Design of a Sediment Removal and Processing System to Reduce Sediment Scouring Potential from the Lower Susquehanna River Dams

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***Abstract* – The Conowingo, Safe Harbor, and Holtwood dams located on the Lower Susquehanna River have historically acted as a system of sediment and nutrient pollution traps, retaining and thereby preventing large amounts of ecologically harmful sediment from entering the Upper Chesapeake Bay. However, extreme storm events, termed as scouring events, cause substantial amounts of the trapped sediment to be swept downriver into the Upper Chesapeake Bay, blanketing benthic organisms, affecting subaquatic vegetation growth, and the overall water quality. In addition, all three reservoirs have reached a state of near maximum sediment storage capacity termed as dynamic equilibrium. Based on prior research, this study seeks to reduce the sediment buildup in the LSR Dams through a continuous sediment removal and processing system, and thereby reduce the ecological impact of major scouring events. A set of scour performance curves derived from a regression analysis, and a stochastic lifecycle cost model were used to evaluate the sediment scouring reduction and economic feasibility of three processing alternatives: Plasma Vitrification, Cement-Lock, and Quarry/Landfill, and three removal amount cases: Nominal, Moderate, and Maximum. Since the scour performance curves treat the dams as static, a fluid system dynamics model was used to determine if there is a dynamic interaction between the capacitance of the dams during major scouring events. A utility vs. cost analysis factoring in time, performance, and suitability of the alternatives indicates that a Cement-Lock processing plant at moderate dredging is the most cost-performance effective solution.**

Index Terms – Chesapeake Bay, Cost-Benefit Analysis, Dredged Sediment Management, System Dynamics Model

INTRODUCTION

The Susquehanna River flows through New York, Pennsylvania, and Maryland, and empties into the Upper Chesapeake Bay [1]. The Lower Susquehanna River consists of a series of three major dams and reservoirs that sit within 32 miles of the Upper Chesapeake Bay. The Safe Harbor Dam is the northernmost dam, and has a sediment storage capacity of 92.4 million tons. The Holtwood Dam is the smallest with a capacity of 15.6 million tons, while the Conowingo Dam is the southernmost and largest dam, with a capacity of 198 million tons. These dams, collectively referred to as the Lower Susquehanna River (LSR) Dams, provide hydroelectric power generation, water storage, and recreation for the surrounding areas [2].

The LSR Dams have also acted as a sediment and nutrient pollution trap for the past eighty years; from 1929 to 2012, approximately 430 million tons of sediment were transported down the Susquehanna River, with approximately 290 million tons being trapped by the dams. However, all three reservoirs have reached near maximum storage capacity and fluctuate asymptotically from near 100 percent capacity. Although the reservoirs still trap sediment to some degree in this dynamic equilibrium state, their trapping ability is reduced significantly [3].

The greatest danger of the diminished trapping capacity of the LSR Dams is the risk of short-term extreme storms known as scouring events. Scouring events comprise of major storms or hurricanes, which cause the river flow rate to exceed 400,000 cubic feet per second (cfs). Although scouring events occur on average every 5 to 60 years depending on the streamflow, they cause extensive flooding in the reservoirs, which in turn release episodic loads of sediment and nutrients into the Upper Chesapeake Bay leading to major ecological damage. These effects can be seen in historical case studies of major scouring events such as Hurricane Agnes in 1972 and Tropical Storm Lee in 2011 [4] [5]. In addition, the current annual sediment limit to be met by 2025 for the Lower Susquehanna River is 985,000 tons. It is estimated that scouring events can transport from 1.5 to 1200 percent above the regulation limit [6] [7].

