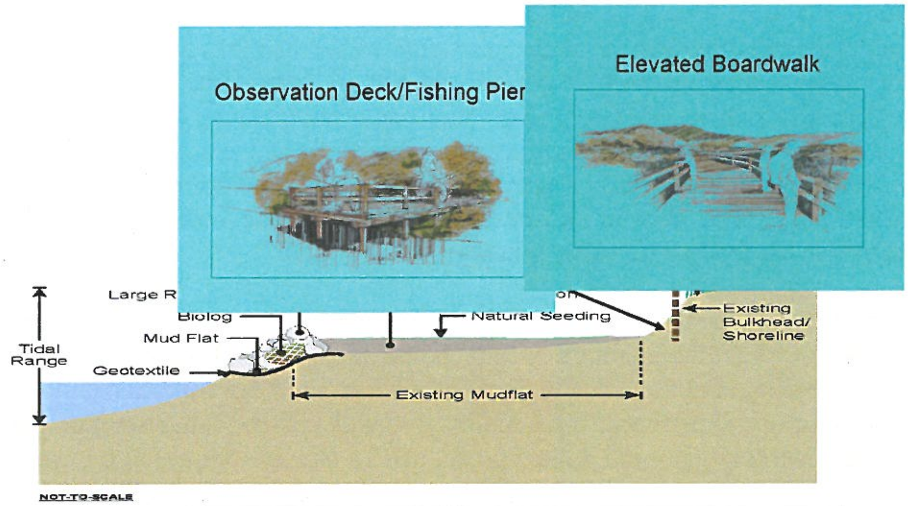

Figure 3. Conceptual Design of a Habitat Enhanced Sediment Management Project

The conceptual design includes stabilizing elements (riprap and biologs to control erosion while wetland vegetation colonizes), with capping and possibly growth amendments of the existing surface sediment. Project components for this conceptual design are illustrated in Figure 4, including projected costs and implementation time.

Table 1. Project Details for the Habitat Enhanced Sediment Management Project

In-River Wetland Module EpiCap	30.5 cm sand 15.24–30.5 cm of cover material Establish *Spartina alterniflora* wetland
Other Project Components	1.5 ha of adjacent wetland/upland habitat 305 m of elevated boardwalk 3 m × 9 m observation deck
Cost	$1.3 to $1.5 million (US)
Timing	Preparation time: 18 months Duration of construction: 4 to 6 months Follow-up monitoring/maintenance required

This comprehensive conceptual sediment capping project, incorporating habitat value enhancements and human use infrastructure, is one example among many of enormous benefits that could be realized from the linkage of ecology and engineering in sediment management programs.

CONCLUSIONS

Effectively designed sediment management projects can contribute to waterway maintenance, and, simultaneously, to ecosystem restoration in urbanized or otherwise impacted areas. Where contaminated sediments are managed by in-water capping, providing high-quality habitat as an integral component of cap design maximizes the value of the cap both for controlling exposure to chemical pollutants and for ecological restoration.

A basic design approach for accommodating ecological restoration in capping activities is to incorporate two layers in the cap—an inner layer or subcap to constrain chemical transport, and an outer layer or EpiCap to provide habitat value. This concept can be implemented in modular fashion, and EpiCaps can be designed to provide various kinds of aquatic habitats, including emergent wetlands, submerged aquatic vegetation, and hard and soft open substrates. A capping program can include different EpiCap modules in different portions of the cap, allowing planners to select a preferred combination of habitat types appropriate for a particular waterway.

Properly configured EpiCap habitat modules can provide natural resource services ranging from direct production of fish and shellfish to aesthetically pleasing conditions for human recreation. The flexibility of the subcap/EpiCap concept, and the cost efficiency that can be realized by incorporating EpiCap preparation and installation directly in the design and construction process, make this an attractive option for many applications.

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NOTES FOR CONTRIBUTORS

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