PRODUCTION AND COST ESTIMATING FOR TRAILING SUCTION HOPPER DREDGE

A Thesis

by

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ABSTRACT

Major dredging projects in the United States are typically contracted out by the government using a competitive bidding process. A method for accurately estimating the total cost associated with performing the dredging work is essential for both government solicitation and the bidding contractors. This thesis presents a method to determine production rate for trailing suction hopper dredges when minimal information is known about both the site to be dredged and the hopper dredge being used. The calculated production rate is then combined with financial inputs to estimate a total dredging cost and project duration.

The production and cost estimation is incorporated into a publically available program designed on Microsoft Excel. The program utilizes fluid transport fundamentals, dimensionless pump curve analysis, and overflow loss assumptions to create a highly customizable program across a wide range of hopper dredge project types. In addition, the program allows a user to reduce or expand the scope of cost estimating depending on project requirements.

Results for the program were found to satisfactorily estimate total project costs and dredging operation costs for eight major dredging projects between 2013 and 2015. Through the utilization of default hopper specifications and project specific site characteristics the program generated a mean absolute percent difference of 21% for the total project costs and 20% for the dredging operation costs alone.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

INTRODUCTION

Dredging is the excavation, transport, and placement of sediment from the bottom of a body of water and is typically performed as a means to deepen navigational waterways, increase coastal land area, or a combination of the two. As an approximately $1 billion annual industry in the United States, dredging is a vital aspect of maritime transportation and the habitability of many coastal communities. The positive effects of dredging can be seen in everything from maintaining navigability of the Mississippi River to the creation of a recreational beach along Florida's coastline.

There are two primary methods of dredging: hydraulic and mechanical. While mechanical dredging utilizes buckets or scoops to mechanically excavate and lift sediment out of the water, hydraulic dredging utilizes a pump to entrain the sediment particles with water for removal and transport. The trailing suction hopper dredge is a category of hydraulic dredge used primarily for coastal and open ocean navigation channels. Hopper dredges accounted for nearly 30% of the total dredging expenditure in the United States from 2013-2014, with over 400 million dollars spent in 2014 alone (NDC, 2015). The majority of these projects were funded by the US Army Corps of Engineers (USACE), which either performs the work using corps owned vessels or contracts the work out to American dredging companies.

Dredging contracts are awarded through standard government procurement process, and typically through the competitive bidding process. In this manner, multiple companies bid on the cost of completing a dredging project and the contractor with the lowest reasonable bid is selected to complete the work. Most dredging is on a per-unit basis, so that the contractor estimates a cost per the volume of material specified in project plans. The actual final cost of the project is the per-unit cost bid times the actual amount excavated (Huston, 1970). It is crucial for the contractor to have an accurate cost estimation process to not only submit a competitive bid, but to also ensure a desired profit margin is maintained. The USACE also utilizes a cost estimating system in order to secure necessary government funding and verify the plausibility of the bids. Both private contractors and the government agencies use proprietary estimating systems which are not readily available to the public. For individuals outside the government-contractor community there has been extensive works written on the procedures of dredging project cost estimation.

In general terms, a cost estimate is based on site conditions, dredging equipment, and contract restrictions. Provided with detailed knowledge of these factors, a reasonable production rate can be predicted for the average dredging site. The production rate is then used to estimate the total cost of the project. A higher production rate will result in less time spent on the project and a lower total cost, while if a lower production rate is maintained, the time and cost required to complete the work will increase.

Objectives

The objective of this research is to develop, test, and validate a new user friendly software to forecast the cost of hopper dredge projects. The software is based in Microsoft Excel spreadsheet format and readily available to individuals outside the government-contractor community. In order to predict the cost of a dredging project, a production rate must first be determined. Estimating the production can be difficult due to the uncertainty of dependent variables, but once calculated, the total cost can be determined relatively easily using general pricing assumptions. Building upon a previously developed cost estimating software from the Center for Dredging Studies (CDS, 2014), this research will increase the programs breadth of application, scope of inputs, and simplify the user interface. The operator will need only to input known or estimated equipment and site characteristics to have the software yield a total cost estimation.

TRAILING SUCTION HOPPER DREDGE

Trailing suction hopper dredges are self-propelled vessels with the capability to excavate, transport, and discharge seabed material. As a category of hydraulic dredge, which also includes cutter-suction dredges, hopper dredges utilize a centrifugal pump to entrain sediment in water for removal and transport. A typical hopper dredge is illustrated in Figure 1. During dredging, the suction pipes, or drag arms, are lowered by winches and gantries so that the drag head reaches the desired dredging depth. As the vessel slowly moves ahead, typically one to two knots, the drag head is pulled along the sea floor as water flows into the suction pipe. Automatic swell compensators maintain consistent contact with the sea floor even when operating in wave heights of several meters, a major advantage over other hydraulic dredges which typically cannot operate is sea conditions greater than one meter. Depending on the type of drag head used, the combined effect of the dragging drag head and flowing water entrain and erode the sediment for removal. This mixture of sediment and water is called slurry, and upon reaching the desired sediment concentration, is drawn up the suction pipe, through the centrifugal pumps located onboard the vessel, and into the hopper bins.

The type of drag head employed for a project is a significant concern and the improper drag head has the potential to make the dredge ineffective. There are many different types used in the dredging industry, but the common drag heads used include: the Fruehling (Dutch), California, venturi and waterjet. The type of drag head selected for optimal production depends on the type of material to be dredged and the dredge being used (Bray et. al, 1997). Though drag heads are typically limited to use on silts and sands, there has been some recent success in dredging large gravel and rock outside the United States with a ripper drag head (Bray and Cohen, 2010).

The hopper is typically outfitted with a distribution system that minimizes turbulence and ensures solids quickly settle out of the slurry mixture to the bottom of the hopper bin.

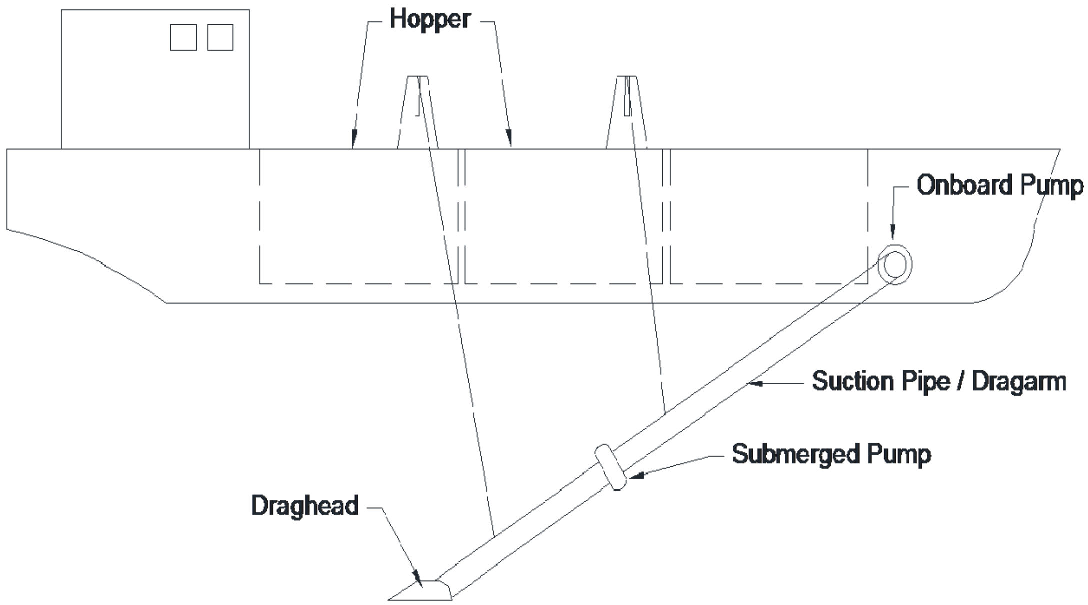

Figure 1: Typical Trailing Suction Hopper Dredge Components

Overflow weirs are also installed in the hopper bins so that as the sediment falls to the bottom, the cleaner water can flow back out of the dredge and more slurry can be pumped into the hopper. Overflow enables the hopper dredge to continue loading past the time it takes to initially fill with slurry mixture, maximizing the concentration of sediment in the hopper bin. The rate of settlement depends largely on the type of material being dredged so that medium to coarse sands settle faster than smaller diameter particles like silt and clay which may not settle at all. The use of overflow is typically omitted while dredging fine particles or when site restrictions prohibit the overflow of sediment back into the water (Bray et al., 1997).

When the hopper reaches full capacity, the pumps are secured, drag arms are stowed back aboard, and the vessel sails to the designated placement site. The dredged material is typically removed from the hopper through a bottom discharge or pump discharge. The placement method depends on the type of dredging project being conducted and capability of the dredge. Bottom discharge is used for maintenance dredging of a channel or harbor, the hopper sails to an offshore disposal site and the dredged material is discharged through doors or valves in the bottom of the hull. This allows for fast and total offloading at a specific location. Some dredges have a split-hull design where the vessel splits open along the centerline to unload the hopper contents. Pump discharge is a method of sediment placement used for beneficial use projects such as beach nourishment. The dredged material is removed from the hopper through onboard pumps and into submerged or floating pipeline system to the shore. Rainbowing is a variant of the pump discharging where the dredged material is sprayed through a bow-mounted nozzle, into the air, and onto the shore reclamation site as far as 100 meters away (Bray et al. 1997).

When the contents of the hopper are emptied, the dredge sails back to the dredging area and the cycle of load, sail to discharge area, discharge, and sail to dredging area begins again. This is called the production cycle and depending on the hopper specifications and site characteristics can take from less than an hour, up to several hours, per cycle.

Trailing suction hopper dredges are ideally suited for the removal of non-cohesive materials like sands or loose silts, and are most commonly employed for maintenance dredging, or maintaining navigable depths in previously dredged channels or harbors. Hopper dredges can also be used for expanding existing channels or for dredging untouched sea beds, but lose effectiveness on hard packed soils and boulders.

The main advantage of the trailing suction dredge arises from its mobility. While other hydraulic dredges, such as a cutter-suction dredge, are require to be partially anchored to the work site, hopper dredges are fully mobile and self-propelled. The mobility provides a major advantage over fixed dredging systems while operating in active shipping channels or harbors. While a pipeline dredge requires a large working footprint that could inhibit navigation, hopper dredges have minimal impact on the traversing commercial vessels. Conversely, fixed dredges may have work delayed due to obstructions from other commercial vessels, which would result in a lower overall production rate than the hopper dredge, which can work continuously through even heavy shipping traffic. Its mobility also makes the hopper dredge ideal for use in projects that require the excavated sediment be transported a long distance to the placement site, thus making the use of a pipeline impractical. Finally, the costs of transferring to a new dredging site, known as mobilization, tend to be lower than other dredges which would require additional support vessels to transport all the equipment to a new work site. Figure 2, courtesy of the USACE, shows a typical dredging project plan view which includes the intended sections of the shipping channel to be dredged and designated placement sites.

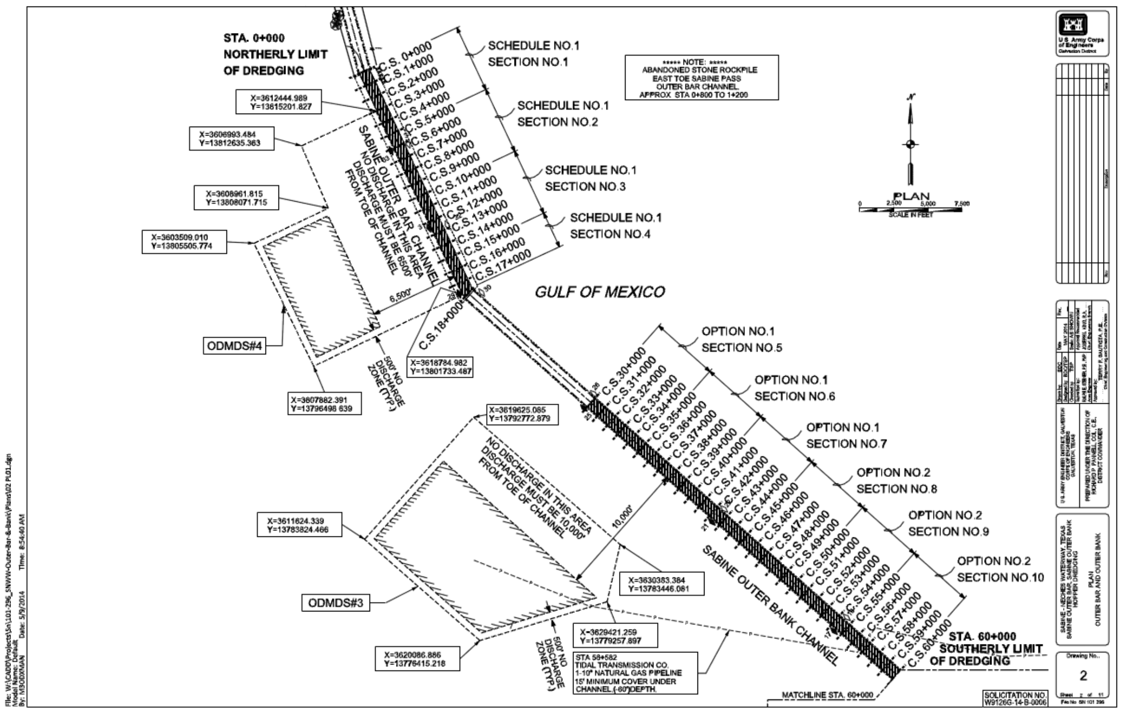

Figure 2: Plan View of Sabine Neches Waterway Dredging Project (USACE, 2014)

REVIEW OF LITERATURE

There has been extensive academic work on the creation of a reliable and replicable cost estimation procedure for hydraulic dredging work. A review of prior work in this field reinforces the importance of an accurate production rate based on hydraulic transport fundamentals and valid adjustment factors.

According to Turner (1996), the production of a hydraulic dredge is only an expression for the solids transported. The production equation in its simplest form then becomes the average flow rate of slurry times the average percent solids. This production rate equation will be incorporated later as a component of the overall production cycle rate.

Bray et al (1997) formulated a total production time, or maximum potential output P_{max}, for hopper dredges by analyzing the overall production cycle. For hopper dredges this is comprised of: loading time, turning time, sailing time to and from the site, and time taken to discharge dredged material. The loading time, t_{load} is dependent on soil type, and is determined using loading graphs which plot the proportion of the hopper filled with sediment, f_e, as a function of loading time in hours. Bray et al (1997) also estimated how to calculate the unproductive components of the production cycle using vessel and site characteristics, and provided reasonable assumptions to make when this information is not available.

Randall (2004) discusses how to arrive at an optimal flow rate by comparing the installed centrifugal pump characteristics and the system head curve. The pump characteristics curves are dimensional curves that graph the total head, power, and efficiency as a function of volumetric flow rate of water for a particular pump. The system head curve is a summation of the dredging system's head losses, from draghead inlet to discharge into the hopper, and static head as a function of flow rate. The point at which the pump curve intersects the system head curve is called the operating point and corresponds to the optimal flow rate.

Wilson et al. (2006) present a method for calculating energy losses of a slurry moving though a piping system. This frictional head loss for slurry flow, i_m, is expressed in foot (meter) of head per foot (meter) of pipe length and explained in the hopper dredge production section. Wilson et al. (2006) also provide solutions for the hydraulic variables used to find the frictional head loss and modifications to account for inclined pipe flow, such as a lowered drag arm.

Miertschin and Randall (1998) describe the creation of a cost estimating program developed for cutter suction hopper dredges. The methodology and program functionality have been influential for all later dredging estimation programs developed by the Center for Dredging Studies (CDS). Most importantly, they utilized non-dimensional pump curves to estimate pump characteristics for a wide range of dredge sizes. The use of non-dimensional pump characteristics makes production estimation more flexible as the total pump head, power, and efficiency can be reasonably estimated across different pump speeds and sizes without the need for specific characteristics curves

Palermo and Randall (1990) studied the impact of overflow time on the loading of hopper dredges and determined that when dredging sediments that settle out of suspension quickly, such as sands and gravel, having a period of overflow can significantly increase the solids load of the hopper. Conversely, when dredging silts and clay solids there is usually no benefit to overflow since the concentration of solids in the hopper does not increase substantially. In addition, due to environmental concerns, many times dredging contracts specifically prohibit any overflow.

Randall (2000) discussed the methodology for estimating dredging costs and the cost components to be considered when making an estimation. The methodology combined the production rate estimation with calculations for various cost components to form a reasonable total cost estimate applicable to hydraulic dredges. In addition, the difficulty for the government to estimate mobilization and demobilization costs was explained as a consequence of not knowing the dredge's proximity to the project site. However, recommendations were made to formulate a reasonable mobilization cost estimate.

Belesimo (2000) formulated a cost estimation software for both cutter suction and hopper dredges using hydraulic transport fundamentals and unit cost assumption. The slurry flow rate was determined based on dredging equipment configurations and the characteristics of dredged material. Belesimo's cost estimate program yielded highly competitive results with an average 17.3% difference from the winning bid, compared to the 16.2% difference between the government estimate and winning bid for the same data.

The most recent cost estimating system publically available from the CDS was published by Hollinberger (2010) and built upon on earlier work by Belesimo (2000). Hollinberger focused the scope of research to only trailing suction hopper dredges, but added the effect of inclined slurry transport and regional cost factors. The production rate was based on an assumption of no overflow condition, and used the flowrate, Q, to determine the time required to fill the hopper. The volume of material in each load was based on the hopper capacity multiplied by the concentration of solids, and the number of cycles was used to determine time required for the project. Hollinberger's cost estimating program improved the results from Belesimo, lowering the average difference from winning bid to 15.9%, compared to the 15.7% difference between the government generated estimates and winning bid.

METHODOLOGY FOR ESTIMATING PRODUCTION

Arguably the most important factor that must be determined is the rate of production sustained by the dredge and dredging crew. The production rate of a dredge is defined by Bray et al. (1997) as the amount of material moved per unit of time. Once the production rate is determined, the time it will take to complete a project can be estimated. The more time a project takes, the more resources and labor will be required to complete it and the more costly it will be. Therefore, an accurate estate of the production rate is required before there can be an effective cost estimate. The production rate for the trailing suction hopper dredge is determined using a combination of slurry transport theory, non-dimensional pump characteristics, and recommended cycle limiting factors.

Hydraulic Transport

The transportation of solid material suspended in liquid, or hydraulic transport, is of major interest for the dredging industry. The efficient operation of hydraulic dredges depend on accurate calculation of the power required to pump slurry mixture, and the rate at which sediment can be removed. In the context of a trailing suction hopper dredge, these calculations are utilized for slurry pumped through the drag arm, into the hopper bin, and out to a shore reclamation project. The hydraulic transport components are broken down into three components: critical velocity, energy lost to the system, and power supplied by the pump.

Critical Velocity

A fluid must maintain a certain velocity through a pipe to prevent particles suspended in that fluid from falling out of suspension and becoming stationary on the bottom. If the slurry does not maintain this critical velocity (V_c) the sediment will settle out, restrict flow, and likely clog the pipe. The velocity maintained by the system should not fall below the critical velocity. Matousek (1997) developed the following equation based on the nomograph presented in Wilson et al. (2006) to determine the critical velocity in horizontal slurry pipe flow.

$$V_c = \frac{8.8\left[\frac{\mu_s(SG_{so} - SG_f)}{0.66}\right]^{0.55} D^{0.7} d_{50}^{1.75}}{d_{50}^2 + 0.11D^{0.7}} \tag{1}$$

where μ_s is the dimensionless coefficient of mechanical friction between particles, taken as 0.44 or 0.55, SG_{so} is the specific gravity of the solids, SG_f is the specific gravity of the fluid, D is the inside pipe diameter in meters, and d_{50} is the median particle diameter in millimeters. The critical velocity is then used to calculate the critical flow rate (Q_c) which is the minimal flowrate the dredge should operate.

