

Turbidity Reduction for the West and Rhode Rivers

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Abstract—The West and Rhode Rivers (WRR), two mezohaline sub-estuaries of the Chesapeake Bay, contain a total volume of 26 million m³ of water and have a 78 km² watershed. Due to local runoff and the excess nutrients and total suspended solids (TSS) entering the WRR from the Chesapeake Bay, water quality in these sub-estuaries has steadily declined over the last forty years. Models and data analysis have shown that as much as 90% of nutrient and TSS inputs to the WRR enter via inflowing tidal water from the Chesapeake Bay; therefore, community outreach efforts are predicted to have little impact on water quality.

Three alternative designs have been identified that have the potential to decrease turbidity and stimulate growth in subaquatic vegetation (SAV): addition of eastern oysters (*Crassostrea virginica*), soft-shell clams (*Mya arenaria*), and living shoreline restoration (LSR). The oysters and clams act as water filters, while LSR prevents runoff from entering the water. A 2-D Tidal Mixing Model (2DTMM) was developed to simulate the dynamic interaction between these alternatives and the nutrients and TSS entering the sub-estuary. The goal of this project is to find the design alternative, amount, and placement that would maximize the water quality in the WRR at minimum cost.

The optimal placement and dollar-value configurations for each design alternative were further modeled in the Estuarine Eutrophication Model, which simulates improvements in dissolved oxygen concentrations and provides more precise water clarity calculations than the 2DTMM. An analysis of cost versus utility (water quality improvement, sustainability, and public approval) shows that the addition of approximately 20 million clams would be the most cost-effective alternative.

I. INTRODUCTION

THE West and Rhode Rivers (WRR), two tidal sub-estuaries of the Chesapeake Bay located in the mesohaline zone, have a combined volume of 26 million m³ of water and have a 78-km² watershed. These well-mixed sub-estuaries are influenced heavily by the Chesapeake Bay’s tide, have an average depth of 2 meters, and salinity variations from 4-17 ppt.

The environmental degradation of the Chesapeake Bay and its sub-estuaries is a direct result of population growth

and expanding agriculture in the Chesapeake’s watershed, causing high concentrations of nutrients (nitrogen and phosphorus) and total suspended solids (TSS).

The West and Rhode Riverkeeper Inc. collects data throughout the WRR for water clarity, dissolved oxygen, nutrients, chlorophyll, and sub aquatic vegetation (SAV). Table 1 shows this data compared to thresholds set by the Chesapeake Bay Program [1]. This data shows that a significant portion of samples in water clarity, chlorophyll, and SAV do not meet the threshold levels.

Table 1: Current water quality conditions in WRR

Water Quality Indicator	Threshold	Samples meeting threshold			
		2009		2010	
Water Clarity	1m	11%	12%	4%	5%
DO	5 mg/L	49%	75%	58%	68%
N/P	0.65/0.037 mg/L	10%	13%	18%	21%
Chlorophyll	6.2 µg/L	0%	5%	8%	0%
SAV	298 Acres	0%	0%	0%	0%

Water clarity is one of the best indicators of water quality. Chlorophyll (stimulated by excess nutrients) and TSS reduce the distance that sunlight can travel through the water column. This lack of sunlight restricts the growth of SAV that is important for aquatic life because it provides habitat and produces dissolved oxygen. The last recorded existence of SAV in the Rhode River was in 1978 and minor amounts were recorded in the West River in 1994, 1998, and 2003. Due to the excess nutrients and TSS flowing in from the Chesapeake Bay, the Secchi depth (measurement of water clarity) in the WRR has significantly declined in recent decades by an average of 2 cm per year (Figure 1).