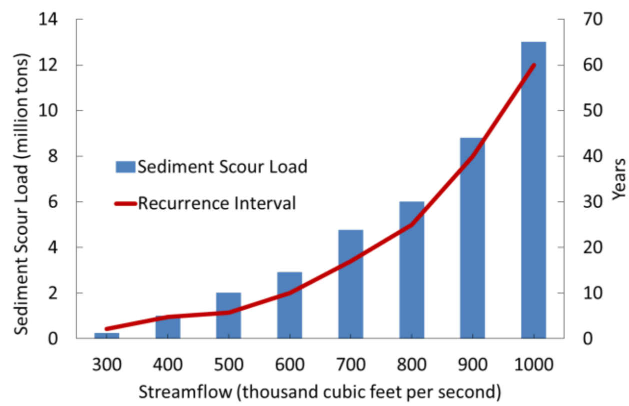

FIGURE 1
PREDICTED SEDIMENT SCOUR LOAD FOR HIGH STREAMFLOW EVENTS

I. Previous Research

The LSR Dams, particularly the Conowingo, have been the subject of several studies conducted by the U.S. Army Corps of Engineers (US ACE) from 2011 to 2014, all evaluating the feasibility of various sediment management techniques during high flow scouring events [4]. A study was also done at George Mason University (GMU) from 2013 to 2014, hereon referred to as the "GMU 2014" study [8]. Both studies evaluated similar strategies, including: minimizing sediment deposition by using an artificial island or flow diverters to bypass sediment; modifying dam operations; and recovering sediment trapping volume by removing sediment and placing it in quarries, or reusing the sediment to make beneficial products. The studies concluded that though sediment bypassing is more cost-effective than other alternatives, it will result in adverse effects on the Bay's ecosystem due to constant increases in sediment and nutrient loads. The US ACE study concluded that for dredging to be effective, the dredging must operate annually or on a continuous cycle. The GMU 2014 study concluded that reusing sediment to make glass slag via Plasma Vitrification may yield a positive ROI; however, a more detailed economic assessment needs to be conducted. In addition, the GMU 2014 study suggested to evaluate sediment reuse strategies for the dams north of the Conowingo, namely the Holtwood and Safe Harbor dams.

STAKEHOLDER ANALYSIS

I. Hydroelectric Power Companies

Exelon Generation, Pennsylvania Power and Light, and Safe Harbor Water Power Corporation are the licensed operators of the Conowingo, Holtwood, and Safe Harbor dams, respectively. Their objective is to provide clean renewable energy for the residents in the Maryland and Pennsylvania regions.

II. Riverkeepers

The riverkeepers, particularly the West/Rhode Riverkeeper, are members of the Waterkeeper Alliance, whose objective is to protect waterbodies of the Upper Chesapeake Bay.

III. Residents of Maryland and Pennsylvania

Maryland and Pennsylvania residents include those residing within the Lower Susquehanna River watershed who use the Susquehanna River for agriculture and recreation, as well as residents that receive power from the hydroelectric dams.

IV. Private Environmental Organizations

Private environmental organizations such as the Chesapeake Bay Foundation (CBF) and the Clean Chesapeake Coalition (CCC) are organizations that are concerned with specific environmental issues related to the Chesapeake Bay, in addition to advocating for environmental policy legislation.

V. State and Federal Regulatory Bodies and Legislatures

State and federal regulatory bodies consist of government agencies involved in legal or regulatory issues surrounding activities in the Lower Susquehanna River watershed such as the Maryland Department of the Environment (MDE), or the Federal Energy Regulatory Commission (FERC) which is responsible for licensing hydropower projects as well as regulating transmission of electricity, natural gas, and oil. These organizations work together with Maryland and Pennsylvania state legislatures to enact laws to improve and promote environmental restoration of the Chesapeake Bay and the Lower Susquehanna River.

VI. Stakeholder Tensions

While every stakeholder has an interest in the removal of sediment from behind the dams, no single organization has accepted responsibility for the pollution collected in the reservoirs. The Clean Chesapeake Coalition believes that Exelon Generation should take responsibility and pay for the expensive removal process. Exelon Generation, however, believes that the responsibility falls on those living in the Susquehanna River watershed, and if required to pay for the sediment mitigation may want residents to pay more in utilities to cover the cost.

