

Design and Analysis of a Sustainable Oyster Aquaculture Business for the West and Rhode Rivers

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Abstract— The water quality in the West and Rhode Rivers (WRR), two mezohaline sub-estuaries of the Chesapeake Bay, has declined due to local runoff of excess nutrients and total suspended solids (TSS) entering from the Chesapeake Bay. Previous research identified the feasibility of using large colonies of bi-valves (e.g. oysters or clams) in the river to remove the excess nutrients. Based on this research, an experiment conducted by the Smithsonian Environmental Research Center failed to establish a colony of clams due to naturally arising variability in salinity levels. Unlike clams, oysters are resilient to variations in naturally occurring environmental conditions, however, due to a lack of frequent reproduction by the oysters they are unable to build and sustain a viable oyster colony with critical mass. The goal of this paper is to evaluate the feasibility of a self-sustaining oyster colony, by harvesting a portion of the colony to fund the purchase of additional oyster.

Design alternatives were evaluated for growing the colony (i) Remote Setting aquaculture, (ii) Nursery aquaculture, and (iii) Spat-on-shell aquaculture), and for distribution of the oyster product (shucked, half-shell). Three models were used to evaluate these design alternatives; (1) an oyster growth model to simulate the growth rate and survivability of oysters using stochastic environmental variables, (2) a 2D Tidal Mixing Model (2DTMM) to simulate the dynamic flow of nutrients and sediment within the WRR, and (3) a financial model to simulate the sustainability of an oyster aquaculture business with deterministic prices and demand.

An analysis of cost versus utility (sustainability, public approval) shows that a 10 million remote setting aquaculture system sold at half shell would be the most cost-effective and sustainable alternative.

I. INTRODUCTION

THE West and Rhode rivers are two sub-estuaries of the Chesapeake Bay which contain 26 million cubic meters of water. The watershed covers 78 square kilometers and has an average depth of 2 meters. Fresh water flows into the Chesapeake Bay from the Susquehanna River and is mixed with salt water flowing up from the Atlantic, causing constant fluctuations in the salinity of the water.

Excess sediment and nutrients, which mostly flow into the sub-estuaries with the tide, as well as run-off sediments from the land, have over time increased turbidity which has

caused a decrease in the secchi depth of the rivers. Secchi depth is the measure of the clarity of water. As a result, sub aquatic vegetation (SAV) are not receiving proper sunlight and oxygen to sustain life. In 2010, no under-water grasses were found in the rivers from samples taken [1].

A study in turbidity reduction in 2011, determined the best ways to filter the water and increase the secchi depth. The proposed solutions were clams, oysters, and living shoreline restoration with clams as the recommended solution due to continued filtering in cold temperatures and the ability to reproduce in the fall and spring. Oysters were ranked second due to low filtering in cold temperatures, low probability of reproducing, and high costs to place oysters on river bottom. Living Shoreline Restoration was significantly below the two filter feeders in reduction of turbidity [1].

Based on the recommendations the Smithsonian Environmental Research Center implemented a pilot project in the summer of 2011. All of the clams died due to low salinity in the rivers. However, oysters in the same river in an unrelated study did not die under the same conditions in the summer [12].

Unlike clams, oysters are known to be more resilient to varied and low salinity changes. Oysters in the Chesapeake Bay are at 1% of historic levels since the 1860's due to overharvesting and most recently disease which has also contributed to the low probability of the reproduction of oysters. To mitigate these problems private aquaculture business are used to protect property rights and to grow oysters yearly through aquaculture methods [2].

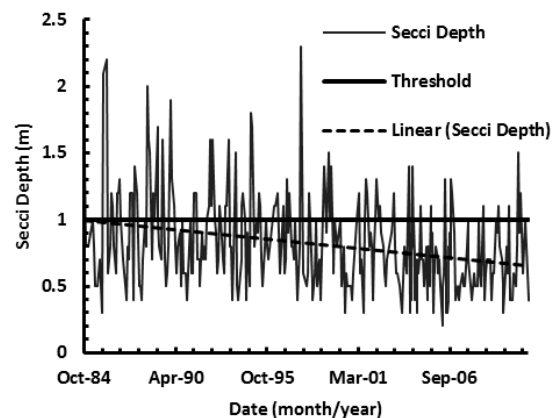


Fig. 1. Secchi Depth of Rhode River (1984-2011) has steadily decreased and the max values have started peaking at lower values than historic values.

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II. STAKEHOLDER ANALYSIS

A. West Rhode Riverkeeper Inc.

West/Rhode Riverkeeper Inc. is a non-profit organization established in 2005 with the mission to reduce pollution, enforce environmental laws, and promote restoration in the West and Rhode rivers. The organization is funded through grants and the community through fundraisers and donations.