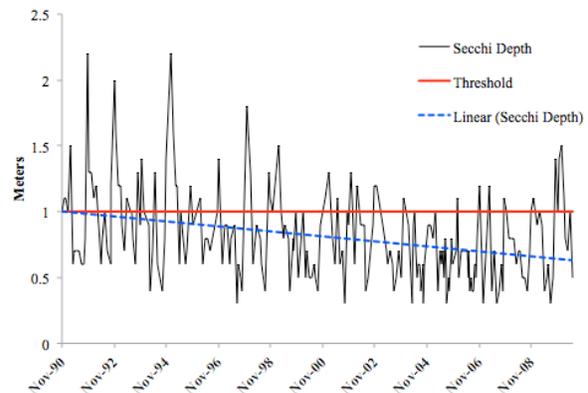


Fig. 1. Rhode River Secchi Depth [1]

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II. STAKEHOLDER ANALYSIS

The West and Rhode Riverkeeper Inc. is a community-supported, non-profit organization founded in 2005 whose mission is to stop pollution, enforce environmental laws, and promote restoration in the WRR. The local community and businesses in the WRR watershed exhibit complex relationships as they contribute to the pollution but benefit from improved water quality through increased commercial fishing, recreation, and property value.

III. STATEMENT OF NEED

A system is needed to increase the Secchi depth to at least one meter in the WRR so sunlight will stimulate SAV growth and the sub-estuaries will become a more habitable environment for aquatic life.

IV. DESIGN ALTERNATIVES

The alternatives considered in this study must be (1) able to survive in the WRR, (2) commercially available, and (3) indigenous to the Chesapeake.

A. Eastern Oyster (*Crassostrea virginica*)

Oysters are native to the Chesapeake and play an important role in the aquatic ecosystem because they filter nutrients and TSS from up to 0.19 m^3 of water per oyster per day, allowing light to reach the bottom [2]. Oysters are capable of surviving in a wide range of conditions, but they require a hard substrate on which to rest. Since the majority of the WRR bottom is mud/silt, oysters will require an additional substrate. Included in the evaluation of oysters is the evaluation of alternative substrate materials such as natural oyster shells, hard clam shells, concrete rubble, cement reefballs, and aquaculture cages. To reproduce in the spring, oysters require salinity concentrations of at least 10 ppt. and water temperatures greater than $20 \text{ }^\circ\text{C}$. In the spring, these conditions occur in the WRR 5% of the time [3] [4]. Oyster live up to 20 years; therefore, they are expected to reproduce once in their lifetime.

B. Soft-Shell Clams (*Mya arenaria*)

Clams are indigenous to the Bay, commercially valuable, and capable of filtering nutrients and TSS from up to 0.18 m^3 of water per clam per day [5]. Clams prefer a soft mud or silt substrate because they burrow into the substrate and filter water through a siphon. Once burrowed, clams are less susceptible than oysters to predators and poachers. Because the bottom of the WRR is primarily soft mud, clams do not require an artificial substrate. Unlike oysters, clams spawn twice a year, increasing the likelihood of successful reproduction in a given year to 30% due to the increase salinity concentrations in the fall. Clams live approximately 12 years, so they are expected to reproduce 4 times in their lifetime.

C. Living Shoreline Restoration (LSR)

LSR reduces erosion by fortifying existing shorelines and

provides a natural shoreline habitat for aquatic plants and creatures. LSR uses logs and underwater grasses to build a natural wall between the tidal action of a sub-estuary and the loose soil of its shoreline. LSR decreases TSS and nutrient runoff from the watershed, grounds TSS, and removes nitrogen from the water column.

V. METHOD ANALYSIS AND SIMULATION

The goal of this project is to find the design alternative, amount, and placement that would maximize the water quality in the WRR at minimum cost. A user-friendly 2-D Tidal Mixing Model (2DTMM) was developed to simulate the numerous configurations of alternatives varied by alternative type, placement, and amount. The configurations that showed the highest removal rates were then modeled in the Virginia Institute of Marine Science's (VIMS) Estuarine Eutrophication Model [3] [6].

The VIMS model was used to simulate improvements in dissolved oxygen concentrations and provide more precise water clarity calculations than the 2DTMM. The results from the VIMS model were used to determine the final water quality improvement utility value. The overall utility (public approval, sustainability, and water quality improvements) was then used to perform a cost/benefit analysis among the alternatives.