STATEMENT OF NEED

There is a need to develop a sediment removal and processing system to reduce the sediment buildup in the Lower Susquehanna River Dams, in order to reduce the ecological impact of future scouring events.

CONCEPT OF OPERATIONS

The proposed solution to the problem of the diminishing trapping capacities of the dams is a sediment removal and processing plant operation. This operation consists of three parts: dredging, transport, and processing. The sediment will be removed through a hydraulic dredging operation which removes and transports sediment in slurry form through pipelines connected directly to the processing plant. The removal and processing will be a steady state operation that will continuously dredge sediment from each of the reservoirs lasting for a lifecycle of 20, 25, or 30 years.

DESIGN ALTERNATIVES

The design alternatives consist of sediment processing techniques which convert dredged sediment into products which can be marketed and sold in an effort to minimize the total cost of the operation. An exhaustive survey for the suitability of dredged sediment processing techniques was conducted, of which several processes were chosen to be evaluated further.

I. Plasma Vitrification

Plasma Vitrification is a process piloted by Westinghouse Plasma Corp. in which dredged sediment is exposed to plasma torches reaching temperatures of 5000 deg. C destroying nearly all toxic organic and microbiological contaminants. This produces a glass slag product which can be sold as a replacement for glasphalt, roofing granules, coal slag, or as a three-mix glass substitute [9].

II. Cement-Lock

Cement-Lock is a thermo-chemical process developed by the Gas Technology Institute and Unitel Technologies, in which dredged sediment is placed through a rotary kiln reaching temperatures between 1315 and 1425 deg. C. During the combustion process, the contaminated sediment is mixed with a set of chemical feed materials. The end product is finely ground down to produce EcoMelt, a pozzolanic material that can be used as a 40 percent replacement for Portland cement used in concrete production [10].

III. Quarry/Landfill

The quarry/landfill alternative serves as the control for this study. It is essentially removing the dredged sediment and placing it in a deposit site. Although this alternative may cost less than the processing alternatives, there is no decontamination that takes place, thus there is a risk of potential environmental degradation in the future.

Other processes that were initially considered included:

- **Thermal Desorption**
- **Particle Separation/Soil Washing**
- **Fluidized Bed Treatment**
- **Flowable Fill**
- **Glass Furnace Technology**
- **Electrochemical Remediation**
- **Solidification/Stabilization**
- **Base Catalyzed Decomposition**

METHOD OF ANALYSIS

The sediment removal and processing plant operation provides a solution to address the retained sediment buildup in the Lower Susquehanna River Dams. However two questions remain: How does dredging a certain amount of sediment affect scouring potential, and what is the return on investment for dredging this amount and processing it into glass slag or EcoMelt products?

A set of three models were used to address these questions: The Scour Performance Curves, a set of regression models derived from the GMU 2014 Hydraulic Model, are used to approximate sediment scouring potential from varying amounts of dredged sediment. Since the Scour Performance Curves treat the dams as static entities, a Fluid System Dynamics Model was used to determine if the water velocity reduction from dredging one dam in relation to the following dam is considerable or negligible during major scouring events. Lastly, the Processing Plant Lifecycle Cost Model is a Monte Carlo simulation used to determine the net present value for each of the design alternatives to be evaluated.

SCOUR PERFORMANCE CURVES

I. Method of Analysis

A hydraulic model was developed in the GMU 2014 study to simulate sediment transport over the course of 20 years, after dredging 1, 3, and 5 million cubic yards of sediment annually from behind the Conowingo. The model calculated the flow rate through the river based upon a lognormal distribution of precipitation. The velocity profile of the river was adjusted according to the bathymetry of the river in order to satisfy the continuity principle. Finally, sediment scouring and re-deposition were calculated as functions of flow velocity and river bathymetry. The river bathymetry was subsequently updated to account for sediment deposition and scouring [8].