B. Maryland Watermen

The local Maryland Watermen are citizens who make a living from fishing/harvesting fish, crab, and oysters from the Chesapeake Bay and its tributaries. Once a prosperous industry, currently Maryland has seen a decline in working watermen due to overharvesting and environmental changes. As excess nutrients and sediment runoff into the Chesapeake Bay, aquatic species have been affected by the ecological decline in sub aquatic vegetation. In response to this change, watermen require new methods to continue earning an income from the Chesapeake Bay.

C. Maryland Department of Natural Resources

The Maryland Department of Natural Resources (MDDNR) governs the Chesapeake Bay and its tributaries, as well as manages the coastal regions. In addition to regulating the use of the waters, the MDDNR also promotes and supports the aquaculture enterprise. Through providing leases and loans for local watermen, the MDDNR plays an active role in sustaining the profitability of aquatic harvesting in Maryland. The objective of the MDDNR is to regulate Chesapeake waterways, as well as support the aquaculture industry.

D. Watershed Residents

The residents surrounding the West and Rhode Rivers support the restoration and protection of the water; however, they also contribute excess runoff through yard and storm water drainage. Construction sites, fuel stations, and boating communities also contribute to this nutrient runoff and sediment erosion. With the creation of the West/Rhode Riverkeeper Inc. these negative impacts have been measured and solutions to reducing environmental impact have been publicized over the past decade.

E. Stakeholder Tensions

The W/R Riverkeeper Inc. and the MDDNR have limited resources and funding with which to implement sustainable projects to clean the river and improve the water quality. The Watermen have little incentive to clean the rivers because there is no financial benefit to doing so. The local residents continue to use the waterways and contribute to pollution, but also have little incentive to fund or work to clean the river.

Oyster aquaculture is a way to merge the needs and objectives of the stakeholders and create a win-win solution financially and for the environment. Introducing oysters into the river will help remove excess nutrients. Implementing

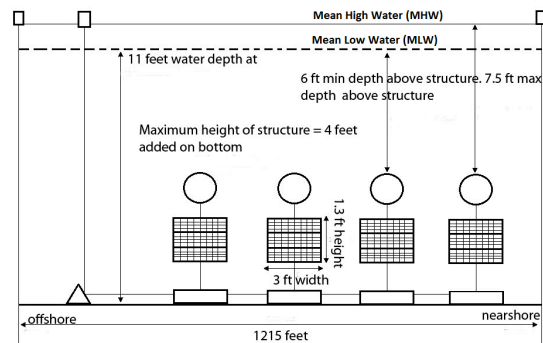
the oysters through aquaculture provides a way for watermen to make money from the process and creates an incentive to protect the oysters and keep them alive. Oyster aquaculture overcomes the limited resources and budget of the W/R Riverkeeper Inc. and the MDDNR while helping the Watermen with employment and income.

III. STATEMENT OF NEED

There is a need for an oyster aquaculture system in the West and Rhode River to reduce nitrogen and sediment and to be financially sustaining, with a positive return on investment within 5 years.

IV. DESIGN ALTERNATIVES

Due to the reduced filtering which occurs for bottom feeding oysters, a vertical cage system will be used in order to maximize filtration. The cage system will be based on a previous study and allow for optimal oyster filtration rates [16].



Tray with max dimension (L/W/H)= 4 feet x 3 feet x 1.3 feet

Fig. 2. Vertical Cage Design – The cages will be anchored to the river bottom with deadweight anchors and lifted with trawl floats. The cages will consist of triple stacked trays capable of holding 3000 market size oysters.

A. Method of Grow-Out

The first alternative, **remote setting**, is a land based operation requiring large tanks (size can vary but we assume 3,000 gallon tanks for this study) with cages to hold the shell to which the oysters will attach. The process takes approximately ten days before the oyster can be placed in the river [10].

The second alternative, **nursery**, requires bucket and floating upwelling systems for initial growth. The seed is placed in the buckets with micro-cultch or crushed shell. The seed each attach to attach to a piece of cultch. The process requires approximately twenty-one days until the oysters are ready to be placed in the river [13].

The third alternative, **spat-on-shell**, comes from the hatchery and are ready to immediately be placed in the river.

B. Method of Sale

In addition to the method of grow-out alternatives, oysters can be sold as a half-shelled or shucked oyster.

The first sale alternative, **half-shell oyster**, typically sells between 0.60 to 0.70 dollars per oyster. Half-shell oysters

can be sold to restaurants to be served. Depending on quality and packaging the oysters can also be sold in a range of prices up to 1.50 dollars.

The second sale alternative, **shucked oyster**, has the meat of the oyster removed from the shell. The price is typically much lower around 0.06 to 0.20 dollars.

V. METHOD OF ANALYSIS

The method of analysis (shown in Fig. 3) includes evaluating the growth and survivability of the three design alternatives for harvesting the oysters in the growth model, then evaluating the amount of nutrients and sediment filtered with the GMU Two Dimensional Tidal Mixing Model (2DTMM) [1] while evaluating the financial feasibility in the business model. Next the design alternatives are evaluated by using a utility function, and finally the utility is compared to cost.