A. 2-D Tidal Mixing Model (2DTMM)

A 2DTMM was designed to predict the amount of nutrients and TSS removed from the WRR by the design alternatives, which act as sinks in the model. Since there are numerous different combinations of alternatives, placement, and amounts, it would be impractical to model all combinations in the complex VIMS model. Therefore, the 2DTMM was designed to determine which configurations should be modeled in the VIMS model. The model was developed in Java for portability and to meet the sponsor's requirements of usability and versatility.

The continuous tide flow process is modeled in discrete time steps of 1.5 hours. This duration was selected because the 6-hour flood and ebb tides cross a series of 4 cells in each river, shown in Figure 3. Note that the transitions from cells 7-8 and 7-9 occur simultaneously. The state variables in the model are recalculated after each time step and at the end of each tide cycle; the state variables are stored and used in the next tide cycle iteration. The inputs and outputs of the 2DTMM are shown in Figure 2, with N and P referring to nitrogen and phosphorus.

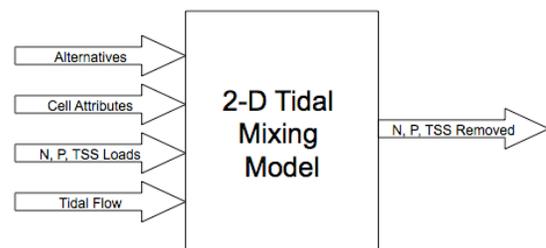


Fig. 2. Model Inputs and Outputs

The tide flow is calculated as the difference between the mean high tide and the mean low tide. Data from six months of high and low tides were used to determine that the mean difference in tide heights is 0.29 m. Also included in the tidal flow is the concentration of nutrients and TSS.

1) Model Assumptions

Model assumptions include: (1) tidal mixing in each cell occurs instantaneously, (2) complete turbulent mixing occurs, (3) wind shear is neglected, (4) the Chesapeake's volume is considered limitless, therefore the sub-estuaries' output concentrations do not affect the Chesapeake's concentration, (5) concentrations of nutrients and TSS are equally distributed within cells, (6) filter-feeders are adult-sized, and (7) filter-feeding alternatives are distributed uniformly within the cell.

2) Cell Partitions

In order to model the dynamic exchange of water throughout the WRR, the sub-estuaries were segmented into cells (Figure 3) in coordination with the VIMS model. The Rhode River contains cells 1 through 4 and the West River contains cells 5 through 9.

Based on data from the West and Rhode Riverkeeper's monitoring program from 2007 to 2010, the average salinity, dissolved oxygen, and water temperature was calculated for each cell [7]. These attributes are important because they affect the clearance rates of the bivalves. TSS is used in the calculation of the clearance but is not included as a cell attribute since TSS concentrations are dynamic and recalculated during the simulation. Other cell attributes included cell volume, tide volume, and nutrient loads.

Cell and tide volumes were calculated in coordination with VIMS through GIS analysis from the Chesapeake Bay's bathymetric grid data.

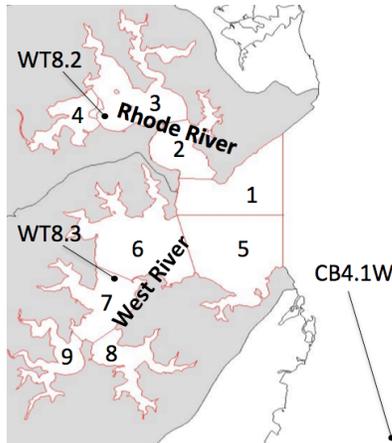


Fig. 3. Cell Breakdown

3) Modeling Equations

The model equations for the tidal flow of water being exchanged by cells are the same for all concentration measurements [8] [9]. The following example shows the nitrogen concentration calculation for the flood tide (equation 1) and ebb tide (equation 2). Watershed inputs are

added between time steps and are not included in the fluid transfer equations. The model uses similar equations for the West River. Phosphorus and TSS have similar sets of equations.