The hydraulic model also simulated three future water flow rates using the hydraulic record from 1967 to 2013: a ‘dry world’ with a maximum flow rate of 400,000 cubic feet per second (cfs), a ‘future is the past’ world matching historical data with a maximum flow rate of 700,000 cfs, and a ‘wet world’ with a maximum flow rate of 1 million cfs. Using the simulation data, a correlation between dredging and the percent of scouring reduced was derived and extrapolated to a time frame of 30 years for each dredging amount. Figure 2 below shows the relationship between dredging 1, 3, and 5 million cubic yards annually and the percent of scouring reduced using the average of the three future water flow test cases.

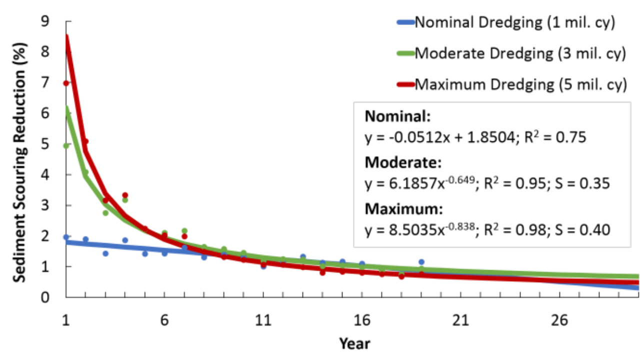

FIGURE 2
SCOUR PERFORMANCE CURVES FOR NOMINAL, MODERATE, AND MAXIMUM DREDGING

II. Results

The set of regression curves show that there is a trend of diminishing returns in regard to sediment scouring reduction as the dredging amount increases. The benefits of dredging 1 million cubic yards annually decreases at a constant rate, while the benefits of dredging 3 and 5 million cubic yards decreases substantially after the first several years. From the correlation, nominal, moderate, and maximum dredging amounts were derived for the Conowingo, Holtwood, and Safe Harbor dams for 30, 25, and 20 years respectively. The weights for the dredging amounts were prorated from the capacity of the specific reservoir over the combined total capacity of all three reservoirs.

TABLE I
ANNUAL DREDGING AMOUNTS FOR 30, 25, AND 20 YEARS

Dam	Nominal Dredging	Moderate Dredging	Maximum Dredging
Conowingo	650,000 cy	2 million cy	3 million cy
Holtwood	50,000 cy	150,000 cy	250,000 cy
Safe Harbor	350,000 cy	1 million cy	2 million cy

Figure 3 below shows the respective scour reductions from the Conowingo, Holtwood, and Safe Harbor dams from the nominal, moderate, and maximum dredging cases. The results indicate that the Conowingo Dam would result in the greatest scour reduction, followed by Safe Harbor, while Holtwood has the least.

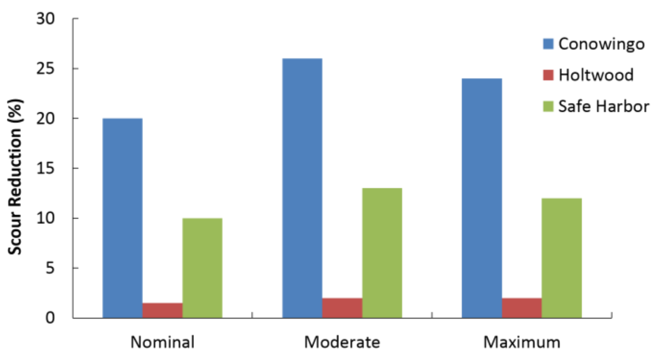

FIGURE 3
SCOUR REDUCTION FOR NOMINAL, MODERATE, AND MAXIMUM DREDGING

SYSTEM DYNAMICS MODEL FOR SEDIMENT TRANSPORT

I. Method of Analysis

The Scour Performance Curves treat the reservoirs as static entities. In other words, if a reservoir is dredged and its sediment capacity is reduced, this may subsequently reduce the water velocity flow rate transport in the following reservoir, and therefore the resulting sediment scour. During major scouring events ranging from 400,000 to 1 million cubic feet per second (cfs), this dynamic interaction between the dams may be considerable or negligible in regard to the resulting sediment scour.