System Losses

The energy lost as a slurry is transported through a piping system is referred to as head loss, and is used to determine the power required to deliver a certain flowrate. The system head losses are the summation of head losses from frictional effects of the pipe, termed major losses, and head losses from various pipe components, termed minor losses. The minor losses (H_m), result from the loss of energy as fluid travels through piping components such as valves, joints, bends, and pipe entrance, and exit conditions. These minor head losses are characterized by the loss coefficient K and calculated by the following equation recommended by Munson et al. (2009).

$$H_m = K\frac{V^2}{2g} \tag{2}$$

H_m is given in units of feet (meters), V is the mean velocity of the slurry, g is the acceleration due to gravity. The value of K is dependent on component geometry and

Table 1 contains common values found on trailing suction hopper dredges based on Randall (2014) and other common values from Munson et al. (2009). The h_m for the dredge is thus found by summing the K values of all components in the hopper pipe system to find a solution for Equation 2.

Table 1: Minor Loss Coefficients for Common Dredge Components

Component	**K**
Suction Entrance	
Plain end suction	0.8
Slightly rounded suction	0.2
Well-rounded suction	0.04
Nozzle	5.5
Funnel	0.1
Elbow	
Regular 90°, flanged	0.3
Long radius 90°, flanged	0.2
Long radius 45°, flanged	0.2
Return bend, 180°, flanged	0.2
Ball Joint	
Straight	0.1
Medium cocked	0.4-0.6
Fully cocked (17°)	0.9
Valves	
Globe, fully open	10
Gate, fully open	0.15
Ball, fully open	0.05
Swing check, forward flow	2.0
Other	
End section, discharge	1.0

The major losses are a result of frictional interaction between the slurry and inner pipe walls during flow. The frictional head loss (H_f) within the hopper pipe system is determined by procedures described in Wilson et al. (2006), and apply to heterogeneous slurry flow in both horizontal and inclined pipes. For horizontal flow

$$i_{m(horizontal)} = \frac{fV^2}{2gD} + 0.22(SG_{so} - 1)V_{50}^M C_v V^{-M} \quad (3)$$

where

$$V_{50} = w\sqrt{\frac{8}{f}}\cosh\left[\frac{60d_{50}}{D}\right] \quad (4)$$

and

$$w = 0.9v_t + 2.7\left[\frac{(\rho_s - \rho_f)g\mu}{\rho_f^2}\right]^{\frac{1}{3}} \quad (5)$$

so that i_m is the head loss due to friction in feet (meters) of head per feet (meters) of pipe, f is the friction factor for water, V_{50} is mean velocity of the fluid at which 50% of the solids are suspended in the fluid flow, M is a particle size parameter normally equal to 1.7, C_v is the concentration of solids by volume, v_t is the particle terminal velocity in meter per second, ρ_s and ρ_f are the density of solid and fluid respectively, and μ is the dynamic viscosity.

The friction factor chart developed by Moody (1944), is normally used to determine f, but Herbich (2000) and Randall (2000) recommend the following formula developed by Swamee and Jain (1976) as a substitute

$$f = \frac{0.25}{\left[\log\left(\frac{\epsilon}{3.7D} + \frac{5.74}{R^{0.9}}\right)\right]^2} \quad (6)$$

where ϵ is the pipe surface roughness in millimeters, and R is Reynolds number

$$R = \frac{\rho_f VD}{\mu} = \frac{VD}{\upsilon} \quad (7)$$

where ν is the kinematic viscosity.

The terminal settling velocity (v_t) is the velocity achieved by a settling sediment particle at which there is zero acceleration, so that the weight of the particle is in equilibrium with the drag and buoyant forces. Herbich (2000) and Randall (2004) demonstrate that reasonable results can be achieved using the following equation:

$$v_t = 134.14(d_{50} - 0.039)^{0.972} \tag{8}$$

This yields v_t in mm/s but must be converted to m/s for use in Equation 5; in addition, for purposes of this production estimating software, d_{50} values less than 0.039mm are assumed to result in a settling velocity of zero.

The concentration of solids by volume, C_v, which is the ratio of solids to the total amount of water and sediment mixture, known as slurry, is expressed as:

$$C_v = \frac{SG_s - SG_f}{SG_{so} - SG_f} \tag{9}$$

where SG_s is the specific gravity of the slurry, SG_f is the specific gravity of the carrier fluid, normally taken to be 1.03 for sea going hopper dredges, and SG_{so} is the specific gravity of the solids normally taken to be 2.65 for sand a silt particles; however, an in situ solids value of 1.8 - 2.1 is often used as SG_{so} in calculating the C_v for dredging projects (Randall, 2004).

As previously mentioned, Wilson et al. (2006) also provides procedures to calculate the frictional head loss due to heterogeneous slurry flowing through an inclined pipe. This approach is used to approximate the major losses experienced by the slurry flowing through a lowered drag arm and can be expressed as

$$i_{m(incline)} = \Delta i(\theta) + i_w \tag{10}$$

$$i_w = \frac{fV^2}{2gD} \tag{11}$$

where θ is the inclination angle of the pipe with respect to the horizontal, i_w is the frictional head loss of water through a pipe and Δi(θ) is the excess frictional head loss due to the effects of inclination on solids in a slurry expressed as

$$\Delta i(\theta) = \Delta i(0) \cos\theta + (SG_{so} - 1)C_v \sin\theta \tag{12}$$

The solid effects in a horizontal pipe Δi(0) is found by subtracting the head loss of water from the slurry so that

$$\Delta i(0) = i_m - i_w \tag{13}$$

While major losses tend to make up the predominant component of the total system losses when dealing with many thousands of feet or meters of straight pipe, as might be found in pipeline dredging or beach nourishment, it is a small component on a hopper dredge pipe system, which does not typically extend beyond a few hundred feet or meters.

Pump Power

Trailing suction hopper dredges utilize large centrifugal pumps to excavate dredged material off the sea floor. These pumps induce pressure energy, or dynamic head, into the hopper piping system by changing the velocity of the slurry as it passes through the pump. The slurry enters the pump through the impeller eye, and the fluid is then thrust outwards toward the pump casing by a high speed rotating impeller. Upon exiting the impeller and entering the casing, the fluid velocity decreases causing the pressure to increase. The pressure, or head, developed by the pump (H_p) is the difference in head at the pump discharge (H_d) and head at the pump suction side (H_s):

$$H_p = H_d - H_s \tag{14}$$

These pressures can be expressed using the Bernoulli equation so that

$$H_d = \frac{p_d}{\gamma} + \frac{V_d^2}{2g} + Z_d \tag{15}$$

$$H_s = \frac{p_s}{\gamma} + \frac{V_s^2}{2g} + Z_s \tag{16}$$

where p is the pressure, γ is the specific weight of the fluid, V is the velocity, g is gravitational acceleration, Z is elevation, and subscripts d and s indicate discharge or suction respectively.

The modified Bernoulli equation, or energy equation, can be used to represent the flow from suction pipe inlet to pump discharge into the hopper bin as shown in Equation (17) below:

$$H_p + \frac{p_s}{\gamma} + \frac{V_s^2}{2g} + Z_s = \frac{p_d}{\gamma} + \frac{V_d^2}{2g} + Z_d + H_f + H_m \tag{17}$$

Here the suction side, denoted by subset s, is assumed to be at the draghead inlet, and the discharge side, denoted by subset d, is assumed to be at the outlet into the hopper bin. The equation also includes the addition of pump power, H_p, system frictional losses, H_f, and system minor losses, H_m. The discharge into the hopper bin is typically assumed to be at sea level, therefore, if the seafloor is used as at the vertical reference datum, Z_s becomes zero and Z_d represents the dredging depth. In addition, V_s is assumed to be zero just outside the draghead and P_d is the local atmospheric pressure at the discharge of the piping system into the hopper.

The high complexity of flow through centrifugal pumps makes it necessary to determine performance experimentally through pump testing. Manufacturers present the test findings and detail the performance of a specific pump on characteristic curves. As shown in Figure 3, these characteristic curves typically graph any variation of pump head (H), brake horsepower (P), and pump efficiency (η) as a function of volumetric flow rate (Q) for water. These curves are in dimensional format and are only valid for a pump with the same impeller diameter and operating at a certain speed. Figure 3 shows the pump characteristics curve for 30 inch suction and 30 inch discharge centrifugal pump with a 46 inch impeller designed by GIW Industries Inc. (GIW, 2010).

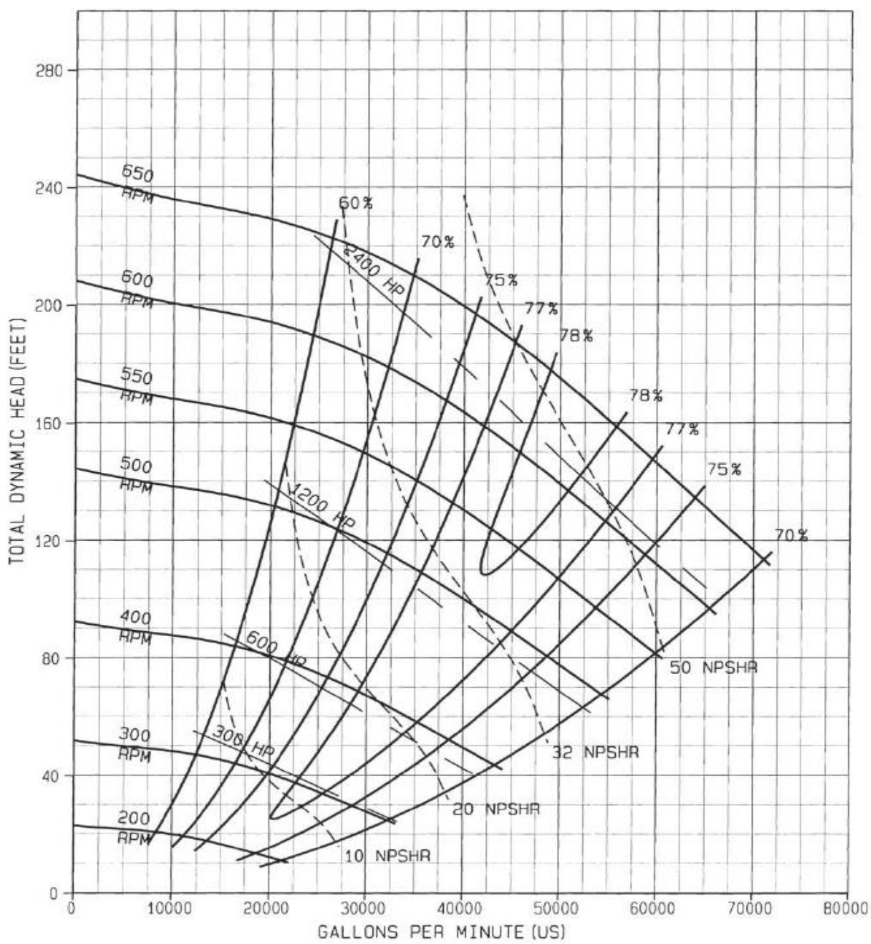

Figure 3: Pump Characteristics Curve (GIW Industries, 2010)

To maintain an advantage when bidding on dredging projects, most companies do not make the characteristics curves for their pumps readily available to the public. Therefore, in order to ensure compatibility with a wide range of dredging projects, this estimating program utilizes dimensionless characteristic curves which can find values of H, P, and Q for similar pumps operating at any speed. The dimensionless values are:

$$H_{dim} = \frac{gH}{\omega^2 D_i^2} \tag{18}$$

$$P_{dim} = \frac{P}{\rho\omega^3 D_i^5} \tag{19}$$

$$Q_{dim} = \frac{Q}{\omega D_i^3} \tag{20}$$

where ω is the angular velocity, D_i is the pump impeller diameter, and ρ is the fluid density.

The dimensionless curves used by this program were created by transforming dimensional curves of different pump sizes provided by Georgia Iron Works (GIW). With the set of dimensionless curves it is possible to obtain values of pump head, by keeping impeller diameter constant for each pump model and changing the pump speed based on assumed pump power. The dimensionless values can be adjusted by manipulating the pump affinity laws and matching the curve to the selected power. The efficiency of a pump is defined by Herbich (2000) as

$$\eta = \frac{water\ horsepower}{brake\ horsepower} = \frac{\rho g Q H}{P} \tag{21}$$

It is assumed that a pump operates at or near its best efficiency point, so that efficiency is nearly constant. Therefore the dimensionless parameters are equal to a constant (C) so that

$$H_{dim} = C_1 \tag{22}$$

$$Q_{dim} = C_2 \tag{23}$$

$$P_{dim} = C_3 \tag{24}$$

and the dimensionless head can be adjusted to match changes in power. So that at the same Q, ω, and D_i, a dimensionless Equation (21) can be expressed as

$$H_{dim_2} = \frac{P_{dim_2} H_{dim_1}}{P_{dim_1}} \tag{25}$$

where H_{dim_2} is the dimensionless head produced by the pump with some dimensionless power P_{dim_2}; and, H_{dim_1} and P_{dim_1} are the dimensionless head and power of the pump from the dimensionless curve and change along the flowrate envelope of the pump. This enables the creation of a new pump head curve as a function of flowrate for any input power.

The total system head curve is created by plotting the calculated head losses from Equations (2), (3), and (10) as a function of flowrate. This system head curve is then superimposed on the pump head curve created by plotting the dimensionalized solution to Equation (25) as a function of the same flowrate operating range as shown in Figure 4.

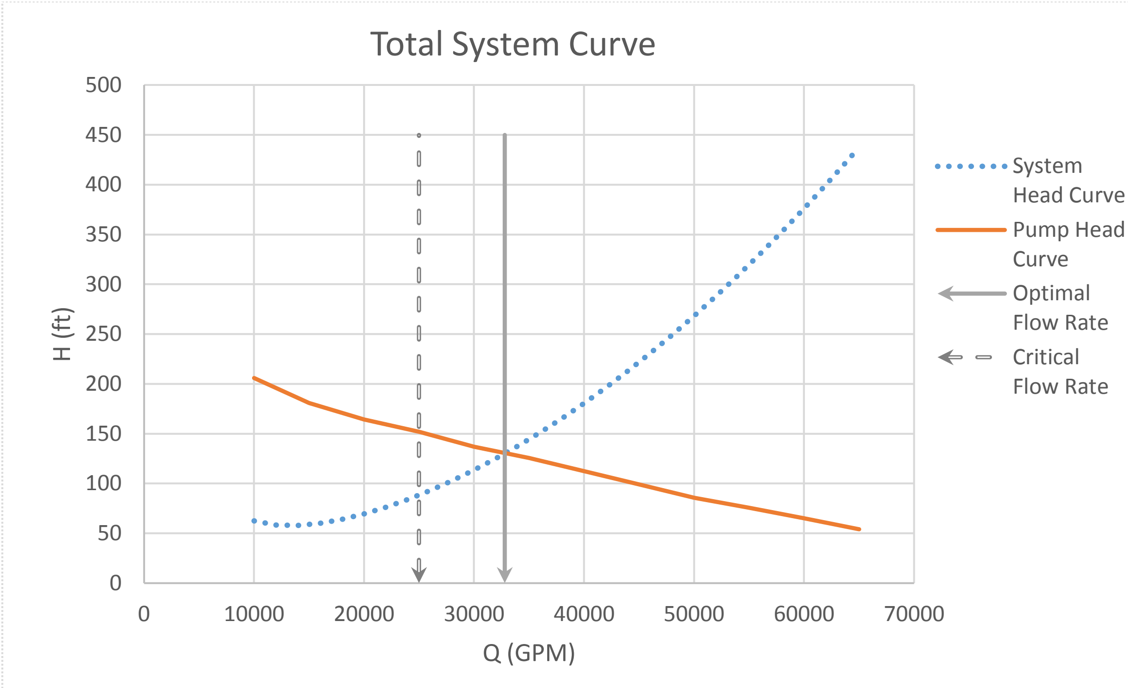

Figure 4: Example of System Head Curve Superimposed on Pump Head Curve

The point at which the system head curve intersects the pump head curve is the optimal flowrate for the system and is assumed to be the point of highest efficiency. This optimal flowrate is used as the flowrate Q of the dredge for estimating production and must be greater than the critical flowrate, Q_c.

The Total Production Rate

The total production rate for a trailing suction dredge is a metric for determining the amount of dredged material excavated during the dredging cycle. Bray et al. (1997) estimated the total production time to be

$$P_{max} = \frac{C_H f_e}{B(t_{load} + t_{turn} + t_{sail} + t_d)} \tag{26}$$

where P_{max} is the maximum, or ideal, total production rate in yd^3/hr, C_H is the capacity of the hopper in yd^3, f_e proportion of the hopper filled with sediment, B is a bulking factor, and t_{load}, t_{turn}, t_{sail}, and t_d denote the time to complete different components of the dredging cycle in hrs. For simplicity, f_e will be assumed to equal C_v found using Equation (9).

Turning time in hours, $t_{turn,}$ is the total time taken turning the dredge during the loading phase and is found by multiplying the number of turns by the time it takes for the dredge to make a turn. If it is assumed dredging is conducted with a hopper dredge traveling at a speed of 2.0 knots:

$$t_{turn} = \frac{7.1 t_{load} t_{180}}{L} \tag{27}$$

where t_{180} is the time it takes to turn the dredger around 180 degrees at each end of the dredging area, and L is the length of the dredging area in nautical miles (NM). The term t_{180} is assumed to be 4 minutes or 0.07 hrs based on recommendation from Bray et al. (1997). The sailing time in hours, t_{sail}, is the time it takes the dredger to travel to the disposal area and back to the dredging site, so that:

$$t_{sail} = \frac{2Y}{V_f} \tag{28}$$

where Y is the distance to the disposal site in NM, and V_f is the fully loaded sailing speed of the dredger in knots. Finally, the time to discharge the dredged material, or disposal time t_d, depends on the method of disposal. If the material is simply bottom-dumped, the default t_d is 0.1 hrs, but if the dredged material is pumped to shore by either pipeline or rainbowing the default time is 1 hr.

The time to load, t_{load}, of the hopper depends on whether overflow time is utilized or not. If overflow of the hopper is not permitted by the specification of a project or given sediment properties is not beneficial, then calculating the loading time is simply

(no overflow) $$t_{load} = \frac{C_H}{0.297Q} \quad (29)$$

where Q is the optimal flow rate found from the total system curve, and 0.297 is a factor to convert gallons per minute (GPM) to cy/hr.

To efficiently load the hopper, and thus increase production, it may be practical to continue loading and overflow the hopper until a high concentration of solids is discharged through the top of the hopper bins and overboard. If hopper overflow is used then Equation (29) becomes

(overflow) $$t_{load} = \frac{C_H}{0.297Q} + t_o \quad (30)$$

where t_o is the overflow time and depends heavily on the sediment characteristics and is difficult to determine ahead of time. This program uses a default overflow of 0.75 hrs based on typical loading times observed in both Bray et al. (1997), and Palermo and Randall (1990).

The use of overflow while dredging also changes resulting P_{max} so that Equation (26) now becomes

(overflow) $$P_{max} = \frac{\mathrm{C_H} C_v + P t_o (1 - r_l)}{B(t_{load} + t_{turn} + t_{sail} + t_d)} \quad (31)$$

where P is the production rate at which dredged material is excavated from the sea floor and collected in the hopper. Using the simple equation by Turner (1996), the excavation production rate can be approximated as

$$\mathrm{P} = 0.297 Q C_v \tag{32}$$

The overflow ratio or overflow losses, r_l, is based on the sediment properties so that larger heavier sediments tend to have a lower overflow ratio than smaller lighter sediments. The r_l values used for this program are based on findings from Boogert (1973), and represent the mean overflow loss for various sand grain sizes.