Table 2: 2-D Tidal Model Equation Variables

Variable	Description
V_n	Volume of Cell n (L)
T_n	Tide volume of Cell n (L)
$N_{n,i}$	N con of Cell n for time step i (mg/L)
$S_{n,j}$	Sink amount in Cell n of type i
F_{MC}	River volume (L)
B_N	Bay Concentration of N (mg/L)
R_N	River Concentration of N (mg/L)
CR_j	Clearance rate of sink i (L/ts)

$$N_{n,i+1} = (N_{n,i} \cdot V_n + N_{n-1,i} \cdot T_n - S_{n+1,j} \cdot CR_j) / (V_n + T_n) \quad (1)$$

$$N_{n,i+1} = (N_{n,i} \cdot (V_n - T_n - F_{MC}) + F_{MC} \cdot N_{n+1,i} - S_{n,j} \cdot CR_j) / (V_n + F_{MC}) \quad (2)$$

4) Clearance / LSR Prevention Rate Equations

Clearance rate refers to the rate at which bivalves filter water. This rate differs between species and can be dependent on bivalve size, TSS concentration, salinity, dissolved oxygen, and water temperature. The maximum clearance rates of oysters and clams are similar, but the difference in the individual cell parameters affects the optimal placement location. Since the TSS concentration is dynamic, the clearance rates are recalculated after every time step.

Oyster clearance rates (L/hr), shown in equations 3-8 are a function of size $f(\max CR)$, salinity $f(S)$, dissolved oxygen $f(DO)$, TSS concentration $f(TSS)$, and water temperature $f(WT)$ [10].

$$\text{oyster } CR = f(\max CR) \cdot f(S) \cdot f(DO) \cdot f(TSS) \cdot f(WT) \quad (3)$$

$$f(\max CR) = (0.55 \text{ m}^3 \text{ g}^{-1} \text{ oyster carbon d}^{-1}) \quad (4)$$

$$f(S) = 0.5 \cdot (1 + \tanh(S - 7.5)) \quad (5)$$

$$f(DO) = \left(1 + \exp(3.67 \cdot (1.0 - DO))\right)^{-1} \quad (6)$$

$$f(TSS) = \begin{cases} 0.1 & \text{when } TSS < 5 \text{ g m}^{-3} \\ 1.0 & \text{when } 5 \text{ g m}^{-3} < TSS < 25 \text{ g m}^{-3} \\ 0.2 & \text{when } 25 \text{ g m}^{-3} < TSS < 100 \text{ g m}^{-3} \\ 0.1 & \text{when } TSS > 100 \text{ g m}^{-3} \end{cases} \quad (7)$$

$$f(WT) = \exp(-0.015 \cdot (T - 27)^2) \quad (8)$$

Clam clearance rates (L/hr), shown in equations 9-12, are determined by clam size $f(\max CR)$, water temperature $f(WT)$, and TSS concentration $f(TSS)$ [5] [11].

$$\text{clam } CR = f(\max CR) \cdot f(WT) \cdot f(TSS) \quad (9)$$

$$f(\max CR) = 0.0007 \cdot L^{2.47}, \quad 21 \text{ mm} \leq L \leq 45 \text{ mm} \quad (10)$$

$$f(WT) = 0.03 \cdot WT + 0.33 \quad (11)$$

$$f(TSS) = -0.189 \cdot \ln(TSS) + 1 \quad (12)$$

LSR prevents nutrients and TSS from entering a body of

water. The plants in the LSR also remove small amounts of nitrogen from the water column, but according to the Smithsonian Environmental Research Center (SERC), this amount is negligible and therefore was not modeled. The LSR prevention rates, shown in equations 13-15, are constant and were obtained from the average prevention rates of 258 LSR projects in Maryland [12]. These rates were converted to amount of nutrients and TSS prevented from entering the water per meter of LSR per time step.