In addition, the variable cost of dredging is a significant expenditure in the dredging and processing operation. As such, a system dynamics model for river and sediment flow was developed in order to predict the amount of scouring that would occur in various dredging operations. Minimizing the scouring model assists in determining the least cost dredging operation that would most substantially improve the environment.

The capacitive nature of the dams, with respect to sediment, suggests that a system dynamics model may approximate sediment transport, provided that the system can be approximated as closed and linear. The applicability of these assumptions necessitate review in future studies.

A system dynamics model may be preferable to study sediment transport for several reasons. Calculating sediment transport by predicting changes in river bathymetry is highly unreliable. Predicting sediment transport is further confounded by eddy currents and turbulence. The system dynamics model attempts to avoid nonlinearities of turbulence by modeling sediment flow averaged over the area. Reducing fluctuations also permits the use of other alternatives, such as oysters and subaquatic vegetation to further reduce the impact of major scouring events.

II. Formulation

The system dynamic model represents the three dams within the Lower Susquehanna River as a series of tanks. Each tank receives a flow of water and a flow of sediment. The sediment entering the tank is deposited if the velocity is less than the critical deposition velocity; otherwise, it remains suspended and is transported through the tank. Sediment that has been deposited will later scour if the velocity of the water is above the critical entrainment velocity.

The flow of water is approximated by a sinusoidal average of flow rates. The concentration of sediment is calculated upstream of the Safe Harbor Dam based upon a power regression of historical water and sediment data taken at Marietta, PA water station. This can be seen in (1) below, where Q represents the volumetric flow of water in cubic feet per second, and $\rho_{sediment}$ represents the concentration of sediment within the flow [3].

$$\rho_{sediment} = .0007 * Q^{.9996} \quad (1)$$

The sediment leaving a tank can be related to the sediment entering a tank by applying the conservation of mass. The conservation of mass requires that the amount of mass, m, leaving the control volume (cv) within a given timespan (t) is equal to the rate mass enters the control volume minus the amount of mass accumulating within the control volume over a given time period.

$$\frac{dm_{out}}{dt} = \frac{dm_{in}}{dt} - \frac{dm_{cv}}{dt} \quad (2)$$

As represented in the figure below, the amount of mass within the control volume is the difference between the sediment deposited and the sediment entrained. This is shown in (3).

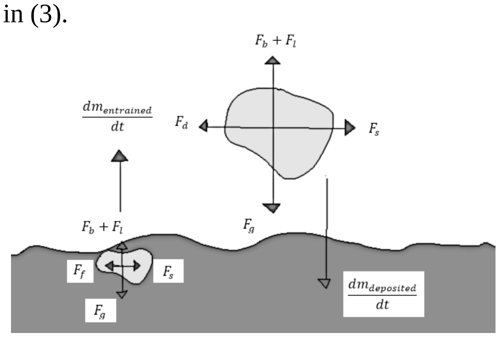

FIGURE 4
ENTRAINMENT AND DEPOSITION WITHIN CONTROL VOLUME

$$\frac{dm_{cv}}{dt} = \frac{dm_{deposited}}{dt} - \frac{dm_{entrained}}{dt} \quad (3)$$

The rate of sediment deposition is a function of the mass flow into the tank and the velocity of the flow (*v*). The velocity of the flow is calculated by applying the continuity equation to the flow within a reservoir. In (4), *A* represents the cross-sectional area of the reservoir.

$$v = Q_{in}/A \tag{4}$$

After determining the velocity, the behavior of entrained and deposited sediment is determined. Studies suggest three regions for sedimentation and scouring based upon flow velocity and sediment size, as shown in Figure 5 [11].