The P_{max} attained from Equation (26) or (31) must be adjusted to account for the less than ideal efficiency of operating in a real world environment. Bray et al. (1997) recommended the use of three adjustable reduction factors that can be tailored to any specific project. The delay factor (n_d) accounts for production lost due to bad weather and maritime traffic. The operational factor (n_o) accounts for the inefficiency of the dredging crew and management, in good climate the n_o ranges from 0.90 for a very good crew to 0.60 for a poor crew. The mechanical breakdown factor (n_b) accounts for the inevitable breakdown of equipment that leads to work stoppages. The n_b typically ranges from unity for new dredges, down to 0.85 before a full overhaul (typically 20 years). The corrected total production rate can be calculated with:

$$P_{avg} = n_d \times n_o \times n_b \times P_{max} \tag{33}$$

where P_{avg} is the average total production rate of the hopper dredge.

COST ESTIMATION

The total average production rate is used in conjunction with various price assumptions to estimate the cost of a dredging project. The cost is comprised of numerous factors but can be divided into two major components: mobilization/demobilization costs and operating cost. Procedures set forth by Bray et al. (1997) and Randall (2004), will be used to combine the cost data with the estimated project completion time in order to calculate the total cost estimation.

Mobilization and Demobilization

Mobilization and demobilization cost is the price associated with the transportation of dredging equipment to and from the job site. These costs are difficult to predict for any given project. As Randall (2000) outlines, the difficulty comes from the fact that no two dredges are the same distance away from a job site or in the same condition of readiness to mobilize. For trailing suction hopper dredges, estimating the mobilization/demobilization cost is primarily a function of the distance to and from the job site, the cost of flying in additional crew and equipment, and may include revenue lost due to set-up downtime. This program allows the user to either estimate the mobilization cost, choose a program default mobilization cost, or leave the mobilization completely out of the final estimated project cost.

The user may enter a self-determined mobilization/demobilization cost or use the program to estimate the mobilization cost with factors described later in the “Defaults” section. However, a user that does not have the information to estimate the mobilization costs, may select the program’s default mobilization/demobilization cost of $1.0 million. The default cost is based on the median value of the mob/demob cost estimates from the eight recent dredging projects investigated. A graphical representation of the government estimate and winning bid mobilization costs is shown in Figure 5 below.

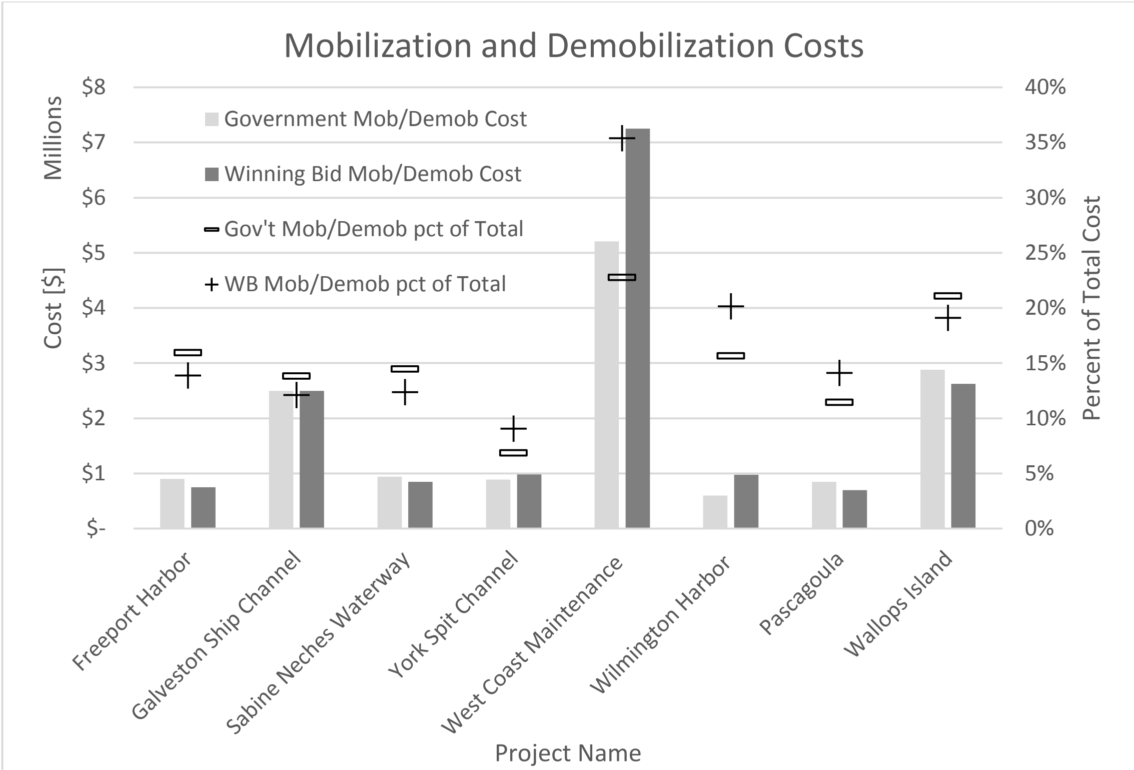

Figure 5: Mobilization and Demobilization Costs

In addition to the cost in dollars, Figure 5 shows the mobilization cost as a percentage of the total cost of the dredging project, which averages to approximately 16%.

Operating Costs

Operating costs are the summation of costs associated with operating during the timespan of project execution. The duration of the project is determined by dividing the average production rate, which is measured in cubic yards per hours, by a known volume of material to be dredged. The costs of various factors over this project duration are summed to find a total operating cost. Randall (2004) recommend that the operating costs be comprised of the following factors: dredge crew, land support crew, fuel, lubricants, routine maintenance and repairs, major repairs and overhauls, insurance, depreciation, overhead and profit. Bray et al. (1997) provided assumptions and parameters that can be applied to each of the cost factors for estimations purposes.

Crew and Labor

Hopper dredges require a sufficient crew to conduct both dredging operations and the operations of a seagoing vessel. The crew includes both deck and engineering department personnel typical of commercial vessels, as well as special dredge operators. The number of crew members may vary widely from ship to ship depending on the size of the dredge, automation of equipment, and duration of voyage. Hollinberger (2010) and Bray et al (1997) gives a recommendation for a complete hopper crew, while the USACE provided the crew organization for dredges Essayons, Yaquina, and McFarland. The program lists various crew positions based on these three sources and allows the user to select the crew applicable to a specific job. The hourly wage rate for each position can be entered by the user, but the program includes estimated 2015 rates based on information obtained from the U.S. Bureau of Labor Statistics (2015), the Federal Wage System (FWS) Special Salary Rate Schedules (DCPAS, 2015), and RSMeans Heavy Construction Cost Data (RS Means, 2015).

Fuel and Lubricants

Fuel costs make up a significant portion of the hopper dredge operating budget, and a significant effort is made to limit excessive fuel usage. The total operating power of a dredge is used to determine average diesel fuel consumption based on procedures outlined by Bray et al. (1997) so that

$$Consumption\left(\frac{gal}{day}\right) = Installed\ Power(hp) \times Daily\ Power\ (hrs) \times .0481\left(\frac{gal}{hph}\right) \quad (34)$$

where the installed power is the hoppers total installed horsepower, the daily power is a theoretical estimation of how many hours a day the dredge is operating at 100% of its installed horsepower, and 0.0481 is gallons of fuel consumed per horsepower-hour (hph). The program averages the default inputs for hours spent at 100%, 75%, and 10% power to find the 100% power per day, and the user can adjust these values to match a specific project. Diesel fuel costs were obtained from the U.S. Energy Information Administration (2015), and the daily lubricant costs were assumed to be 10% of daily fuel cost.

Capital Cost

The capital cost, or initial price, of a dredge is used to estimate the maintenance, insurance, and depreciation costs. Capital investment for a new hopper dredge costs a dredging contractor tens of millions of dollars, depending on its size, and as a result many hopper dredges in the United States are several decades old. Information from Bray et al. (1997) and RS Means Heavy Construction annual cost indices are used in Figure 6 to provide a way for the user to estimate the capital cost of a hopper dredge based on year of construction and hopper capacity. Bray et al. (1997) provided an approximate capital cost in Dutch Guilders (f) for various hopper metric ton capacities for the year 1996. In order to convert metric tons, a unit of mass, to a volumetric capacity, a density for the material must be assumed. Since the density of dredged material is variable, and the density assumed by hopper dredge manufacturers may also vary, the capacities of ten foreign built dredges were compared to find a reasonable conversion from metric tons to cubic meters. These foreign dredges ranged in size from 1000t to 18,500t and exhibited an average slurry density of 1,550 kg/m^3 or SG of 1.55, which is a reasonable assumption for dredged mixture. To convert costs from Guilders to U.S. Dollars, the twelve month average conversion rate for the year 1996 of 1.68 f per \$ was obtained from the Federal Reserve Foreign Exchange Rate records (Federal Reserve Statistical Release, 1999). Finally, RS Means Heavy Construction historical cost indexes were used to adjust values to the years shown in Figure 6. The estimated average capital cost of all major hopper dredges in the

United States, based on year built, was found to be approximately $18 million and is a reasonable input when the capital cost of a hopper dredge is not known.

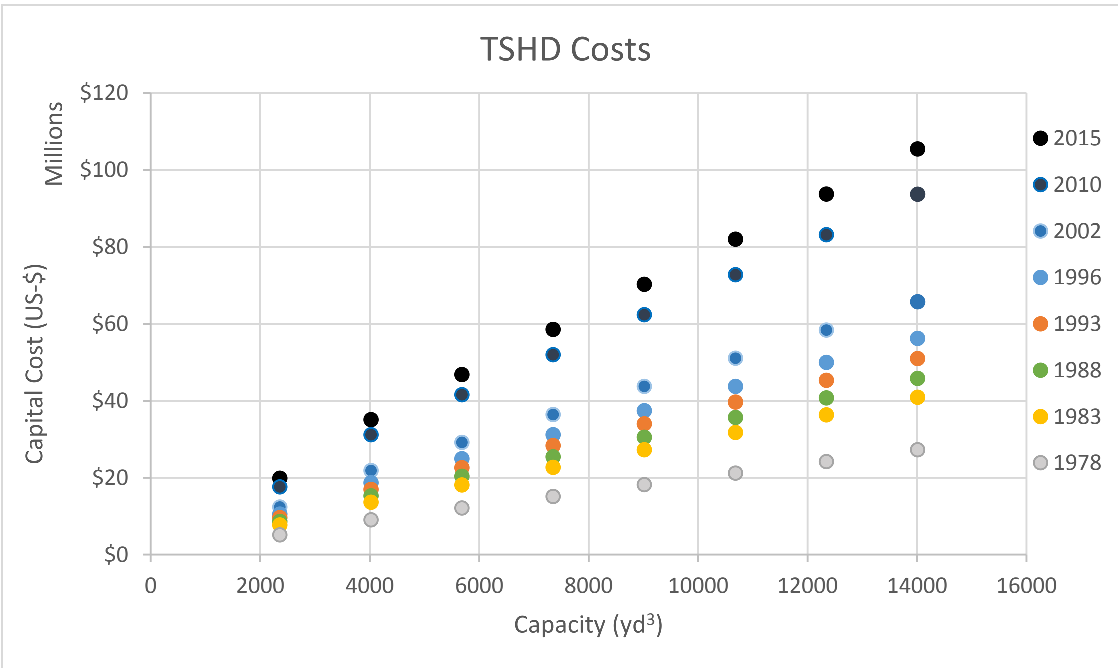

Figure 6: Hopper Dredge Capital Cost

Repairs and Maintenance

The repair and maintenance of a dredge can be divided into two categories: routine maintenance and overhauling. Routine maintenance and running repairs are minor maintenance and repair jobs that can be completed during dredging operations and have minimal or no impact to the work schedule. Overhauling is a major repair or maintenance that cannot coincide with dredging and typically requires the vessel to be out of operation until the work is completed. According to Bray et al. (1997) the daily cost of minor and major repairs for a trailing suction hopper dredge can be found by multiplying the capital cost of the dredge by 0.000135 and 0.000275 respectively.

Depreciation and Insurance

Depreciation is the rate at which the dredge losses value over time, and will depend on the owner's fiscal policy. For simplification, linear depreciation to zero value is used with an assumed service life of thirty years. To calculate daily depreciation in the program, the annual depreciation is then divided by the average number of working days per year. The insurance on a hopper dredge is also variable and will be different from owner to owner. Bray et al. (1997) recommends an annual premium of 2.5 percent of insured plant value so that the daily insurance cost is the capital cost of the dredge multiplied by 0.025 and divided by the number of working days per year.

Overhead and Bonding

The additional operating expenses of a dredge that can't be conveniently identified or traced are covered by overhead cost. Naturally, overhead costs vary from contractor to contractor but this program assumes nine percent of the total operating cost as recommended by Bray et al. (1997). Bonding is a guarantee of performance of work and a protection against losses for the client. Belesimo (2000) recommends a project bonding cost between 1.0% and 1.5% of the operating cost. The overhead and bonding can typically be combined to be ten percent of the operating cost. Finally, since profit is solely determined by the individual contractor and is different on every job, the program allows the user to input a desired amount.

Cost Factors

Since wages and fuel costs are location dependent, they must be adjusted to reflect regional differences. The USACE collects data from various sources on regional differences and publishes a quarterly report containing state adjustment factors for civil works construction (USACE, 2015). RS Means Heavy Construction Cost Data (2015) contains a yearly cost index table which can be used to adjust project costs for past years. The total cost estimate may be adjusted by regional and yearly index to produce results more accurate to a specific location or time period.

Additional Costs

There are additional operational costs that are common to dredging projects but do not fall into any of the above cost categories. These costs vary greatly from project to project and may include site surveys, environmental protection devices, trawlers, and other miscellaneous items. The program allows the user to manually enter these costs, select default values, or to exclude these costs from the final estimate altogether. The default values are based on the median price of the government estimate for the items found in USACE dredging project bids shown in

Figure 7 below with the data presented in Table E-2 of Appendix E.

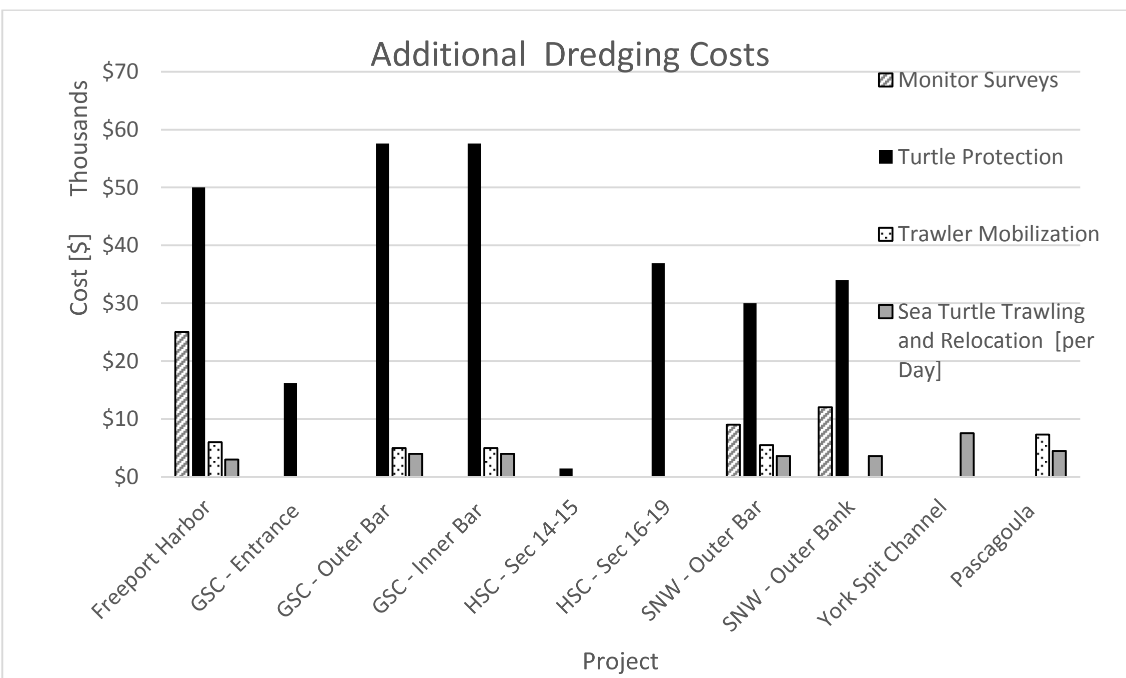

Figure 7: Additional Dredging Costs

HOW TO UTILIZE THE PROGRAM

The hopper dredge cost estimating program is written for Microsoft Excel and comprised of eight separate sheets. Each sheet contains information regarding a separate aspect of production or cost estimation. The program is designed so that the user can enter all necessary information and receive a reasonable cost estimation without leaving the "Data Input" sheet. If more vessel or project specific results are desired, certain defaults and reference numbers can be adjusted throughout the program. The spreadsheet is color coded based on which information need to be input by the user so that green blocks require user input, blue-grey blocks contain default values that the user can change if more specific information is known, and light grey blocs contain auto-fill functions. The default values are selected so as to provide the most accurate cost estimation over a wide range of dredging projects when many specifications are not known. The auto-fill values incorporate both functions of other separate user inputs or correlations to user selected drop down lists.

Data Input

The Data Input sheet is where the user inputs all required information about the dredge and project. The program returns an estimation of the final cost estimate on the same sheet. There are four types of required inputs: dredge information, suction pump and pipe information, project site information, and crew information. There is also a fifth optional section for the inclusion of mobilization/demobilization costs and additional costs such as environmental protection devices.

Table 2 below displays the section for entering hopper dredge properties. The first input is the capacity of the hopper in cubic yards, which is the standard method of measuring dredge capacity in the United States. The next inputs are number and length of dragarms, speed of the vessel, and total installed power (P_{tot}). The value for total installed power must be entered manually, and if the hopper dredge power is not known, the user may reference the table of major American hopper dredges on the "Ref Sheet" of the program for typical power values (see Table B-1, Appendix B). The capital value of the dredge and equipment lifespan are both user optional input default values. A default capital value of $18M is the estimated average price at the time of construction for major hopper dredges operating in the U.S., found from applying the price trends of Figure 6.

Table 2: Hopper Dredge Properties from Data Input Sheet

DREDGE INFORMATION			
Hopper Capacity:		5300	yd^3
Number of Dragarms:		2	
Length of Dragarms:		100	ft
Sailing Speed Empty:		12	knots
Sailing Speed Fully Loaded:		9	knots
Total Horsepower		9800	HP
Capital value of dredge		$18,000,000	
Equipment Lifespan		30	Yrs

The suction pump and pipe information section shown in Table 3 below describes the arrangement of the suction pipes. The user selects the correct pump configuration from a drop down list and inputs the appropriate pipe diameters and pipe material. The user also selects whether to use the program's default pump head calculator or manually enter a pump head curve. The manual pump curve entry only requires the input of pump head at known flowrates, but pump power and efficiency may also be input as a reference. The default flowrates envelope represent the likely extent of flowrates for most hopper dredges.

Table 3: Hopper Dredge Pipe and Pump Properties from Data Input Sheet

SUCTION PUMP & PIPE INFORMATION			
Pump Configuration:		Submerged & Onboard Pump	
Pump Curve Head:		Default	
Draghead to Submerged Pump			
	Length:	50	ft
	Dia:	29	in
Submerged Pump to Onboard Pump			
	Length:	50	ft
	Dia:	29	in
Onboard Pump to Hopper			
	Length:	100	ft
	Dia:	29	in
Pipe Characteristics:			
	Minor Losses:	10	
	Material:	Commercial Steel	
	Roughness, ε	0.00015	ft

The project site information section is shown in Table 4 below. Estimated volume of dredged material is typically estimated by the project employer, but it is customary for the dredging contractor to conduct their own survey or have an independent survey completed. Site specifications used for comparison of USACE projects were found from the USACE Navigation Data Center website (NDC, 2015) and contract solicitation's obtained on "FedBizOps.gov" (Federal Business Opportunities, 2015) or via Freedom of Information Act (FOIA) request. The depth of dredging area, length of dredging area, distance from disposal site, sediment type and other site descriptions can be found using information provided in the contract solicitation plans and NOAA navigational charts (OCS, 2015). It was assumed sediment overflow was permitted for a project unless explicitly stated otherwise in the solicitation documentation.