$$Np\text{ prevention rate} = 60 \text{ mg leng h(m) hr}^{-1} \quad (13)$$

$$Pp\text{ prevention rate} = 45 \text{ mg leng h(m) hr}^{-1} \quad (14)$$

$$TSSp\text{ prevention rate} = 72 \text{ kg leng h(m) hr}^{-1} \quad (15)$$

5) Model Verification and Validation

The first step in the model verification and validation plan was to run baseline simulations to ensure that the model responds in a predictive manner. The baseline simulation shown in Figure 4 includes a freshwater stream input in cell 4 and a surge of nitrogen from the Bay in tide cycles 100-104. This surge is intended to represent a surge in nitrogen released from the Susquehanna River [13] [14]. Cell 1 shows a sharp spike in nitrogen concentration in response to the surge because it is closest to the bay. Cell 2 showed a slightly delayed and moderate spike in nitrogen concentration. This is due to the nitrogen traveling through and mixing in cell 1 before it gets to Cell 2. Cells 3 and 4 have smaller, and even more delayed spikes in nitrogen than cells 1 and 2. This simulation shows that the model responds in a predictive manner to the nitrogen surge.

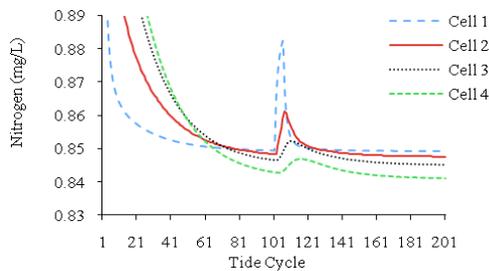


Fig. 4. Baseline Simulation with Nutrient Spike from Bay

The model was validated by comparing the predicted nitrogen concentrations against the observed values from March–November 2005. This period was selected because it contained the most comprehensive set of sampling data. The observed data (sampled weekly) was taken from points WT8.2 and WT8.3 within the WRR (Figure 3) [1]. Inputs to the model were the Chesapeake nitrogen concentration, point CB4.1W in Figure 3 (sampled monthly), and the watershed nitrogen load. The Chesapeake nitrogen input between monthly samples was assumed to be a linear transition. Figures 5 and 6 show the comparison of the actual versus the predicted values. The relative error of the model is 7.3% and 15.6% for the West and Rhode Rivers, which is

acceptable since the Chesapeake Bay nitrogen concentration input was only provided once a month. The likely reason the Rhode River is less accurate than the West is due to its larger watershed nitrogen input.

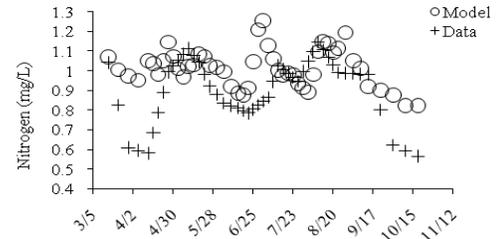


Fig. 5. Rhode River model validation

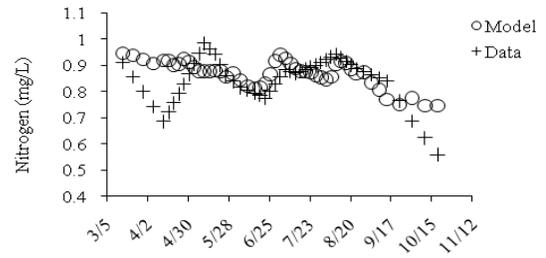


Fig. 6. West River model validation

B. VIMS Model

The VIMS model is an estuarine eutrophication model that is specifically calibrated to the WRR (Figure 7) [6]. It predicts the effects of nutrients and TSS on a tidal estuary ecosystem. Specifically, this model provides Secchi depth predictions that are important in determining the overall water quality improvements. The inputs to the VIMS model are temperature (TEMP), salinity (S), and sunlight (PAR), and the outputs are biological oxygen demand (BOD) and macroalgal grazers (GZR).