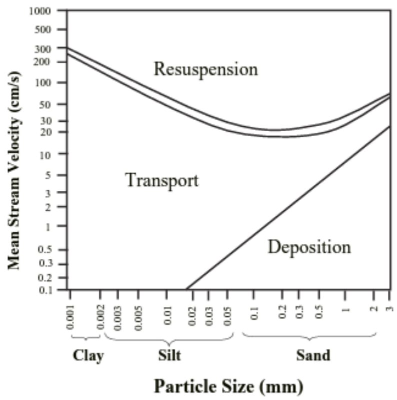

FIGURE 5
MEAN STREAM VELOCITY VS. PARTICLE SIZE

Resuspension, transportation, and deposition may be represented by the following binary variables:

$$x_1 = \begin{cases} 1, & if\ v - v_{resuspension} \geq 0 \\ 0, & if\ v - v_{resuspension} < 0 \end{cases} \tag{5}$$

$$x_2 = \begin{cases} 1, & if\ v_{deposition} - v \geq 0 \\ 0, & if\ v_{deposition} - v < 0 \end{cases} \tag{6}$$

If the amount of mass entrained is proportional to the surface area (*SA*) of the river bed and the amount of sediment deposited is proportional to the flow of sediment flowing into the control volume, then:

$$\frac{dm_{entrained}}{dt} = k_1 * x_1 * SA \tag{7}$$

$$\frac{dm_{deposited}}{dt} = k_2 * x_2 * \frac{dm_{in}}{dt} \tag{8}$$

Substituting the control volume mass rate relationships into the original mass balance equation and integrating the result with respect to time yields the following equation:

$$m_{out} = \int (1 - k_2 * x_2) * (.0007 * Q_{in}{}^{1.9996}) + k_1 * x_1 * SA\, dt \tag{9}$$

Constants k_1 and k_2 are derived from the training set, which is a subset of historical data. These constants are expected to be related to the forces acting upon suspended sediment and sediment deposited on the riverbed, as shown in Figure 4.

III. Results

The model is in the process of being verified with historical data. Results will show the amount of sediment leaving the Lower Susquehanna River Dams after major scouring events under three precipitation scenarios consisting of 400,000, 700,000, and 1,000,000 peak volumetric water flow. By varying the initial conditions on (8), the model will test various dredging scenarios.

PROCESSING PLANT LIFECYCLE COST MODEL

I. Method of Analysis

The inputs to the lifecycle cost model include the dredging amount, the costs, revenue, and other variables associated with the processing plant operation, the cost of the dredging operation, and the cost of land.

TABLE II
COST OF PROCESSING ALTERNATIVES

Variable	Plasma Vitrification	Cement-Lock	Quarry /Landfill
Plant Capital (millions)	$60 to $715	$50 to $625	N/A
Net Processing Cost(per ton)	$150 to $205	$60 to $90	$5 to $40
Dredging Capital (millions)	$7.7 to $8.5	$7.7 to $8.5	$3 to $7
Dredging Transport (per ton)	$17 to $27	$17 to $27	$30to$130
Land Costs (per acre)	$15 to $40 K	$15 to $40K	N/A
Revenue Prices (per ton)	$140 to $170	$75 to $90	N/A
Sediment to Product Ratio	2.5 tons	1.5 tons	N/A
Interest Rate (Yield Curve)	2.7 to 3.5%	2.7 to 3.5%	2.7to3.5%

II. Results

Baseline cost estimates were obtained for each variable in the lifecycle cost model and were extrapolated for cases specific to this study, in addition to normal and triangular distributions used to model the uncertainty associated for each cost variable. Market research was conducted for glass slag and EcoMelt replacement products (coal slag and Portland cement) from which it was assumed 70 to 85 percent of the replacement product's average selling price can be met.