Table 4: Project Site Properties from Data Input Sheet

PROJECT SITE INFORMATION			
Location:		Gulf Coast	
Avg Dredging Depth:		42	ft
Estimated Volume:		2,489,000	yd^3
Length of Dredge Area:		1	NM
Distance to Disposal Site:		2	NM
Overflow Permitted:		Yes	
Discharge Method:		Bottom Discharge	
Discharge Time:		0.1	hrs
Sediment Composition			
Sediment Type	Percent	d_{50} (mm)	
Gravel	0.00%	6	
Sand, Coarse	0.00%	1.3	
Sand, Medium	0.00%	0.4	
Sand, Fine	0.00%	0.13	
Silt	0.00%	0.013	
Clay	0.00%	0.002	
Other	100.00%	0.13	
Median Particle Diameter (d_{50}):		0.1300	mm
Specific Gravity of Slurry (SG_s):		1.3	
Specific Gravity of Water (SG_w):		1.025	
Specific Gravity of Solids (SG_{so}):		1.9	

The hopper crew composition section is shown in Table 5, with the positions, number of employees, and hourly wage defaults based on typical hopper dredge operational requirements and average 2015 hourly wages.

Table 5: Crew Information from Data Input Sheet

CREW INFORMATION			
Type		Number	Hourly Rate
Hopper Crew			
Master		1	$ 62.00
Assistant Master		1	$ 51.00
Mates (2nd or 3rd)		3	$ 35.00
Dredge Operator		3	$ 27.00
Chief Engineer		1	$ 61.00
Assistant Chief Engineer		1	$ 37.00
Assistant Engineer (2nd or 3rd)		3	$ 35.00
Marine Electrician		1	$ 31.00
Marine Oiler		3	$ 26.00
Electronics Mechanic		1	$ 30.00
Cook		2	$ 24.00
Beneficial Use Crew			
Foreman		0	$ 39.60
Equipment Operator		0	$ 48.60

The cost information, shown in Table 6, shows the user index values and unit prices based on the above inputs. This section also includes the entry for the overhead and bonding rate, the mobilization costs, and any additional costs not covered previously. A default setting of 9.0% overhead and 1.0% is recommended by the program, but the user may change this any desired rate. Additional costs typically include surveying, environmental protection equipment, and environmental trawling. Based on project requirements, the user my choose to manually enter these additional costs, use the program defaults, or omit them from the final cost estimate.

Table 6: Cost Information Section from Data Input Sheet

COST INFORMATION			
Hours Worked per Day:		24	hrs
Fuel Cost, (see Indices)		3.71	$/gal
Location Index (see Indices)		1.08	
Year Index		0.991	
Crew Cost per Hour:		874.4	$/hr
Overhead:		9.00%	
Bonding:		1.00%	

Mobilization/Demobilization:		Estimate Cost	
Sailing Distance:		500	NM
Sailing Speed:		10	kts
Fuel Cost (see Index)		3.71	$/gal
Total Mob/Demob Cost:		$824,282	

Additional Costs		Manual Entry	
Monitor Surveys		$ 20,000.00	
Environmental Protection		$ 35,000.00	
Trawler Mobilization		$ 5,500.00	
Enviro. Trawling/Relocation		$ 4,000.00	$/day
	Days:	30	
Other:		$ -	
Total Additional Costs:		$ 180,500.00	

As mentioned, the final cost estimate results are also generated on the "Data Input" sheet. As shown in Table 7, the results include total project cost, cost per cubic yard of sediment removed, and time required to complete the project in weeks.

Table 7: Final Cost Estimate from Data Input Sheet

Final Cost Estimate			
Total Cost of Project:		$ 6,883,371.43	
		$ 8.10	per yd^3
Time Required		11.6	Weeks

Defaults

The "Defaults" sheet contains program assumptions relating to dredge operation, reduction factors, physical constants, and mobilization costs. These defaults can be applied to most dredging projects, but may be changed by the user if more accurate information is known. Table 8, taken from the Default sheet, contains the default values for dredge working hours, pump power ratio, overflow time, reduction factors, mobilization/demobilization rates, and overflow loss ratios.

The ratio of pump power to total installed power is assumed to be 0.3, which is the rounded average of the typical ratio obtained from the technical specifications of sixteen foreign built hopper dredges. Foreign built dredges were used since U.S. dredging companies do not typically provide a detailed installed power breakdown. The sixteen different hopper dredges were from four different companies, ranged in size 850 yd^3 (650 m^3) to 60,000 yd^3 (46,000 m^3), and had a pump power ratio ranging from 0.2 – 0.4 (Damen, (2015); DEME, (2015); Jan De Nul, (2015); Van Oord, (2015); See Appendix C)

The mobilization and demobilization default rates for personnel daily traveling costs are based on 2015 federal government per diem rates (GSA, 2015) and the air travel costs are based on average 2014 air fare data from the Department of Transportation (Bureau of Transportation Statistics, 2015). The default overflow loss ratios are based on a diagram from Boogert (1973) and represents the mean ratio of overflow.

Table 8: Program Default Values

Dredge Operation		
Hours worked per day	24	hrs
100% Power	1	hrs
75% Power	18	hrs
10% Power	5	hrs
Days in use per year	300	
Pump Power / Total Power	0.30	
Overflow Time	0.75	hrs
100% Pwr/day (hrs)	15	hrs

Reduction Factors		
Delay Factor, n_d	0.90	
Operational Factor, n_o	0.75	
Mechanical Breakdown, n_b	0.90	
Total Reduction	0.61	

Mobilization and Demobilization		
Dredging Crew	20	
Travel Days	5	
Per Diem Rate	$83.00	/person/day
Meals & Incidentals	$46.00	/person/day
Air Travel	$400.00	/person
Stand-by Cost	$100,000.00	/day

Sediment Composition		
Type	d50 (mm)	Overflow Loss, r_l
Sand, Coarse	$d_{50} \geq 0.6$	0.15
Sand, Medium	$0.2 \geq d_{50} < 0.6$	0.25
Sand, Fine	$0.06 \geq d_{50} < 0.2$	0.5
Silt	$0.006 \geq d_{50} <0.06$	1
Clay	$d_{50} <0.006$	1

Pump Selection

The "Pump Selection" sheet contains information about the provided pump characteristic curves and dimensionless curves used to select pump head. Four dimensional pump characteristic curves were provided by GIW Industries, Inc. with pump suction diameters of 24 in, 26 in, 30 in, and 38 in (GIW, 2010). In addition to pump head (H), pump power (P), and efficiency (η), the dimensional curves also include pump speeds as a function of flow rate. Table 9 shows an example of the numerical conversion from dimensional to dimensionless pump characteristics or 30 inch diameter pump. There are similar conversions for each pumps size, for a total of four dimensionless curves

Table 9: Relationship between Dimensional to Dimensionless Pump Characteristics

Pump Characteristics								
Georgia Iron Works dredge pump					Nondimensionalized pump characteristics			
30X30 dredge,46in impeller, 550rpm					D_i:	46	3.83	
					Speed:	550	57.60	
Q (gpm)	BHP	H (ft)	Efficiency %		Q (dim)	BHP (dim)	H (dim)	Efficiency
10000	1200	168	40	→	6.87	2.15	11.09	40
15000	1350	166	50	→	10.30	2.42	10.96	50
20000	1450	162	55	→	13.74	2.60	10.70	55
25000	1500	155	64	→	17.17	2.69	10.23	64
30000	1600	149	71	→	20.60	2.87	9.84	71
35000	1650	141	75	→	24.04	2.96	9.31	75
40000	1700	130	77.3	→	27.47	3.05	8.58	77.3
45000	1750	118	78	→	30.91	3.14	7.79	78
50000	1800	105	77	→	34.34	3.23	6.93	77
55000	1825	94	74	→	37.77	3.27	6.21	74
60000	1850	82	70	→	41.21	3.32	5.41	70
65000	1900	70	65	→	44.64	3.41	4.62	65

The selection of which dimensionless characteristics are used is a function of the suction pipe diameter input from Table 3. With one of the four pumps selected based on the pipe diameter, the brake horsepower dictates the assumed pump speed. To determine the power of each centrifugal pump, the total installed power of the hopper, seen on Table 2, is multiplied by the ratio of pump power to total installed power (Table 8), and divided by the number of pumps installed onboard the hopper. The pump speed is then determined based on estimations from the dimensional characteristics curve, so that a certain range of power corresponds to a specific pump speed. Speeds are selected that maintain the pump operating at or near peak efficiency.

Using the selected speed and the provided impeller diameter, the new dimensionless parameters are calculated and a dimensionless curve, shown in Figure 8 is created for that pump size. The assumed power for the pump is also non-dimensionalized, and using this value with the pump affinity law from Equation (25), new non-dimensional values of pump head are calculated along the flow rate envelope. The pump head values are then dimensionlized and used as the dredge pump characteristic curve. A detailed walk through of the procedures for calculating pump head curve are shown in Appendix B.

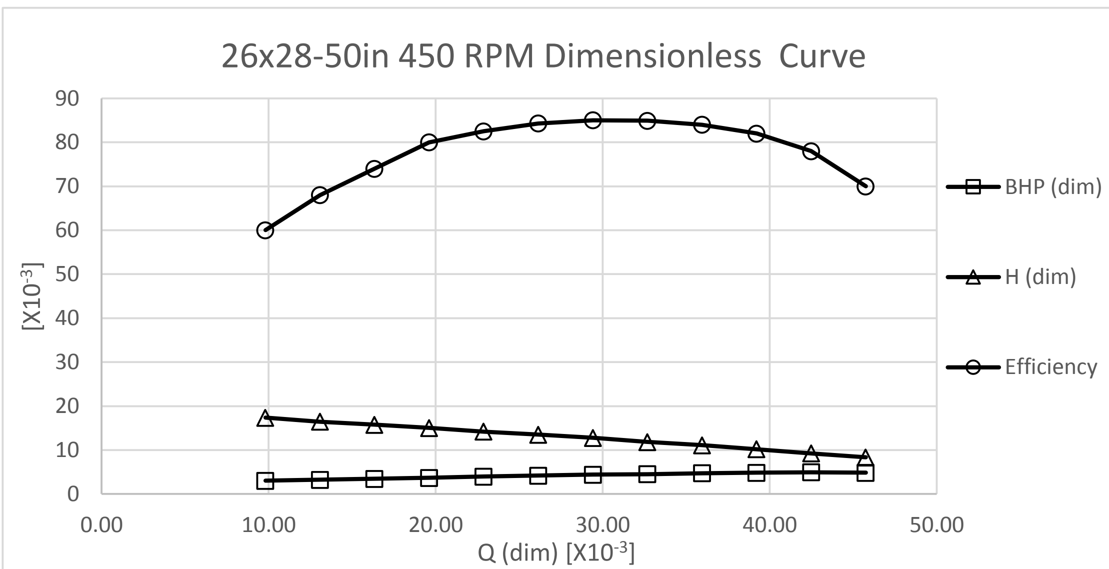

Figure 8: Dimensionless Characteristics Curve

Cost Indices

The "Cost Indices" sheet contains the tables of diesel retail prices and cost indices utilized by the program. Diesel retail prices are in dollars per gallon of No. 2 diesel averaged over an eighteen month period from January, 2014 to June, 2015 and broken up by region. Location cost indices are listed by state and then grouped into regional cost indices that closely match the diesel price regions identified by the Energy Information Administration (EIA). The yearly cost indices are shown annually going back to 2006. Dates going forward from the baseline of 2015 are assumed to have an annual cost increase of 1.0%. Cost indices should be updated on an annual basis to maintain accuracy.

Flow Calculations

The "Flow Calculations" sheet contains all the calculations made to arrive at an optimal flow rate, Q, for the dredge. All the calculations associated with finding the critical velocity and system losses are found on this sheet. The pump head and system head losses along the entire flowrate envelope are shown, and the flowrate corresponding to the smallest absolute difference in the two head values is selected as the Q. These points are then used to create a total system curve as shown in Figure 4. The calculated Q must be greater than the critical flow rate Q_c, otherwise an error message will appear on the "Data Input" and "Flow Calculations" sheet.

Production Cost

The "Production Cost" sheet contains the calculations for production rate and dredging costs. The rate of production is calculated as described earlier in the total production rate section. The step by step results are shown in Table 10. The optimal slurry flowrate, Q, is used to find the sediment production (P), from Equation (32). The dredging cycle times are found using Equations (27 -30), the total reduction rate come from multiplying the three reduction factors shown in Table 8, P_{max} is calculated with either Equation (26) or (31) depending if overflow is permitted, and the P_{avg} is found with Equation (33). The total time to complete the operation is calculated by dividing the estimated project volume by P_{avg}.

Table 10: Production Rate Calculations and Results

Production Calculation			
Number of Drag Arms		2	
Concentration (C_v)		0.314	
Bulk Factor (B)		1	1.250
Project Volume (Insitu)		2,149,000	cy
Hopper Capacity		5,300	cy
Number of Loads		1290.14	
	Per Dragarm	Total	
Slurry Flowrate	32,200.00	64,400.00	GPM
	4,304.81	8,609.63	cf/min
	9,566.25	19,132.50	cy/hr
Sediment Flowrate			
	3,005.64	6,011.28	cy/hr
Dredging Cycle			
Time to turn (t180) =		0.07	hrs
Time to Load (t_{load})		1.027	hrs
Time to Sail (t_{sail})		0.88	hrs
Number of Turns		7.29	
Time to Turn (t_{turn})		0.49	hrs
Time to Unload (t_d)		0.10	hrs
Cycle time		2.49	hrs
Cycles per Day		9.6	cycles
Total Reduction		0.61	
Production Rate (P_{max})		1,575.43	cy/hr
		3,919.94	cy/cycle
		37,810.43	cy/day
Production Rate (P_{Avg})		957.08	cy/hr
		2,381.37	cy/cycle
		22,969.83	cy/day
Total Loading Time (ideal)		357.49	hrs
Total Operating Time (ideal)		1,364.07	hrs
Total Operating Time (real)		2,245.38	hrs
Work Per Day		24.00	hrs
Days on Job		93.60	days

The breakdown of cost calculations are also on the Production Cost sheet. Table 11 shows the daily costs for equipment based on the procedures outlined earlier in the Cost Estimation section. The total daily equipment cost is than added to the daily crew costs multiplied by the days on the job and adjusted for overhead and indexing.

Table 11: Daily Equipment Costs from Production Cost Sheet

Equipment		
Capital Value of Dredge:	$ 18,000,000	
Routine Maint. & Repairs:	$ 2,430	/Day
Major Repairs, etc.:	$ 4,950	/Day
Insurance:	$ 1,500	/Day
Installed Horsepower	9800	HP
Fuel Consumption:	7,068	gal/day
Total Fuel Cost:	$ 23,991	/Day
Cost of Lubricants:	$ 2,399	/Day
Depreciation:	$ 2,000	/Day
Useful Life:	30	yrs
Total Cost:	$ 37,270	/Day

Production Chart

The "Production Chart" sheet contains the total system curve created from the data on the Flow Calculation sheet.

Reference Sheet

The "Reference Sheet" contains values, graphs, and assumptions used throughout the program. The assumptions made by drop down lists on "Data Input" sheet are referenced in tables from the "Reference Sheet" and are shown in Table E-1 of Appendix E. Some of these values, such as sediment characteristics and additional costs, may be changed if the user has more accurate information. This sheet also contains a table of specifications for the major U.S. hopper dredges, Figure 6 calculations, additional project cost data, and specifications of foreign hopper dredges used to make assumptions for the conversion from metric tonnes to cubic meters, and the default pump power to total installed power ratio from Table 8.

RESULTS

The validity of this production method and accuracy of the cost estimating program was tested with data from actual dredging projects. The USACE maintains records of all the past and present projects on the Navigation Data Center dredging website (NDC, 2015). These NDC records typically contain basic project information such as: name of project, date, location, volume of material to be dredged, type of dredge utilized, government cost estimate, and the contractors winning bid. If not found on the NDC website, additional project information, such as bidding cost breakdowns, may be found on the federal government's database of contracting opportunities, FedBizOpps.gov (Federal Business Opportunities, 2015). The bidding cost breakdown, known as the bid abstract, breaks down project costs into separate line items for mobilization, dredging, and various additional costs. In addition, many bids breakdown the dredging project into multiple channel sections or even optional additional work. Finally, information not readily available online, such as project solicitations and site plans, were obtained from the USACE using Freedom of Information Act (FOIA) requests. These FOIA requests were instrumental in attaining the most accurate data to input for the estimating program.

Cost Comparison

The project costs estimated by the program were compared to actual project cost estimates made by the government and the winning contracting company bid. The government estimate is prepared by the USACE to evaluate acquisition feasibility of proposed project, and to determine the reasonability of a contractor's bid. The winning bid is the lowest price submitted by a contractor that can complete the project requirements. The scope and specifications of a project are provided to bidding contractors in the contract solicitation. In this manner, any information available in creating the government estimate is also available for contractors to formulate a bid. The dredging contractor has the advantage of knowing the status of equipment and personnel to likely formulate a more accurate cost estimate. Contracting companies also utilize proprietary estimating systems to ensure they obtain the most accurate estimate possible.

The accuracy of this program's cost estimate was evaluated using two different methods. The first method compared total projects costs estimated by the program to the total actual estimates from the bid. However, since mobilization costs and additional costs are typically project specific and difficult to estimate, a second method compared only the dredging operation costs, and omitted line items pertaining to mobilization costs and additional costs.

Both comparison methods utilized program cost estimates with preset variable, and is referred to as the "Wowtschuk Program Estimate." The estimates used default values for most of the data inputs used in Table 2 – Table 8 so that each cost estimate assumes the same: dredge information, suction pump, pipe information, crew information, and sediment composition. A complete list of default variables and data inputs used for the Wowtschuk Program Estimate are shown in Table 12 below.

These values are used as inputs for the projects since detailed and specific information was not available for each project. Additionally, these Wowtschuk inputs for the program estimate comparison can be selected by the user as reasonable data input assumptions for projects with minimal project information. There reasonable were made based on average dredge characteristics, past academic findings, and program iteration.

Table 12: Wowtschuk Program Estimate Values

		Wowtschuk Program Estimate
Dredge Information		
	Hopper Capacity (yd^3)	5,300
	Total Horsepower (HP)	9,800
	Sailing Speed (kts)	8
	Capital Value ($)	18,000,000
	Equipment Lifespan (yrs)	30
Suction Pipe Information		
	Suction/Discharge. Diameter (in)	29
	Dragarm Length (ft)	100
Project Site Information		
	Length of Dredge Area (NM)	1.0
	Particle Diameter (d_{50}) (mm)	0.13
	SG of Slurry	1.3
	SG of In-Situ Solids	1.9
Crew Information		
	Cost per day ($)	16,536
Defaults Parameters		
	Pump Power / Total Power	0.30
	Overflow Time (hrs)	0.75
	100% Power per day (hrs)	15
	Reduction Factor	0.61
	Overflow Loss	0.50

As mentioned earlier in the Data Input section, the default dredge information assumed for the Wowtschuk Program estimates are based on the average dredge data for all major American hopper dredges. The default specific gravity of the in-situ sediment material was assumed to be 1.9 for all projects, which is within limits of typical dredged material (Randall, 2004). A fine sand sediment, with a median particle diameter of 0.13 mm was assumed for all projects, which maintains an overflow ratio of 0.5 as per the defaults in

Table 8. This d_{50} value was chosen because larger sediment sizes tended to result in a critical flowrates above the calculated optimal flowrate. A d_{50} of 0.2 mm or greater also results in a lower overflow loss ratio and pushes the program cost estimate further away from the winning bid on average. A complete program walk-through of the inputs and resulting calculations for one of the projects can be found in Appendix A.