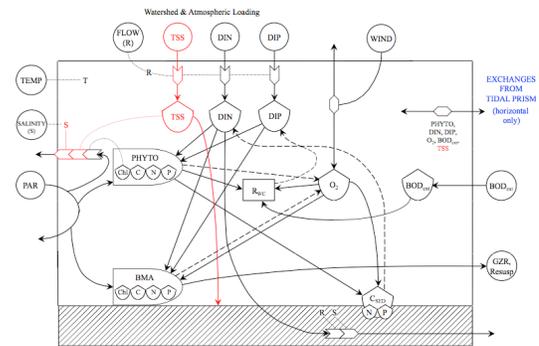


Fig. 7. VIMS Estuarine Eutrophication Model [6]

C. Utility Function

The utility function (equations 16-19) was developed through numerous conversations and interviews with the Riverkeeper, stakeholders, and ecologists. Although the fundamental objective is to maximize water quality, the solution must also be sustainable and supported by the stakeholders. The top-level weights for stakeholder approval, sustainability, and water quality were determined

in an interview with the Riverkeeper using the swing weight method. Dr. Brush from VIMS and ecologists from SERC recommended that the most important indicator of water quality was water clarity. Because the 2DTMM does not calculate water clarity, the TSS and nutrient concentrations were used as proxies and were weighted equally. The nutrients were also weighted equally. The VIMS model output includes water clarity estimates, which were used for the final utility and cost/benefit analysis. Sustainability and stakeholder approval were weighted equally based on recommendations from the Riverkeeper, Dr. Brush, and SERC.

$$utility = 0.33 \cdot Sa + 0.30 \cdot Su + 0.37 \cdot Wq \quad (16)$$

$$Sa = 0.5 \cdot (Pa + Cv) \quad (17)$$

$$Su = 0.44 \cdot Re + 0.22 \cdot Pe + 0.22 \cdot Di + 0.12 \cdot Pd \quad (18)$$

$$Wq = 0.5 \cdot TS.S + 0.25 \cdot N + 0.25 \cdot P \quad (19)$$

D. Optimization Process

To determine which alternative and cell combinations provided the greatest overall water quality improvements, simulations were run with oyster, clams, and LSR in every cell ranging from 1-40 million bivalves and 100-4000 meters for LSR. Each simulation was completed in separate runs for each alternative and only in one cell at a time.

The water quality improvement results were weighted with the stakeholder approval and sustainability for each combination to determine its overall utility. The highest utilities for each design alternative were simulated in the VIMS model to determine final water clarity improvement.

VI. RESULTS

A. Modeling Results

1) 2DTMM Model Results

Figure 8 shows the system-wide weighted percent removed by adding 10 million oysters/clams or 1000 meters of LSR in each cell. Cells 2 and 3 have the highest returns in the Rhode River and cells 6 and 7 provide the highest returns in the West River. As the number of alternatives is increased, the weighted percent removed increases but does so at a diminishing rate. This can be seen in Figure 9 and is because there is less N, P, and TSS to filter. The optimal placement location does depend on the amount oyster/clam.

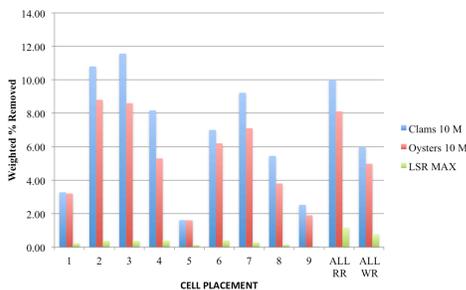


Fig. 8. Weighted Percent Removed

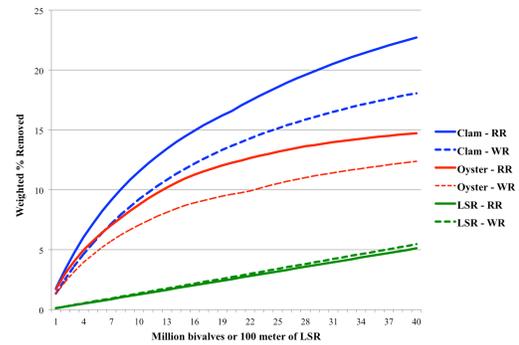


Fig. 9. Alternatives: Weighted Percent Removed

2) VIMS Model Results

The results from the VIMS model support the results from the 2DTMM. The VIMS model also confirms that clams increase the Secchi depth better than oysters and LSR in all cells due to their higher average clearance rate, although the optimal locations differ. In the VIMS model, optimal single cell placement was cell 2 in the Rhode River and cell 7 in the West River, while in the 2DTMM, optimal placement was cells 3 and 7, followed closely by cells 2 and 6. Figure 10 shows the system-wide increase in Secchi depth for single-cell placement of 10 million oysters or clam or the maximum amount of LSR.