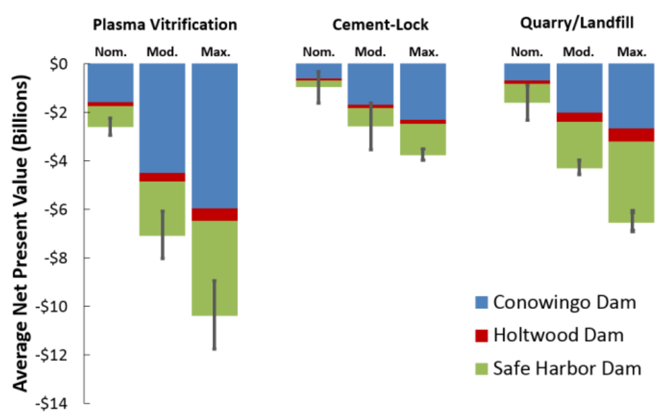

FIGURE 6
AVERAGE NET PRESENT VALUE (BY ALTERNATIVE)

The lifecycle cost model consists of 27 unique test cases (three reservoirs, three product alternatives, and three dredging amount alternatives). The average net present value from 100,000 simulation iterations, along with their respective 95% confidence intervals is shown in Figure 6 above. The results indicate that dredging and processing sediment, or placing it in quarries/landfills is a very expensive operation ranging from millions to billions of dollars, of which none of the alternatives evaluated resulted in a positive net present value. The results also indicate the Cement-Lock alternative results in the least cost, lower than both Plasma Vitrification and the Quarry/Landfill control case. This indicates that Cement-Lock may be the most viable option among the design alternatives evaluted.

UTILITY ANALYSIS AND RECOMMENDATIONS

The utility analysis consists of the following factors: time of the processing plant lifecycle, product suitability, and the percent of scouring reduction potential. The time of the processing plant lifecycle is either 30, 25, or 20 years with respect to the nominal, moderate, or maximum dredging cases. The product suitability is the percent of contaminants removed from the contaminated sediment. Scouring reduction potentials are derived from the Scour Performance Curves for each dredging case for each of the reservoirs. In the utility graph below, each line on the graph represents the utility for each processing alternative and dam combination, while the points on the lines represent the dredging cases in the following order: nominal, moderate, and maximum. The weights for the utility were determined through discussion with the project sponsor, the West/Rhode Riverkeeper, Inc.

$$U(x) = 0.10*Time + 0.30*Suitability + 0.6*Performance \quad (10)$$

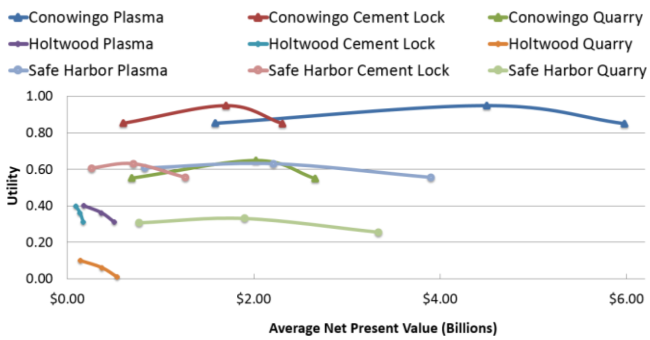

FIGURE 7
UTILITY VS. COST ANALYSIS

Based on the analysis of the utility function, it is recommended a sediment removal and processing system comprising of moderate dredging for 25 years, with the Cement-Lock product alternative be implemented at the Conowingo and Safe Harbor dams. For the Holtwood Dam, a removal and processing operation is not needed due to its low scour reduction potential.

However, a sediment removal and processing operation may not be needed at each reservoir. It is recommended that further study be conducted to determine if the dynamic interaction between the dams during major scouring events is considerable or negligible. This may indicate that there is an optimal reservoir which can be used as a dynamic trap, in which case a sediment removal and processing operation may only be needed at one or two of the dams which will reduce the resulting cost of the system. Secondly, since it is the nutrients attached to the sediment that primarily cause long term environmental degradation, it is recommended that an exhaustive survey of nutrient management strategies be conducted. Lastly, if nutrient management is not more cost-performance effective, it is recommended that the patent holders of Cement-Lock be contacted for a pilot study on Lower Susquehanna River sediment.

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