The Wowtschuk Program Estimate only requires the user to know the geographical location, volume to be dredged, distance to disposal site, and dredging depth. The project site information used for the program estimate comparison are shown in Table 13 below. This table also shows how each project was broken down into subsidiary channel sections.

Table 13: Project Site Information

Project Name	Location	Volume (yd^3)	Distance to Disposal Site (NM)	Depth (ft)
Freeport Harbor (2013)	Gulf Coast	**2,149,000**	**3.5**	**47**
Galveston Ship Channel (2015)	Gulf Coast	**2,407,000**	**9**	**45**
Entrance Channel Sec 1-4		386,000	4.0	45
Entrance Channel Sec 5-6		463,000	3.0	45
Outer Bar Sec 7-9		433,000	6.5	45
Inner Bar Sec 10-13		725,000	9.0	45
Houston Ship Channel Sec 14-15		13,000	13.0	45
Houston Ship Channel Sec 16-19		387,000	16.0	45
Sabine Neches Waterway (2014)	Gulf Coast	**5,100,000**	**1.5**	**42**
Outer Bar		2,611,000	1.0	42
Outer Bank		2,489,000	2.0	42
York Spit Channel (2015)	Central Atlantic	**1,747,000**	11.0	51
West Coast Maintenance (2015)	West Coast	**5,900,000**	**3**	**49**
San Francisco Main Ship Channel	California	225,000	5.0	56
Gray's Harbor	West Coast	400,000	3.0	46
Columbia River Entrance	West Coast	2,000,000	2.0	50
Columbia River	West Coast	300,000	2.0	45
Wilmington Harbor (2014)		**825,000**	**8**	**44**
Balhead Shoal Reach Channel 4	Lower Atlantic	800,000	8.0	44
Pascagoula Entrance Channel (2014)	Gulf coast	**1,032,552**	**3.0**	**46**
Wallops Island Beach Restoration (2014	Central Atlantic	**650,000**	**12.0**	**35**

The comparison results for total project costs calculated by the Wowtschuk Estimate to the actual estimates are shown Table 14 below. For this comparison, the Wowtschuk Estimate uses the production rate to calculate the dredging operation cost and adds the default mobilization value of $1M and default additional costs ranging in value from $200K -$300K to find the total cost estimate. The actual estimate includes dredging operational costs, all the mobilization costs, additional environmental costs, and optional dredging line items from the contract bid abstracts.

Table 14: Total Project Cost Accuracy Comparison

	Government Estimate (G.E.) [$1K]	Winning Bid (W.B.) [$1K]	Wowtschuk Estimate (W.E.) [$1K]	G.E. vs. W.B.	W.E. vs. W.B.	W.E. vs. G.E.
Freeport Harbor (2013)	5,637	5,399	5,990	4.41%	10.94%	6.26%
Galveston Ship Channel (2015)	11,202*	11,762*	9,717*	-4.76%	-17.38%	-13.26%
Sabine Neches Waterway (2014)	6,488	6,875	6,455**	-5.63%	-6.11%	-0.51%
York Spit Channel (2015)	12,908	10,859	10,248	18.87%	-5.63%	-20.61%
West Coast Maintenance (2015)	21,733	22,391	17,645	-2.94%	-21.19%	-18.81%
Wilmington Harbor (2014)	3,814	4,836	3,774	-21.14%	-21.96%	-1.05%
Pascagoula (2014)	7,401	4,963	3,296	49.13%	-33.58%	-55.46%
Wallops Island (2014)	13,625	13,743	7,072	-0.85%	-48.54%	-48.10%
Total:	82,808	80,827	64,197	2.45%	**-20.57%**	-22.47%
Mean Absolute Percent Error				13.46%	**20.67%**	20.51%

*Does not include optional beneficial use bid
**Used SG_{so} of 1.5

As can be seen, the government estimate is not the same as the winning bid, and has a certain anticipated error above or below what the contractors estimate. Using +/- 50% as an acceptable tolerance, the Wowtschuk total cost estimate was relatively accurate with percent error of under 50% from the winning bid for all eight projects. However, a separate specific gravity input was required to improve the accuracy of the Sabine Neches Waterway estimate. The default in-situ sediment specific gravity, $SG_{so,}$ of 1.9 resulted in a percent error of over 60%, therefore a value of 1.5 was used for this project instead. This values closely matches the actual specific gravity at the site of 1.3 – 1.5, indicated by the project's daily dredging reports (USACE, 2014).

The program also consistently estimated costs well below the winning bid for the Pascagoula Entrance Channel and Wallops Island Beach Restoration projects. The Pascagoula Entrance Channel called for not only maintenance dredging, but also new dredging work consisting of channel widening. New work dredging is typically more expensive than maintenance dredging due to additional equipment requirements, which is most likely why the program was not able to form an accurate estimation. Likewise, the Wallops Island Beach Restoration involved beneficial use of dredged material, which consists of additional equipment outside the cost estimation scope of this program.

The summation of the eight project cost estimates are also shown in Table 14. The total cost estimation values for the Wowtschuk Estimate was approximately 20% below the winning bid and 22% below the government estimate. The mean absolute percent error, which is the average of the absolute percent error for all eight projects, is approximately 20% between the Wowtschuk Estimate and both the winning bid and government estimate. This level of accuracy indicates that the default inputs and variables associated with the Wowtschuk Program Estimate are realistic assumptions and can be used to provide a reasonable predictor of the total project costs associated with a trailing suction hopper dredge.

In addition to comparing the total cost, a cost comparison method was also conducted for only the estimate of the dredging operation costs. Since the project bid abstracts breakdown costs by different line items, the winning bid and government estimated dredging costs were isolated by omitting the mobilization and additional cost line items. The Wowtschuk Program Estimated dredging costs were assumed to be the costs calculated by the program using the parameters from Table 12, less the addition of mobilization and additional costs. The project site specifications used for the Wowtschuk Estimate were kept close to those used for the winning bid and government estimate by dividing dredging projects into multiple channel sections, as identified on the bid abstract.

By using this process, project cost comparisons may contain multiple subsidiary comparisons of varying size and scope. For example, the large Galveston Ship Channel dredging project was broken down into six separate sections and six different cost comparisons. This strategy was thought to have two major benefits: 1) the programs production and cost estimation equations would be proven with greater confidence since the noisy data from unpredictable additional costs were omitted, and 2) a greater number of comparisons with more data variations were made possible, thereby expanding the scope of program testing. Table 15 shows how the eight projects were divided into different sections of channel, the volume of material to be dredged, and the cost per cubic yard of dredged material calculated by the government estimate, winning bid estimate, and the Wowtschuk Program estimate. As can be seen the costs per cubic yard range anywhere from approximates \$1 to nearly \$12 per yd^3.

Table 15: Dredging Cost per Volume Comparison

Project Name		Volume [yd^3]	Government [$/yd^3]	Winning [$/yd^3]	Wowtschuk Estimate [$/yd^3]
Freeport Harbor (2013)		2,149,000	2.09	2.04	2.26
Galveston Ship Channel (2015)					
	Entrance Channel Sec1-4	386,000	2.39	2.85	2.41
	Entrance Channel Sec5-6	463,000	2.37	3.57	2.18
	Outer Bar Sec7-9	433,000	2.37	3.86	2.99
	Inner Bar Sec10-13	725,000	3.71	4.10	3.55
	Houston Ship Ch. Sec14-15	13,000	5.97	3.57	4.87
	Houston Ship Ch. Sec16-19	387,000	6.15	3.85	5.17
Sabine Neches Waterway (2014)					
	SN-Outer Bar	2,611,000	1.00	1.05	0.97
	SN-Outer Bank	2,489,000	1.05	1.18	1.10
York Spit Channel (2015)		1,747,000	6.50	5.40	5.14
West Coast Hopper Maintenance (2015)					
	San Francisco Main Ship Ch.	225,000	4.11	4.50	3.68
	Grays Harbor	400,000	3.66	3.20	2.76
	Columbia River Entrance	2,000,000	2.59	2.25	2.48
	Columbia River	300,000	2.90	2.50	2.48
Wilmington Harbor (2014)					
	Baldhead Shoal Reach Ch. 4	800,000	3.80	4.45	3.31
Pascagoula Entrance Channel (2014)		1,032,552	6.25	4.05	2.17
Wallops Island Beach Restoration (2014)		650,000	11.20	11.75	6.90

The percent difference between the dredging operation costs calculated by the government estimate and Wowtschuk Program Estimate are compared with the winning bids for the projects in Table 16 below. The percent difference between the summations of the seventeen dredging cost estimates are also shown, along with the mean absolute percent difference.

Table 16: Dredging Operation Cost Accuracy Comparison

Project Name	Government Estimate vs. Winning Bid	Wowtschuk vs. Winning Bid	Wowtschuk vs. Government Estimate
Freeport Harbor	2.6%	10.6%	7.8%
Galveston Ship Channel			
Entrance Channel Sec 1-4	-16.1%	-15.5%	0.7%
Entrance Channel Sec 5-6	-33.6%	-39.0%	-8.1%
Outer Bar Sec 7-9	-38.6%	-22.6%	26.0%
Inner Bar Sec 10-13	-9.5%	-13.3%	-4.2%
Houston Ship Channel Sec 14-15	67.2%	36.5%	-18.4%
Houston Ship Channel Sec 16-19	59.7%	34.3%	-15.9%
Sabine Neches Waterway			
Outer Bar	-4.8%	-7.2%	-2.6%
Outer Bank	-11.0%	-6.9%	4.6%
York Spit Channel	20.4%	-4.9%	-21.0%
West Coast Hopper Maintenance			
San Francisco Main Ship Channel	-8.7%	-18.2%	-10.5%
Grays Harbor	14.4%	-13.6%	-24.5%
Columbia River Entrance	15.1%	10.2%	-4.2%
Columbia River	16.0%	-0.8%	-14.5%
Wilmington Harbor (2014)			
Baldhead Shoal Reach Channel 4	-14.6%	-25.5%	-12.8%
Pascagoula Entrance Channel	54.3%	-46.4%	-65.2%
Wallops Island Beach Restoration	-4.7%	-41.3%	-38.4%
Summation of Dredging Costs:	6.10%	-14.34%	-19.27%
Mean Absolute Percent Error:	23.02%	20.40%	16.43%

By eliminating all but the dredging operation costs and dividing the projects into channel sections, the program's versatility was tested in calculating costs for a wide range of sediment volumes and sediment transport distances shown in Table 13. Under these varying site conditions, the Wowtschuk estimate remained within acceptable tolerance with a percent error under 50% for all seventeen project sites. As with the total project cost estimate, the Sabine Neches Waterway Outer Bar and Outer Bank projects utilized a $SG_{so,}$ of 1.5 instead of the 1.9 used for the remaining projects. This reduced the percent error from approximately +64% to the roughly -7% shown above.

The Pascagoula Entrance Channel and Wallops Island Beach Restoration projects were again the least accurate estimations with percent error at -46.4% and -41.3% respectively. As mentioned, these projects were not typical maintenance dredging projects and required additional equipment outside of normal hopper dredging work. Since this cost discrepancy was virtually unchanged from the total project cost comparison in Table 14, the additional work costs must have been included in the dredging cost line item of the bid and therefore outside the scope of this program to currently calculate.

A graphical representation of the dredging cost estimate comparison data is represented in Figure 9. The project volumes are indicated by shaded bars, and the estimated dredging costs are overlaid on the graph as various markers. It can be seen on Figure 9 that the dredging costs calculated by the Wowtschuk Estimate, with the exception of the Pascagoula Entrance and Wallops Island projects, were often between the Winning Bid and Government Estimate cost. This figure also indicates that the accuracy of the program was not affected by the volume of material to be dredged.

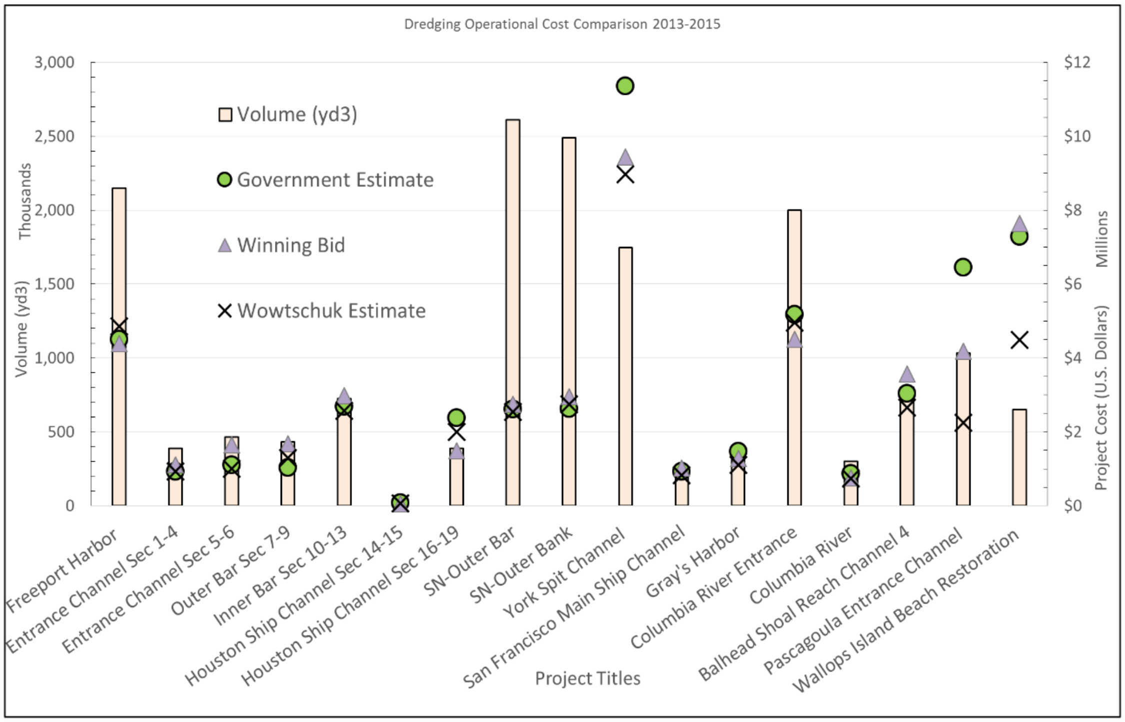

Figure 9: Dredging Cost Comparison

Comparing the results of the total project cost analysis in Table 14 to the dredging cost analysis in Table 16 shows an increase in the percent error between the government estimates and the winning bid. The mean absolute percent error between government estimate and winning bid increases from 13.5% to 23.0%. Conversely, the mean absolute percent difference between the Wowtschuk estimate and winning bid remained essentially identical, decreasing slightly from 20.7% to 20.4%. This increased level of accuracy compared to the government estimates indicates that the dredging cost estimation method utilized for this program is reasonable across various project site specifications. In addition, it demonstrates a potential benefit to separating projects into multiple channel sections for cost estimating purposes.

Production Comparison

In addition to the comparison of total project cost and dredging costs, the accuracy of the program's calculated production rates were compared with actual production rates from daily dredging reports. Daily dredging reports were provided by the USACE for the Freeport Harbor and Sabine Neches Waterway projects. These reports contain numerous details about each day of the project, but most importantly the reports specified the hopper dredge used for the project, in-situ sediment specific gravity, and various production cycle information (USACE, 2013; USACE, 2014). The average production rate (P_{avg}), production per cycle (or sediment transported per cycle), production per day, production cycle time, and number of cycles were averaged over several days of data for each of the available projects (see Appendix D). These actual project values were then compared to the program estimated values from the Wowtshuk Estimate, which keeps hopper dredge specifications constant and from a "Hopper Specific Program Estimate," which uses the specifications of the actual hopper dredge used on the project. Table 17 displays a comparison of the calculated production, while Table 18 compares the Wowtschuk Estimate default hopper specifications to three actual hopper dredges, denoted as "A", "B", and "C" in the tables.

Table 17: Production Rate Comparison

			Actual	Wowtschuk		Hopper Specific Estimate	
Freeport Harbor (B)							
	Production	(yd^3/ hr)	1,088	957	-12.0%	965	-11.3%
		(yd^3/ cycle)	2,928	2,381	-18.7%	2,367	-19.2%
		(yd^3/day)	25,184	22,970	-8.8%	23,150	-8.1%
	Cycle time	(hr)	2.69	2.49	-7.5%	2.45	-9.0%
	Cycles		8.6	9.6	11.6%	9.8	14.0%
Sabine Neches - Outer Bar (C)							
	Production	(yd^3/ hr)	1,095	2,261	106.6%	1,440	31.6%
		(yd^3/ cycle)	2,627	4,261	62.2%	2,864	9.0%
		(yd^3/day)	24,168	54,270	124.6%	34,571	43.0%
	Cycle time	(hr)	2.40	2	-22.5%	1.99	-17.1%
	Cycles		9.2	13	40.2%	12.1	31.5%
Sabine Neches - Outer Bank (A)							
	Production	(yd^3/ hr)	2,496	1,996	-20.0%	3,134	25.6%
		(yd^3/ cycle)	7,185	4,261	-40.7%	7,929	10.4%
		(yd^3/day)	58,916	47,914	-18.7%	75,227	27.7%
	Cycle time	(hr)	2.88	2	-26.0%	2.53	-12.1%
	Cycles		8.2	12	40.2%	9.5	15.9%

Table 18: Hopper Dredge Characteristics

	Wowtschuk Estimate	Hopper Specific Program Estimate		
Dredge Information		"A"	"B"	"C"
Hopper Capacity (yd^3)	5,300	13,500	5,000	4,000
Total Horsepower (HP)	9,800	12,000	10,350	5,400
Sailing Speed (kts)	8	8	8	8
Capital Value ($)	18,000,000	72,000,000	25,000,000	14,000,000
Equipment Lifespan (yrs)	30	30	30	30
Suction Pipe Information				
Suct./Disch. Diameter (in)	29	38	30	26
Dragarm Length (ft)	100	120	100	100

The variables and default settings not relating to the hopper dredge specifications were kept constant between these two estimation methods. For example, both the Wowtschuk Estimate and the Hopper Specific Estimate used the in-situ sediment specific gravity identified in the daily dredging report for the projects. Therefore, the SG_{so} for the Freeport Harbor and Sabine Neches were 1.9 and 1.5 respectively. This enabled the program's method for calculating production to be validated.

As expected, across all three projects the Hopper Specific Program Estimate generated production rates closer to the actual production rates recorded during the project than the Wowtschuk Program Estimate. The differences were most prominent in the Sabine Neches project, which was performed with two different hopper dredges "A" and "C". However, production rate differences were minimal for Freeport Harbor, which was completed with hopper dredge "B". These results are consistent with the nature of the hopper dredge characteristics used from Table 18. The Wowtschuk Program Estimate hopper characteristic assumptions are the average specifications of major United States dredges from Table B-1, while dredge "C" is comparably small dredge and "A" is a large one. This sizeable difference in dredge characteristics creates significant inaccuracy in the production calculations. On the other hand, dredge "B" has specifications similar to the average hopper dredge, which results in comparable production rates between the Wowtschuk Program Estimate and Hopper Specific Program Estimate.

In addition, Table 17 shows that using average dredge characteristics tended to underestimate production rates for the "A" dredging project and overestimate production rates for the "C" dredging project. This is consistent with the concept that in typical conditions, larger hopper dredges tend to have higher production rates than smaller hopper dredges. The level of accuracy and consistency of results indicates that the program, through the use of Equation 31, is a reasonable estimator of the production rate associated with trailing suction hopper dredging.