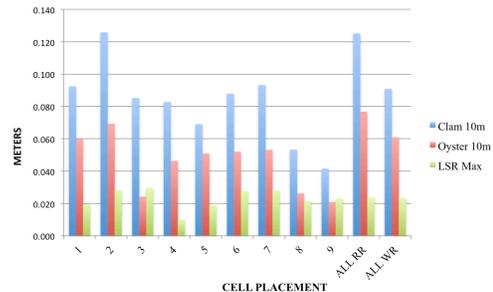


Fig. 10. VIMS: Increase in Secchi Depth

B. Cost / Benefit Analysis

A cost analysis for each alternative was conducted. For the oysters, separate cost analyses were conducted for alternative substrates, oyster shell, hard clamshell, reef balls, concrete rubble, and cages. The most cost effective substrate for oyster was the hard clamshells; this cost plus the cost of oyster spat totals \$52k-\$91k per million oysters. The majority of the variance in cost is due to the survivability of the oyster spat. According to Dr. Gauss from Project Oyster West River, up to 90% of spat die when they are placed in the rivers.

LSR cost estimates range from \$16k-\$164k per 100 meters depending on the location's water depth, ease of access, and the tidal energy level. Higher energy areas need more buffering structures to prevent erosion.

Soft-shell clams cost range from \$27k-\$35k. Included in this cost is the mesh netting that will protect the juvenile clam from predators.

Figure 11 displays the cost versus utility of all three alternatives using the VIMS results for water quality improvement. The horizontal error bars show the variance in cost for each alternative.

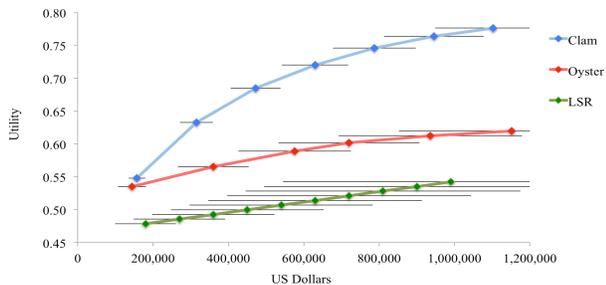


Fig. 11. Cost / Benefit Analysis

C. Sensitivity Analysis

A sensitivity analysis was conducted for the weights used in the utility and the values in the stakeholder approval and sustainability attributes. Top-level weight sensitivity showed that the stakeholder approval weight must increase 67% or the water quality improvement weight must decrease 92% for oysters to be the most cost effective alternative. The sustainability weight must increase 150% for LSR to be the most cost-effective alternative. Lower-level weight sensitivity showed that no change would alter the outcome. The clams' attribute values for "commercially valuable" and "reproduction" must decrease by 0.75 and 1.0 to alter the outcome.

VII. DISCUSSION AND RECOMMENDATIONS

LSR provides little improvement in Secchi depth since the majority of turbidity enters the river from the Bay rather than from the shoreline. Oysters require an additional substrate, significantly increasing their cost compared to clams or LSR. Due to oysters' low filtration rates in cold temperatures, they filter less water than clams. Additionally, the clams' ability to spawn in the spring and fall makes them four times more likely to reproduce than oysters. Therefore, clams are the superior alternative due to their sustainability, filtration rates, and cost.

It is recommended that a two-phase implementation plan be carried out over 10 years. Phase I should consist of annual placements of 1 million soft-shell clams into the WRR into cells 2 and 7. Weekly water quality samples should be taken throughout both phases. A sustainability survey should be conducted annually in both phases to ensure that the clams are able to adapt to the environment. A detailed population survey should take place at the end of year five to determine reproduction rates. Phase II should consist of annual placements of 1 million soft-shell clams which would be discontinued once the population is self-sustaining.

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