Sensitivity Analysis

Many independent variables and factors are utilized for estimating the cost of a dredging project. A sensitivity analysis was conducted to understand how these variables and factors affect the resultant cost and production estimations. The analysis was conducted by incrementally changing one individual variable while keeping all other factors constant. The base case values for the dredge characteristics and defaults were taken to be the Wowtschuk Program Estimate variables from Table 12 and the base case project site characteristics were assumed to be 1,000,000yd^3 of dredged material, at a depth of 45ft, a dredge site to placement site of 6 NM, and no regional cost index adjustment. The sensitivity analysis was first used to analyze the impact of dredging characteristics on the total cost of the project by incrementally changing the capital value of the dredge, the equipment lifespan, the hours equipment operates at 100% of power, the production rate, and the daily crew cost. The results of this univariate sensitivity analysis are shown in Figure 10 below.

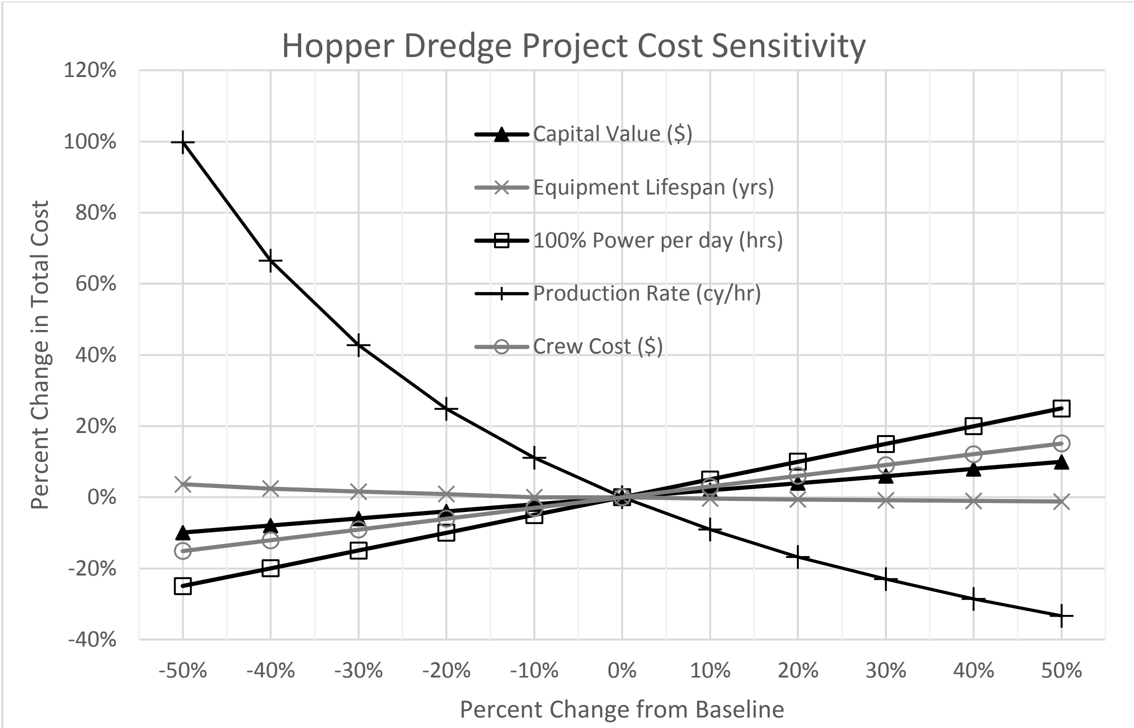

Figure 10: Hopper Dredge Total Cost Sensitivity Analysis

The plot demonstrates the percent change of total project cost as a function of percent change of each variable from baseline value. For example, if the capital value of the dredge increases by 50%, the total cost of the project will increase by 10%. Based on Figure 10, it is apparent that the production rate has the most significant effect on the total cost. This is unsurprising, as the production rate is used to determine the number of days required to complete a project. The 100% power per day, which is used to estimate the daily fuel usage of the hopper and is independent of the production rate calculation, also has a significant impact on the total project cost. The impact of changing the 100% power per day will depend on the total installed power of the dredge and the price of fuel, so that the larger the total power and price of fuel the greater the impact on total cost. This effect can be seen with the bivariate sensitivity analysis in Figure 11 below, where the total project cost at three different values of 100% power per day were plotted as a function of the total installed power.

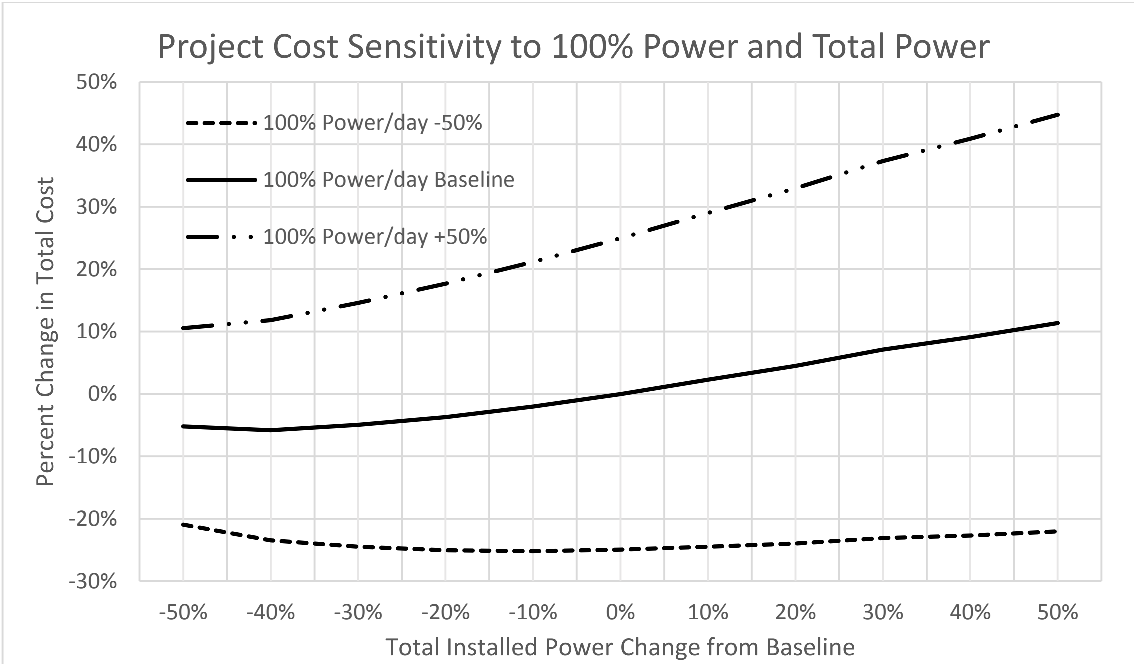

Figure 11: Total Cost Sensitivity to 100% Power per Day and Installed Power

From the plot, as the total installed power increases, the range of percent change in total cost due to the number of hours a dredge is operating at 100% power also gradually increases. Therefore, to optimize a project the operator must be especially mindful of costs associated with increasing daily power operation when utilizing high power dredges.

In order to expand on the total cost analysis, a separate sensitivity analysis was conducted for effects of different variables on the average hourly production rate, P_{avg}, of the dredge. While there are over a dozen program inputs that effect the calculated production rate, eight variables were selected for the univariate analysis shown in Figure 12. These variables are either difficult to know prior to the start of dredging, such as overflow time, or highly dependent on the dredge performing the work, such as hopper capacity.

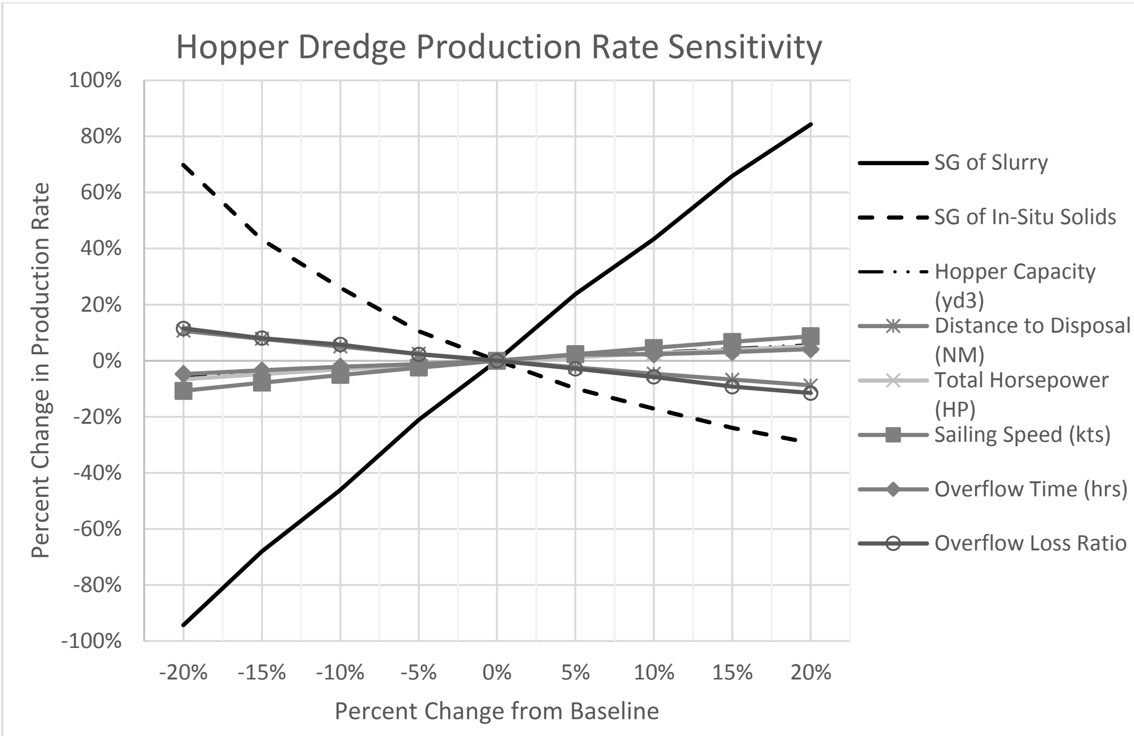

Figure 12: Production Rate Sensitivity Analysis

It is clear from the plot that the specific gravity of the in-situ sediment and specific gravity of the slurry mixture have by far the greatest impact on the production rate of the dredge. For example, a 20% drop in specific gravity of the in-situ sediment results in a nearly 70% increase of the hourly production rate. As shown in Figure 10, the production rate is the primary driver of the total cost, therefore the specific gravity of the sediment and slurry mixture have a huge impact on the total cost. Since the exact specific gravity of the material to be dredged may not be known until arrival on site, estimations are typically made based on contractor site experience. Using an appropriate specific gravity value for the program is crucial to obtaining a reasonable production estimate, and a competitive project cost bid.

The sediment overflow time and overflow ratio are also not easy values to estimate prior to the start of dredging, but can have as significant an impact on production rate as any of the other variables from Figure 12, besides specific gravity. The program recommends values to be used based on academic findings and estimations, but these values will be different for each dredge and dredging project. A bivariate sensitivity analysis, shown as a plot in Figure 13 below, was conducted to demonstrate the effect different overflow loss ratios and overflow times will have on the program's production rate.

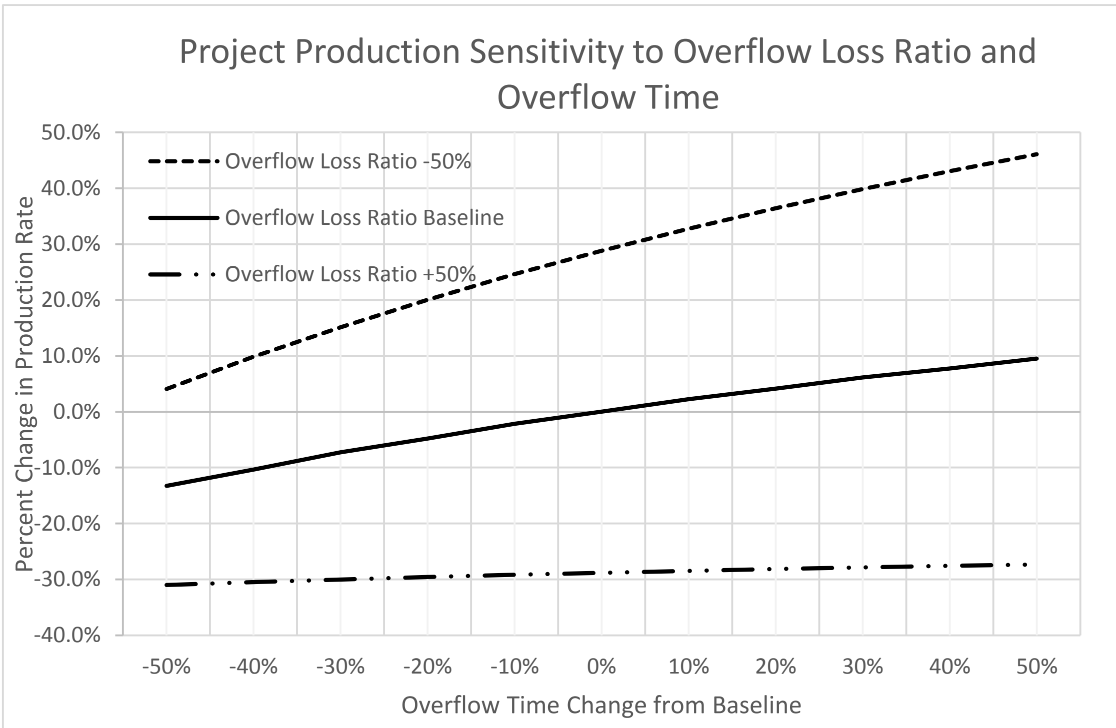

Figure 13: Production Rate Sensitivity to Overflow Loss and Overflow Time

The plot shows that at a lower overflow loss ratio, the production rate increases with longer overflow times, however with a high overflow loss ratio, the production does not significantly increase with more overflow time. This concurs with findings by Bray et al (1997) and Palermo and Randall (1990), which show that there is no significant increased production gained from the overflow of slow settling sediments such as clay and silt. To obtain an efficient production rate, the user must ensure an appropriate overflow time is used for the overflow loss ratio of the sediment being dredged.

CONCLUSION AND RECOMMENDATIONS

A publically available program for estimating trailing suction hopper dredging costs was developed and validated in Microsoft Excel, and builds upon the previous estimating programs created by Belesimo (2000) and Hollinberger (2010). The program uses hopper dredge characteristics and project site specifications to find pump generated head and piping system head losses. The slurry flowrate from the sea floor to the hopper is taken as the intersection of pump head curve and system losses curve as outlined by Randall (2004). The production rate is calculated using the slurry flowrate, slurry concentration, hopper capacity, overflow losses, and production cycle time based on the method proposed by Bray et al. (1997). The final dredging cost estimate is derived by combining the estimation of the dredging production rate with operating cost assumptions.

The program estimation of total project cost varied by a mean absolute percent error of 21% from the project's winning bid when the hopper dredge specifications were kept constant, and default values for mobilization and additional costs were utilized. This was slightly above the 13.5% price difference between the government estimate and winning bids over the same projects, but still within an acceptable tolerance. Subdividing the dredging operation cost estimates for these same projects and excluding consideration for the mobilization and additional costs resulted in a mean absolute percent difference of 20% between the program estimation and winning bid. This matched closely to the 23 absolute difference between the government estimate and winning bid.

The production rates calculated by the program when accurate hopper specifications are input, was shown to compare favorably to the actual production rates from three projects. The accuracy of the program's cost estimation and production rate estimation indicate this program cost estimate is a reasonable predictor of trailing suction hopper dredge maintenance dredging operations.

While the program estimations are reasonable, there are still limitations to the program's use. The operational costs assumption such as fuel and labor are for the year 2014-2015 and must be made to match future cost adjustments. The use of the default hopper dredge characteristics specified in the Wowtschuk Estimate is convenient for estimating costs when no hopper dredge information is known, but may not accurately estimate the production rates. It is recommended to not only include as much hopper dredge and project site information as available, but to confirm the program's default setting with actual project site characteristics. As indicated by the Pascagoula Entrance Channel and Wallops Island Beach Restoration, the program was not proven to be accurate for estimating costs of projects consisting of new dredging work or beneficial use. This is due to the added costs associate with additional equipment and personnel required to complete the job. Fortunately, the open structure of the program allows a user to include these additional costs if the information is known. Finally, the default values for overflow time and overflow losses, are based on a reasonable assumption that may be applied to a broad range of projects and will not likely represent actual overflow figures for a project. As with all program defaults, it is recommend that users gather the necessary hopper and sediment characteristics and match program defaults accordingly.

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APPENDIX A

WOWTSCHUK PROGRAM ESTIMATE TEST CASE,

TRAILING SUCTION HOPPER DREDGE – FREEPORT HARBOR, 2013

Table A-1. Dredge Information Used to Estimate Freeport Harbor, 2013

DREDGE INFORMATION			
Hopper Capacity:		5,300	yd^3
Number of Dragarms:		2	
Length of Dragarms:		100	ft
Sailing Speed Empty:		12	knots
Sailing Speed Fully Loaded:		9	knots
Total Horsepower		9,800	HP
Capital value of dredge		$18,000,000	
Equipment Lifespan		30	Yrs
Pump Configuration:			
Draghead to Submerged Pump			
	Length:	50	ft
	Dia:	30	in
Submerged Pump to Onboard Pump			
	Length:	50	ft
	Dia:	30	in
Onboard Pump to Hopper			
	Length:	100	ft
	Dia:	30	in
Pipe Characteristics:			
	Minor Losses:	10	
	Material:	Commercial Steel	
	Roughness, ε	0.00015	ft

Table A-2. Project Site Information Used to Estimate Freeport Harbor, 2013

PROJECT SITE INFORMATION		
Location:	Gulf Coast	
Avg Dredging Depth:	47	ft
Estimated Volume:	2,149,000	yd^3
Length of Dredge Area:	1.0	NM
Distance to Disposal Site:	3.5	NM
Overflow Permitted:	Yes	
Discharge Method:	Bottom Discharge	
Discharge Time:	0.1	hrs
Median Particle Diameter (d_{50}):	0.13	mm
Sediment Type:	Sand, Fine	
Specific Gravity of Slurry (SG_s):	1.3	
Specific Gravity of Water (SG_w):	1.025	
Specific Gravity of Solids (SG_{so}):	1.9	

Table A-3. Crew Information Used to Estimate Freeport Harbor, 2013

CREW INFORMATION		
Type	Number	Hourly Rate
Hopper Crew		
Master	1	$ 62.00
Assistant Master	1	$ 51.00
Mates (2nd or 3rd)	3	$ 35.00
Dredge Operator	3	$ 27.00
Chief Engineer	1	$ 61.00
Assistant Chief Engineer	1	$ 37.00
Assistant Engineer (2nd or 3rd)	3	$ 35.00
Marine Electrician	1	$ 31.00
Marine Oiler	3	$ 26.00
Electronics Mechanic	1	$ 30.00
Cook	2	$ 24.00
Beneficial Use Crew		
Foreman	0	$ 39.60
Equipment Operator	0	$ 48.60

Table A-4. Cost Information Used to Estimate Freeport Harbor, 2013

COST INFORMATION		
Hours Worked per Day:	24	hrs
Fuel Cost, (see Indices):	3.39	$/gal
Location Index (see Indices):	0.90	
Year Index:	0.973	
Crew Cost per Hour:	689	$/hr

Table A-5. Project Defaults Used to Estimate Freeport Harbor, 2013

DREDGE OPERATION			
Hours worked per day		24	hrs
100% Power		1	hrs
75% Power		18	hrs
10% Power		5	hrs
Days in use per year		300	
Pump Power / Total Power		0.300	
Overflow Time		0.75	hrs
100% Pwr/day (hrs)		15.0	hrs
REDUCTION FACTORS			
Delay Factor		0.9	
Operational Factor		0.75	
Mechanical Breakdown		0.9	
Total Reduction		0.61	
SEDIMENT COMPOSITION			
		Overflow Loss (r_l)	
Sand, Fine	$0.06mm \geq d_{50} < 0.2mm$	0.5	

Table A-6. Pump Characteristics Used to Estimate Freeport Harbor, 2013

PUMP CHARACTERISTICS		
Georgia Iron Works Inc.		
Model LHD	26"x28"-50"	
Power to Pump:	1,470	HP
Speed:	450	rpm
Q (gpm)	H(dim)	Head (ft)
10000	20.30	243.12
15000	18.23	218.40
20000	16.12	193.06
25000	14.50	173.64
30000	12.99	155.65
35000	11.28	135.08
40000	10.20	122.12
45000	9.16	109.71
50000	8.30	99.40
55000	7.42	88.87
60000	6.65	79.71
65000	5.92	70.94
70000	5.45	65.33
75000		

Table A-7. Production Used to Estimate Freeport Harbor, 2013

PRODUCTION RATES			
	Per Dragarm	Total	
Slurry Flowrate (Q)	32,200	64,400	GPM
	9,566	19,132	yd^3/hr
	P_{max}	1,575	yd^3/hr
		3,920	yd^3/cycle
	P_{avg}	957	yd^3/hr
		2,381	yd^3/cycle

Table A-8. Project Estimate Summary for Freeport Harbor, 2013

FINAL COST ESTIMATE			
Total Cost of Project:	$	4,851,233.49	
	$	2.26	per yd^3
Time Required		13.4	Weeks
Government Estimate:	$	4,502,070	
Winning Bid:	$	4,387,200	
Program Estimate:	$	4,851,234	
% Difference			
Gov. Estimate vs Winning Bid:	2.62%		
Program Estimate vs. Winning Bid:	10.58%		
Program Estimate vs. Gov. Estimate:	7.76%		

APPENDIX B

GUIDE TO CALCULATIONS

This guide is designed as a walkthrough of some of the calculations used in this thesis. The guide begins by detailing the procedures for finding the pump head curve for the dredge, then moves to the calculations for production rate and the assumptions made for Equation (31).

Pump Head Curve

The user must first enter specification about the hopper dredge to be used on the project into the Data Input sheet of the program. If dredge information is not known, a table from the Ref Sheet, shown as Table B-1 contains basic information on the major hopper dredges in the Unites States. This table can be used to estimate the hopper capacity, number of dragarms, total installed horsepower, suction pipe diameter, and estimated capital cost. Dredging companies typically publish specifications of their dredging fleet online, and a database of dredge statistics can be found at "DredgePoint.org" (Dredge Point, 2015).

The average dredge specifications from Table B-1 were used as default settings while comparing the estimating program. Using an average of major dredges, the default total installed power and suction pipe diameter (D) were selected as 9,800HP and 29in respectively.

Table B-1: Major American Hopper Dredges

AMERICAN HOPPER DREDGES					
Dredge	Pipe D_i (in)	Power (HP)	Hopper (yd^3)	Year Built	Cost Estimate
A	38	11999	13499	2006	$72,000,000
B	30	10350	5003	1996	$25,000,000
C	26	5399	4002	1982	$13,000,000
D	18	2601	2000	1978	$6,000,000
E	30	15566	6543	2002	$36,000,000
F	33	15206	6400	1981	$19,000,000
G	35	15493	7324	1976	$15,000,000
H	35	15493	7324	1977	$15,000,000
I	27	9391	3602	1980	$11,000,000
J	27	9391	3602	1979	$11,000,000
K	27	9391	3602	1981	$12,000,000
L	35	16288	11065	1982	$34,000,000
M	28	4950	4350	1944	$5,000,000
N	30	9597	4000	1987	$15,000,000
O	30	9727	4000	1985	$15,000,000
P	22	2961	1308	1980	$5,000,000
USACE					
Wheeler	28	10500	7999	1982	$24,000,000
Essayons	28	14399	5999	1983	$19,000,000
Yaquina	18	2249	1044	1981	$5,000,000
McFarland	34	6000	3142	1967	$5,000,000
Average:	28.95	9848	5290	1981	$18,100,000

The total horsepower and pipe diameter values, whether user input or default, is used to determine the pump head curve as follows:

1. The suction pump diameter is used to select from one of the four provided GIW Industries Inc. pump characteristic curves using the following relationship:

$$LHD\ 38X38 - 58in\ impeller, \quad for\ D > 36in$$
$$LHD\ 30X30 - 46in\ impeller, \quad for\ 29in > D \leq 36in$$
$$LHD\ 26X28 - 50in\ impeller, \quad for\ 26in \geq D \leq 29in$$
$$LHD\ 24X24 - 44in\ impeller, \quad for\ D < 26in$$

With a specific pump curve selected, the total installed power value entered by the user is multiplied by the pump power ratio and divided by the number of drag arms to give the power received by each pump (P). The power per pump determines a reasonable pump rotational speed (ω) as per the conditional relationships outlined in Table B-2 below.

Table B-2: Pump Speed as a Function of Pump Power

Pump Curve	Power per Pump (P)	Speed (ω)
$LHD\ 38X38$	$P > 5500HP$	$500rpm$
	$3500HP \geq P \leq 5500HP$	$450rpm$
	$P < 3500HP$	$400rpm$
$LHD\ 30X30$	$P > 2500HP$	$650rpm$
	$1950HP > P \leq 2500HP$	$600rpm$
	$1500HP \geq P \leq 1950HP$	$550rpm$
	$P < 1500HP$	$500rpm$
$LHD\ 26X28$	$P > 3200HP$	$600rpm$
	$2500HP > P \leq 3200HP$	$550rpm$
	$1600HP \geq P \leq 2500HP$	$500rpm$
	$P < 1600HP$	$450rpm$
$LHD\ 24X24$	$P > 5000HP$	$600rpm$
	$3400HP > P \leq 5000HP$	$550rpm$
	$1800HP \geq P \leq 3400HP$	$500rpm$
	$P < 1800HP$	$450rpm$

The correlation of pump speed to pump power range are estimated from the characteristics curve and speeds are selected that maintain the pump operating at or near peak efficiency for any given power.

The selected pump speed and provided impeller diameter are then used to non-dimensionalize the pump characteristics for one of the pumps as shown in Figure B-1 using Equations (18), (19), and (20).

Pump Characteristics								
Georgia Iron Works dredge pump					Nondimensionalized pump characteristics			
30X30 dredge,46in impeller, 550rpm					D_i:	46	3.83	
					Speed:	550	57.60	
Q (gpm)	BHP	H (ft)	Efficiency %		Q (dim)	BHP (dim)	H (dim)	Efficiency
10000	1200	168	40	→	6.87	2.15	11.09	40
15000	1350	166	50	→	10.30	2.42	10.96	50
20000	1450	162	55	→	13.74	2.60	10.70	55
25000	1500	155	64	→	17.17	2.69	10.23	64
30000	1600	149	71	→	20.60	2.87	9.84	71
35000	1650	141	75	→	24.04	2.96	9.31	75
40000	1700	130	77.3	→	27.47	3.05	8.58	77.3
45000	1750	118	78	→	30.91	3.14	7.79	78
50000	1800	105	77	→	34.34	3.23	6.93	77
55000	1825	94	74	→	37.77	3.27	6.21	74
60000	1850	82	70	→	41.21	3.32	5.41	70
65000	1900	70	65	→	44.64	3.41	4.62	65

Figure B-1: Dimensional to Dimensionless Characteristics, 30in Suction Pump

Figure B-1 shows the dimensional to non-dimensional conversion for a 30in diameter suction pump, with a 46in impeller, and a speed of 550rpm. The pump speed may vary in accordance with Table B-2, resulting in slightly different dimensionless values. This pump speed and impeller diameter are also used to non-dimensionalize the calculated power received by the pump.

Then by using definition for efficiency (η) from Equation (21) provided by Herbich (2000), it is assumed that a pump operates at or near its max efficiency point, so that η is nearly constant. It follows from this assumption that the dimensionless parameters of Q, H, and P would also be constant as shown in Equations (22), (23), and (24). Substituting the dimensionless parameters into Equation (21) yields:

$$\eta = \frac{\rho g \frac{Q}{\omega D^3} \frac{gH}{\omega^2 D^2}}{\frac{P}{\rho \omega^3 D^5}} = constant \qquad \text{(B-1)}$$

The Equation (B-1) can be expressed as:

$$\frac{Q_{dim_1} H_{dim_1}}{P_{dim_1}} = \frac{Q_{dim_2} H_{dim_2}}{P_{dim_2}} \qquad \text{(B-2)}$$

Where the subset "1" indicates the initial non-dimensionlized parameters of the pump curve, and subset "2" indicates the parameters of a curve associated with the user entered pump power. Rearranging to solve for the dimensionless pump head (H_{dim2}) along the flowrate envelope for the new pump power yields:

$$H_{dim_2} = \frac{P_{dim_2} H_{dim_1}}{P_{dim_1}} \qquad \text{(B-3)}$$

Where P_{dim2} is the dimensionless power of the pump selected by the user, and remains constant. P_{dim1} and H_{dim1} are the dimensionless pump power and pump head along the curve from Figure B-1. The pump is assumed to always operate within the same flowrate envelope, and H_{dim2} is calculated at each flowrate along this envelope so that the flowrates Q_1 and Q_2 remain constant and cancel out. An example of these calculations are shown in Table B-3, below:

Table B-3: Calculation of Pump Head Curve

Dimensionless pump characteristics (D=46in, ω=550rpm)				Selected Pump Power	Equation (B-3)	New Pump Head Curve	
Q_1(dim)	P_1(dim)	H_1(dim)	η	P_2(dim)	⟶	H_2(dim)	H(ft)
6.87	2.15	11.09	40	2.69	⟶	13.87	210.00
10.30	2.42	10.96	50	2.69	⟶	12.18	184.44
13.74	2.60	10.70	55	2.69	⟶	11.07	167.59
17.17	2.69	10.23	64	2.69	⟶	10.23	155.00
20.60	2.87	9.84	71	2.69	⟶	9.22	139.69
24.04	2.96	9.31	75	2.69	⟶	8.46	128.18
27.47	3.05	8.58	77.3	2.69	⟶	7.57	114.71
30.91	3.14	7.79	78	2.69	⟶	6.68	101.14
34.34	3.23	6.93	77	2.69	⟶	5.78	87.50
37.77	3.27	6.21	74	2.69	⟶	5.10	77.26
41.21	3.32	5.41	70	2.69	⟶	4.39	66.49
44.64	3.41	4.62	65	2.69	⟶	3.65	55.26

The H_{dim2} creates a new pump heard curve as a function of flowrate, pump power, and pump speed. The calculated pump heads reasonably match the pump heads obtained off the corresponding dimensional pump characteristic curve using the same pump power and flowrate.

Production Rate

The total production rate, P_{max}, is the amount dredged material excavated from the removal site per dredging cycle. It is typically defined in units of cubic yards per hour, but can be described in cubic yards per cycle, or cubic yards per day. Depending on the use of hopper overflow, this program uses one of two methods for calculating total production rate. For situations where overflow is not a major factor, such as the dredging of extremely fine particles or when a project explicitly prohibits it, the P_{max} is calculated directly using:

$$P_{max} = \frac{C_H C_v}{B(t_{load} + t_{turn} + t_{sail} + t_d)} \tag{B-4}$$

Where the hopper capacity, C_H, is multiplied by the concentration of sediment solids by volume in the slurry, C_v, to find the volume of sediment in the hopper at the point overflow would begin. The bulk factor is assumed to be 1.0 so the volume of dredged sediment contained in the hopper is not reduced any further. This volume of sediment in the hopper is then divided by the total time it takes to complete one dredging cycle. This method of calculating total production rate is highly dependent on the concentration of solids by volume of the slurry mixture into the hopper, and typically ranges from 0.2 – 0.4 depending on the specific gravity of the in-situ sediment.

For a hopper with a capacity of 5000 yd^3, and a concentration by volume of .25, the volume of dredging material contained in the hopper at the start of overflow is 1250 yd^3. Using a total cycle time of 2 hrs, the total production time becomes 625 yd^3/hr.

In situations that overflow is permitted and beneficial, a second method for estimating total production rate was developed in this thesis based on the following equation:

$$P_{max} = \frac{C_H C_v + P t_o (1 - r_l)}{B(t_{load} + t_{turn} + t_{sail} + t_d)} \tag{31}$$

Where, as before, the volume of dredged sediment in the hopper at the commencement of overflow is found by multiplying C_H and C_v. However, this value is then added to the volume of dredged material added to the hopper during overflow time to find the total volume of dredged material in the hopper. The P used here is the rate of sediment being pumped from the sea floor and into the hopper, found from multiplying the flow rate, Q, by C_v and converting to yd^3/hr as in Equation (32). The overflow time, t_o, is the loading time during overflow conditions. P and t_o multiplied together give the total volume of dredged sediment on-loaded during the overflow time, however, a fraction of this sediment is unable to settle in the hopper and is lost back overboard. This fraction is called overflow losses, represented in the above equation by r_l, and strongly depends on the characteristics of the dredged sediment. Therefore, multiplying (Pt_o) by the (1- r_l), or the ratio of sediment not lost to overflow, a volume of sediment retained on the hopper during overflow time can be calculated.

In reality, since overflow time is dependent on overflow losses, and the specifications of the hopper weir system and the sediment composition need to be known to accurately calculate the ratio of overflow losses, this program is only able to make reasonable assumptions for these values. A default overflow time of 45min was selected based on reasonable loading times presented in Randall and Palermo (1990) and Bray et al. (1997). The loading time, t_{load} is now the time it takes to fill the hopper to the start of overflow plus the overflow time. The default values for overflow losses were taken from a figure presented by Boogert (1973) and displayed in Table B-4 below:

Table B-4: Default Overflow Losses Based on Sediment Size

Sediment Type	Default Grain Size, d_{50} (mm)	Default Overflow Loss, r_l
Coarse Sand	1.3	.15
Medium Sand	0.4	.25
Fine Sand	0.13	.5
Silt	.013	1.0
Clay	.002	1.0

Therefore, a 5000yd^3 hopper, dredging medium sand at a concentration by volume of .25, a flow rate of 50,000gpm, a t_o of 45min, and total cycle time of 2.5 hours would have a total production rate as follows:

$$P_{max} = \frac{C_H C_v + P t_o (1 - r_l)}{B(t_{load} + t_{turn} + t_{sail} + t_d)}$$

$$P_{max} = \frac{(5{,}000 yd^3)(0.25) + (P)(.75hr)(1 - 0.25)}{1.0(2.5hr)}$$

$$P = 0.297(50{,}000 gpm)(0.25) = 3712.5\ yd^3/hr$$

$$\boxed{P_{max} = 1{,}335\ yd^3/hr}$$

APPENDIX C

MISCELLANEOUS DATA

Table C-1: Sample of Foreign Hopper Dredges

	Power		Ratio	Tonnes to Cubic Meter Conversion	
Dredge	Total Installed (kW)	On Pumps (kW)	(pump/Total)	Metric Tons (t)	Cubic Meters
1	1394	570	0.409	1000	650
2	3225	650	0.202	1685	1000
3	3526	843	0.239	2235	1500
4	3875	1005	0.259	3030	2000
5	4062	1080	0.266	3755	2500
6	6542	1755	0.268	7393	4871
7	6826	2025	0.297	8106	5600
8	6826	2025	0.297	8106	5600
9	13110	3400	0.259	18620	11300
10	11037	3250	0.294	18565	11650
11	17880	4500	0.252	26650	16500
12	19559	6328	0.324	24146	17000
13	26800	8800	0.328	26016	18292
14	19061	6000	0.315	30140	24130
15	25445	7600	0.299	48000	30190
16	41650	13000	0.312	78500	46000
AVG			**0.289**		

To make the hopper dredge capital cost values provided by Bray et al. (1997) more applicable to American dredges, the provided hopper metric tons (t), a unit of mass, must be converted to a volumetric capacity. This requires an assumption to be made regarding the density of the dredged material in the hopper. One metric ton is equal to 1,000 kilograms, to convert this weight into cubic volume it is divided by the density of the material. Since the density of dredged material is variable, and the density assumed by hopper dredge manufacturers may also vary, the capacities of ten foreign built dredges were compared to find a reasonable conversion from metric tons to cubic meters. These foreign dredges ranged in size from 1000t to 19,000t and are shown in the first ten rows of Table C-1. The provided metric tons represents the deadweight tonnage or loading capacity of the vessel, which is a measure of the total carrying capacity to include cargo, fuel, and stores. Therefore, this relationship is not the expected density of the dredged material in the hopper, but it provides a reasonable relationship to use for comparing metric tons to hopper capacity for hopper dredges. The relationship between metric tons and cubic meters for these dredges is plotted in Figure C-1 below.

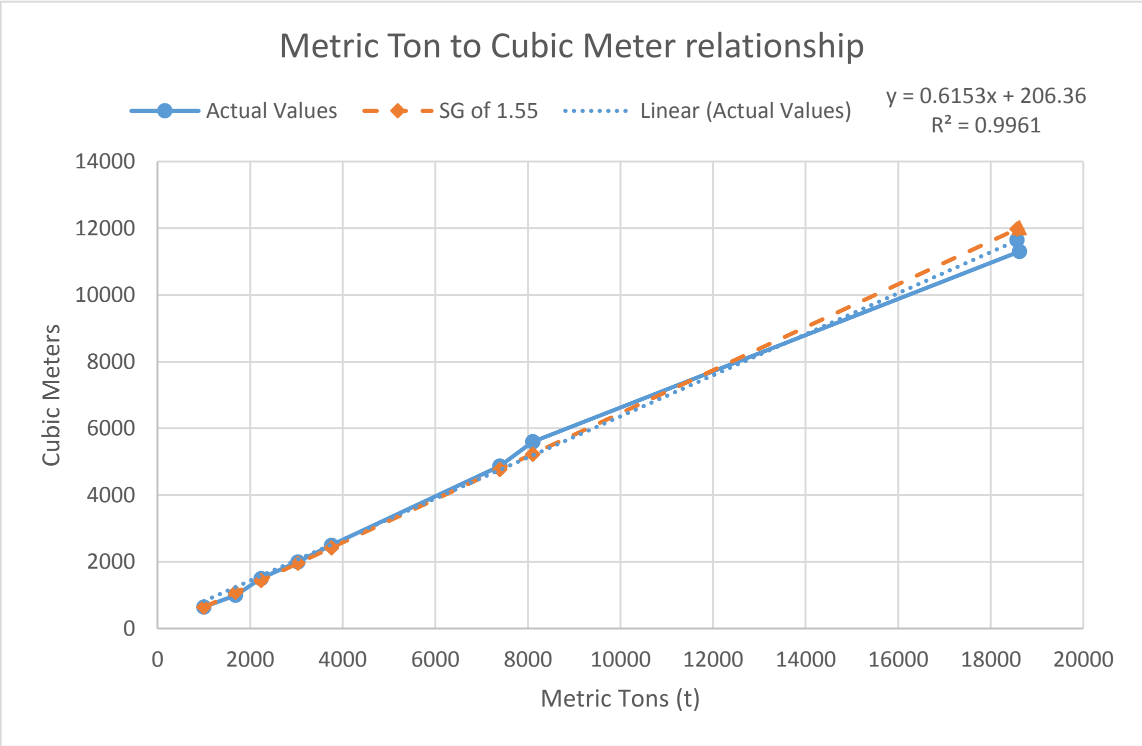

Figure C-1: Foreign Dredge Hopper Capacity Relationship

The blue line indicates the actual metric ton and cubic meter capacities for the ten dredges, with the linear best fit line represented by the blue dotted line. As expected, the relationship is not exactly linear since each vessel is designed with slightly different loading parameters, however the linear best-fit line shows a high correlation with an R^2

value of 0.996. For simple calculations, a single multiplier that closely matches this best-fit line was assumed. This is represented by the orange, "SG of 1.55" line in Figure C-1. A relationship with an average loading density of 1,550 kg/m3 or SG of 1.55, was assumed, which is a reasonable assumption for dredged mixture, so that 1.55 time the capacity in cubic meters yields the hopper size in metric tonnes. This 1.55 relationship was assumed for the conversion represented by Figure 6.

Table C-2 below contains the data on Additional Costs gathered from the dredging projects investigated throughout this thesis. The median value of these additional costs were used as the programs default additional cost values.

Table C-2: Additional Cost Data

Additional Dredging Costs Based on Government Estimate							
Project Name	Mob/Demob	Monitor Surveys	Turtle Protection	Trawler Mobilization	Sea Turtle Trawling and Relocation [per Day]	Days	Mobilization Cost as Fraction of Dredging Cost
Freeport Harbor (2013)	$900,000	$25,000.00	$50,000.00	$6,000.00	$3,000.00	30	20.0%
Galveston Ship Channel (2015)	$2,500,000	$126,000.00					30.5%
Entrance Channel Sec 1-4			$16,200.00			30	
Entrance Channel Sec 5-6							
Outer Bar Sec 7-9			$57,600.00	$5,000.00	$4,000.00	30	
Inner Bar Sec 10-13			$57,600.00	$5,000.00	$4,000.00	30	
Houston Ship Channel Sec 14-15			$1,440.00			30	
Houston Ship Channel Sec 16-19			$36,900.00			30	
Sabine Neches Waterway (2014)	$940,000						18.0%
Outer Bar		$9,000.00	$30,000.00	$5,500.00	$3,600.00	30	
Outer Bank		$12,000.00	$34,000.00		$3,600.00	30	
York Spit Channel (2015)	$890,000				$7,500.00	15	7.8%
West Coast Hopper Maintenance (2015)	$5,207,912						61.7%
San Francisco Main Ship Channel							
Gray's Harbor							
Columbia River Entrance							
Columbia River							
Wilmington Harbor (2014)							
Balhead Shoal Reach Channel 4	$598,400						19.7%
Pascagoula Entrance Channel (2014)	$850,000			$7,300.00	$4,500.00	20	13.2%
Wallops Island Beach Restoration (2014)	$2,878,000						39.5%
Average:	$1,845,539	$43,000	$35,468	$5,760	$4,314	28	26.3%
Median:	$920,000	$18,500	$35,450	$5,500	$4,000	30	19.9%

APPENDIX D

DAILY DREDGING DATA

The daily dredging reports were obtained from the USACE for the Freeport Harbor (FH) and Sabine Neches Waterway (SNWW). The duration of both the FH and SNWW projects were approximately two months. However, the SNWW was subdivided between the Outer Bar and Outer Bank channels, which were carried out concurrently using two dredges. The FH, SNWW-Outer Bar, and SNWW-Outer Bank consisted of over 50 daily dredging reports each, however only data from 5 daily reports were collected for the use of this comparison as shown in Table D-1, D-2, and D-3 below. The name of the dredge conducting the dredging, capacity of the hopper (C_H), number of cycles per day, production per dredging cycle, total dredging time, and pumping time were provided in the daily reports. From this information, the total production rate (P_{avg}), excavation production rate (P), and proportion of hopper filled with sediment (f_e) were calculated per cycle using the following equations:

$$P_{avg} = \frac{Prod.per\ Cycle\ [\frac{yd^3}{cycle}]}{Total\ Cycle\ Time\ [hr]} \quad [\frac{yd^3}{hr}] \tag{D-1}$$

$$P = \frac{Prod.per\ Cycle\ [\frac{yd^3}{cycle}]}{Pumping\ Time\ [hr]} \quad [\frac{yd^3}{hr}] \tag{D-2}$$

$$f_e = \frac{Prod.per\ Cycle\ [\frac{yd^3}{cycle}]}{C_H\ \ [\frac{yd^3}{cycle}]} \tag{D-3}$$

The number of cycles, production per cycle, production per day, P_{avg}, and total cycle time were then averaged across all 5 daily reports to find an assumed average for the project.

Table D-1: Freeport Harbor Daily Dredging

Freeport Harbor (daily dredging)						
Dredge: A			C_H =	4880	yd^3	
Report No 8	Production	Time (min)		P_{avg}	P	f_e
Load No.	(yd^3/cycle)	Total	Pumping	(yd^3/hr)	(yd^3/hr)	
1	3128	184	106	1020	1771	0.64
2	3054	189	109	970	1681	0.63
3	2176	102	35	1280	3730	0.45
4	3207	144	74	1336	2600	0.66
5	3119	168	94	1114	1991	0.64
6	3133	160	86	1175	2186	0.64
7	3143	163	90	1157	2095	0.64
8	3078	185	117	998	1578	0.63
9	3102	190	122	980	1526	0.64
Report No 10						
1	3034	194	123	938	1480	0.62
2	3054	179	105	1024	1745	0.63
3	3059	152	83	1208	2211	0.63
4	3008	143	73	1262	2472	0.62
5	3063	191	114	962	1612	0.63
6	3024	165	98	1100	1851	0.62
7	3069	120	51	1535	3611	0.63
8	3083	177	105	1045	1762	0.63
9	3006	171	104	1055	1734	0.62
Report No 22						
1	2967	143	100	1245	1780	0.61
2	2936	121	76	1456	2318	0.60
3	2905	121	76	1440	2293	0.60
4	2812	195	143	865	1180	0.58
5	2875	120	83	1438	2078	0.59
6	2880	141	86	1226	2009	0.59
7	2943	125	77	1413	2293	0.60
8	2900	147	99	1184	1758	0.59
9	2930	158	107	1113	1643	0.60

Table D-1: Freeport Harbor Daily Dredging (Cont'd)

Report No 33		Production	Time (min)		P_{avg}	P	f_e
	Load No.	(yd^3/cycle)	Total	Pumping	(yd^3/hr)	(yd^3/hr)	
	1	2894	146	112	1189	1550	0.59
	2	2900	143	107	1217	1626	0.59
	3	2870	93	58	1852	2969	0.59
	4	2912	209	163	836	1072	0.60
	5	2826	167	122	1015	1390	0.58
	6	2832	143	107	1188	1588	0.58
	7	2765	127	94	1306	1765	0.57
	8	2784	169	132	988	1265	0.57
	9	2894	205	163	847	1065	0.59
Report No 36							
	1	2792	181	130	926	1289	0.57
	2	2854	192	133	892	1288	0.58
	3	2884	180	125	961	1384	0.59
	4	2730	200	145	819	1130	0.56
	5	2736	176	117	933	1403	0.56
	6	2767	178	121	933	1372	0.57
	7	2792	189	132	886	1269	0.57
Average	8.6	2928	162	105	1088	1824	0.60
			2.69	1.74	(hr)		
		25184	(yd^3/day)				

Table D-2: Sabine Neches Waterway – Outer Bar Daily Dredging

Sabine Neches Waterway- Outer Bar (daily dredging)						
Dredge: Newport			C_H =	4000	yd^3	
Report No 2	Production	Time (min)		P_{avg}	P	f_e
Load No.	(yd^3/cycle)	Total	Pumping	(yd^3/hr)	(yd^3/hr)	
1	2648	139	87	1143	1826	0.66
2	2646	145	88	1095	1804	0.66
3	2650	156	97	1019	1639	0.66
4	2645	130	81	1221	1959	0.66
5	2641	141	90	1124	1761	0.66
6	2650	147	94	1082	1691	0.66
7	2650	139	83	1144	1916	0.66
8	2597	153	91	1018	1712	0.65
9	2601	151	86	1034	1815	0.65
Report No 7						
1	2592	131	78	1187	1994	0.65
2	2592	140	88	1111	1767	0.65
3	2565	156	95	987	1620	0.64
4	2576	138	86	1120	1797	0.64
5	2601	156	90	1000	1734	0.65
6	2637	147	93	1076	1701	0.66
7	2619	130	75	1209	2095	0.65
8	2570	134	79	1151	1952	0.64
9	2592	119	65	1307	2393	0.65
10	2905	139	89	1254	1958	0.73
11	2935	145	91	1214	1935	0.73
Report No 14						
1	2860	178	120	964	1430	0.72
2	2900	153	98	1137	1776	0.73
3	2900	139	90	1252	1933	0.73
4	2900	160	110	1088	1582	0.73
5	2880	166	111	1041	1557	0.72
6	2890	118	74	1469	2343	0.72
7	2875	140	92	1232	1875	0.72
8	2900	160	108	1088	1611	0.73
9	2870	156	104	1104	1656	0.72
10	2850	163	114	1049	1500	0.71

Table D-2: Sabine Neches Waterway – Outer Bar Daily Dredging (Cont'd)

Report No 22		Production	Time (min)		P_{avg}	P	f_e
	Load No.	(yd^3/cycle)	Total	Pumping	(yd^3/hr)	(yd^3/hr)	
	1	2900	211	187	825	930	0.73
	2	2920	138	97	1270	1806	0.73
	3	2860	129	87	1330	1972	0.72
	4	2850	154	98	1110	1745	0.71
	5	2830	168	105	1011	1617	0.71
Report No 43							
	1	2260	128	82	1059	1654	0.57
	2	2256	125	79	1083	1713	0.56
	3	2252	120	77	1126	1755	0.56
	4	2176	126	80	1036	1632	0.54
	5	2276	138	82	990	1665	0.57
	6	2248	125	81	1079	1665	0.56
	7	2252	113	70	1196	1930	0.56
	8	2240	124	81	1084	1659	0.56
	9	2256	151	106	896	1277	0.56
	10	2260	148	104	916	1304	0.57
	11	2268	157	109	867	1248	0.57
Average	9.2	2627	144	93	1095	1761	0.66
			2.40	1.55	(hr)		
		24168.2	(yd^3/day)				

Table D-3: Sabine Neches Waterway – Outer Bank Daily Dredging

Sabine Neches Waterway- Outer Bank (daily dredging)						
Dredge:	Glenn Edwards		C_H =	13500	yd^3	
Report No 40 Load No.	Production (yd^3/cycle)	Time (min) Total	Pumping	P_{avg} (yd^3/hr)	P (yd^3/hr)	f_e
1	8362	100	169	5017	2969	0.62
2	8224	165	89	2991	5544	0.61
3	8224	184	106	2682	4655	0.61
4	9047	177	95	3067	5714	0.67
5	8260	179	97	2769	5109	0.61
6	8059	168	95	2878	5090	0.60
7	7577	172	94	2643	4836	0.56
8	7932	176	100	2704	4759	0.59
9	7476	174	91	2578	4929	0.55
Report No 42						
1	7073	159	89	2669	4768	0.52
2	6666	174	96	2299	4166	0.49
3	6490	176	100	2213	3894	0.48
4	9529	100	40	5717	14294	0.71
5	9251	132	60	4205	9251	0.69
6	9275	152	87	3661	6397	0.69
7	8534	159	93	3220	5506	0.63
8	7503	180	94	2501	4789	0.56
9	7098	153	84	2784	5070	0.53
Report No 45						
1	6392	168	94	2282.857	4080	0.47
2	6083	171	99	2134.386	3687	0.45
3	5737	168	95	2048.929	3623	0.42
4	6962	169	101	2471.716	4136	0.52
5	6284	171	94	2204.912	4011	0.47
6	6494	158	89	2466.076	4378	0.48
7	6436	159	92	2428.679	4197	0.48
8	6519	210	129	1862.571	3032	0.48

Table D-3: Sabine Neches Waterway – Outer Bank Daily Dredging (Cont'd)

Report No 47		Production	Time (min)		P_{avg}	P	f_e
	Load No.	(yd^3/cycle)	Total	Pumping	(yd^3/hr)	(yd^3/hr)	
	1	7774	260	160	1794	2915	0.58
	2	8984	215	128	2507	4211	0.67
	3	8301	167	90	2982	5534	0.61
	4	7435	166	91	2687	4902	0.55
	5	7426	187	109	2383	4088	0.55
	6	6965	199	129	2100	3240	0.52
	7	7042	171	98	2471	4311	0.52
Report No 50							
	1	6404	210	130	1830	2956	0.47
	2	6619	221	125	1797	3177	0.49
	3	5961	172	97	2079	3687	0.44
	4	4731	149	88	1905	3226	0.35
	5	4688	152	88	1851	3196	0.35
	6	5531	160	90	2074	3687	0.41
	7	5721	187	111	1836	3092	0.42
	8	5511	210	132	1575	2505	0.41
Average	8.2	7185	173	101	2496	4693	0.53
			2.88	1.68	(hr)		
		58916	(yd^3/day)				

APPENDIX E

USER'S GUIDE

This guide is designed as a step-by-step walk through of the program estimate for an average sized trailing suction hopper dredge project. The guide begins with data entry and leads through to analyzing the results output.

Step 1: Data Input

Based on the information available for a project, determine which variables will be input by the user and which values will be left as the default settings. At a minimum, the following project site information must be known: dredging depth, volume to be dredged, distance to disposal site, and discharge method. The American Hopper Dredges table from the Reference Sheet may also be used to input dredge information if the default values are not desired.

If suction pump information is not known, the program will calculate a pump head based on an input Total Horsepower and input pipe diameter. The procedures for this calculation were discussed in Appendix B.

If known, the pump curve may be entered manually by selecting "Manual Entry" from the drop down in cell F20, then fill in the Manual Pump Curve Entry table below with the pump head at various flowrates.

The Median Particle Diameter is calculated by taking the average d_{50} grain size based on the percentage of that grain sizes in the sediment. The program recommends particle diameters based on sediment types but the user may input different corresponding sizes or select 100% "Other" and input a known d_{50}. It must be noted, that the Median Particle Diameter calculated in cell K26 is used to assume an Overflow Loss Ratio based on the default recommended particle diameters in accordance with Table E-1 below. This table is also found on the Defaults sheet of the program, and the user has the option to change the default Overflow Loss Ratio values, but cannot adjust the d_{50} range or sediment type name they correspond to.

Table E-1: Overflow Loss Ratio Calculation

Sediment Composition		
Type	d50 (mm)	Overflow Loss
Sand, Coarse	$d_{50} \geq 0.6$	0.15
Sand, Medium	$0.2 \geq d_{50} < 0.6$	0.25
Sand, Fine	$0.06 \geq d_{50} < 0.2$	0.5
Silt	$0.006 \geq d_{50} <0.06$	1
Clay	$d_{50} <0.006$	1

For example, if an Overflow Lost Ratio of 0.33 was expected for a project with a d_{50} of 0.10 mm, the user would input 0.33 in the $0.06 \geq d_{50} < 0.2$ (Sand, Fine) row under the Overflow Loss column.

A recommended crew is provided by the program, but the user may adjust the number of personnel, hourly rates, and even the position names as desired.

Mobilization and Demobilization costs may either be omitted for the final cost calculation, based on the program default value, or estimated by the user by selecting "Do Not Include," "Default Value," or "Estimate Cost" from the drop down list in cell P17. If estimating the cost, the sailing distance, sailing speed, and fuel cost are required inputs. The program will then calculate a cost based on default mobilization costs shown in Table E-2 below. This table is found on the Defaults sheet and the values may be changed by the user if desired.

Table E-2: Mobilization and Demobilization Calculation

Mobilization and Demobilization		
Dredging Crew	20	
Travel Days	5	
Per Diem Rate	$83.00	/person/day
Meals & Incidentals	$46.00	/person/day
Air Travel	$400.00	/person
Stand-by Cost	$100,000.00	/day

Similarly, the Additional Costs may also be omitted, default value selected, or entered manually by selecting one of the options from the drop down list in cell P23. If "Manual Entry" is desired, the user may input costs associated with various items in cells below. Default additional cost values are also provided by the program and are shown in Table E-3 below. The table can be found on the Ref Sheet, and contains most of the reference values, and referenced dropdown lists used by the program. Most of the nomenclature and cell values are integral to the program calculations and must not be altered, however certain values such as the Discharge Method times and Pipe Material roughness may be altered if more accurate values are known. Only cell highlighted in grey-blue or green may be altered while Cells highlighted in dark or light gray must not be changed.

Table E-3: Reference Sheet Table

Suction Line Configuration			
Submerged Only			
Onboard Only			
Submerged & Onboard Pump			
Pipe Material	**ε (ft)**	**ε (mm)**	
Galvanized Iron	0.0005	0.15	
Commercial Steel	0.00015	0.045	
Overflow			
Yes			
No			
Sediment Type	**d50 (mm)**	**OverFlow Loss**	**Bulk**
Sand, Coarse	1.3	0.15	1.15
Sand, Medium	0.4	0.25	1.2
Sand, Fine	0.13	0.5	1.25
Silt	0.013	1	1.2
Clay	0.002	1	1.15
**PIANC			
Discharge Method	Time (hr)		
Bottom Discharge	0.1		
Pump Ashore	1		
Other	2		
Mob/Demob			
Do Not Include	$0		
Default Value	$1,000,000		
Estimate Cost	$ 788,584.18		
Location	**Cost Index**	**18-mo Fuel Avg**	
Alaska/Hawaii	1.19	3.64	
California	1.17	3.73	
Central Atlantic	1.08	3.71	
East Coast	1.03	3.59	
Great Lakes	1.03	3.47	
Gulf Coast	0.90	3.39	
Lower Atlantic	0.89	3.47	
New England	1.14	3.71	
New York	1.17	3.71	
West Coast	1.09	3.64	
No Region Index	1.00	3.51	
Pump Curve			
Default			
Manual Entry			
Additional Costs			
Do Not Include	Monitor Surveys	$ 20,000.00	
Default Value	Turtle Protection	$ 35,000.00	
Manual Entry	Trawler Mobilization	$ 5,500.00	
	Turtle Trawling/Relocatio	$ 4,000.00	
	Days:	30	
	Total Additional Costs:	$ 180,500.00	

Step 2: Default Values Check

With the Data Input sheet completely filled out, the user should check the Defaults sheet and concur with values under Dredge Operation and Reduction Factors shown in Table E-4 and Table E-5 below.

Table E-4: Default Dredge Operation Values

Dredge Operation		
Hours worked per day	24	hrs
100% Power	1	hrs
75% Power	18	hrs
10% Power	5	hrs
Days in use per year	300	
Pump Power / Total Power	0.300	
Overflow Time	0.75	hrs
100% Pwr/day (hrs)	15	hrs

Table E-3: Default Reduction Factors

Reduction Factors		
Delay Factor	0.9	
Operational Factor	0.75	
Mechanical Breakdown	0.9	
Total Reduction	0.61	

The production rate and total cost calculated by the program are highly sensitive to these default values so a change from the program default setting should be deliberate and with good reason.

Step 3: Critical Flowrate Check

With the data input values and default values correctly input, the program should generate a Final Cost Estimate on the bottom right of the Data Input sheet. If an

“ERROR” message appears next to the “Total Cost of Project” in cell Q33 it means that the calculated flowrate is below the critical flowrate. As shown in Figure E-1 below.

Final Cost Estimate			
Total Cost of Project:	$ 4,658,089.22	ERROR - Q < Qcrit	
	$ 2.17	per yd^3	
Time Required	10.5	Weeks	

Figure E-1: Critical Flowrate Error Message

This indicates that the flowrate is not fast enough to pick up the specified sediment. The Flow Calc sheet contains the calculations for the flowrate and critical flowrate and could help indicate how to remedy the issue. Typically, the solution is to decrease the sediment diameter or increase the pump power.

Step 4: Production Rate Check

Assuming the program calculated a Final Cost Estimate with no Error message, the user may wish to check the calculated Production Rate to ensure it is reasonable. The Production Cost sheet contains all the calculations for production cycle times and production rate values. Cells E35-C37 show the average production rate, $P_{Avg,}$ per hour, per cycle, and per day used by the program to estimate the number of days it will take to complete the project (cell E44). Lastly, the programs calculated “Fuel Consumption” shown in cell K31 may be of some interest to the user, however, comparison with real world project data suggests this value is typically twice what would be consumed in reality.