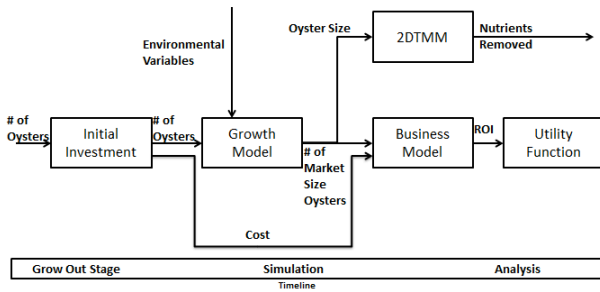


Fig. 3. Method of Analysis – The input for the simulation is the number of oysters. The growth model outputs the number of oysters into the 2DTMM to estimate the amount of nutrients and sediment removed. It also outputs to the business model to then calculate the profit from selling the oysters and the utility function.

A. Growth Model

A mass-balance model was used to calculate the change in oyster growth over time. Oyster biomass is based on grams of organic carbon incorporated in soft tissue per unit area using (1). The change is computed using the oyster biometric variables, shown below and determined based on similar studies on oyster growth rate in the Chesapeake Bay [9].

TABLE I
GROWTH MODEL VARIABLES

Symbol	Description	Value
α	Assimilation Rate ($0 \leq x \leq 1$)	0.77
Fr	Filtration Rate ($m^3 g^{-1} C d^{-1}$)	See (2)
POC	Particulate Organic Carbon (mg/L)	$N(\mu, \sigma^2)$
IF	Fraction Ingested ($0 \leq x \leq 1$)	0.12
RF	Respiratory Fraction ($0 \leq x \leq 1$)	0.1
O	Oyster Biomass (g C)	$\ln N(\mu, \sigma^2)$
BM	Basal Metabolic (d^{-1})	0.008
β	Mortality Rate (d^{-1})	0.0026

$$\frac{dO}{dt} = O \cdot (\alpha \cdot Fr \cdot POC \cdot IF(1 - RF)) - O \cdot (BM - \beta) \quad (1)$$

For the growth model's time (t) variable, time steps are calculated in days. The oyster growth rate will be subject to

the environmental variables (T) temperature, (DO) dissolved oxygen, (S) salinity, (TSS) total suspended solids, and (POC) particulate organic carbon ($g m^{-3}$). The mortality rate is assumed to only take into account mortality from hypoxic conditions and predation, as disease will not affect our design since we will be harvesting oysters for profit at a span of 3-5 years from spat [13]. Due to the stratification of the environmental variables (such as temperature, DO, salinity, and TSS), the growth model will be assumed to have evenly mixed values throughout the total depth of the water column. This assumption is based on water quality data taken while out on the West and Rhode Rivers at two separate dates in order to avoid correlated data.

$$Fr = f(S) \cdot f(DO) \cdot f(TSS) \cdot f(T) \cdot Fr_{max} \quad (2)$$

The filtration rate of the oysters is determined through the oyster's dependence on the water temperature, total suspended solids, salinity, and dissolved oxygen in the water (shown in (2)). These relationships, shown in (3) – (6), are multiplied by the oyster's max filtration rate, known to be $0.55 m^3 g^{-1} d^{-1}$ [4]. Due to the oyster's sensitivity to variations in these variables, the growth model is run using stochastic environmental variables representing the West and Rhode Rivers calculated from MDDNR water quality data taken over the past 26 years [14].

$$f(S) = 0.5 \cdot (1 + \tanh(S - 7.5)) \quad (3)$$

$$f(DO) = \left(1 + \exp(3.67 \cdot (1.0 - DO))\right)^{-1} \quad (4)$$

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

$$f(WT) = \exp(-0.015 \cdot (T - 27)^2) \quad (6)$$

The growth model was run for a period of 10,000 iterations, and then evaluated at a confidence interval of 95% to determine the probability of an oyster reaching market size within the West and Rhode Rivers within 1-5 years.

B. Validation and Verification

The growth model was validated through comparison of the salinity and dissolved oxygen random variable output with the average values taken monthly from the Rhode River over the past 26 years. The random variables were based on a normal distribution with associated mean and standard deviation for each month of the year. The growth model was run a total of 1,000,000 iterations in order to ensure statistically significant model values when comparing to the data ($\alpha = 0.01$). Figures 4 and 5 show the data sets evaluated for dissolved oxygen and salinity. The relative error between the model and data points was found to be 26.7% for dissolved oxygen and 18.2% for salinity. The large error in

dissolved oxygen can be attributed to the difference between watershed DO levels and bay DO levels, as the model used data from Horseshoe Point (CB4.1W in Fig. 6) for variable generation whereas the validation data is taken from the Rhode River station (WT8.2 in Fig. 6).

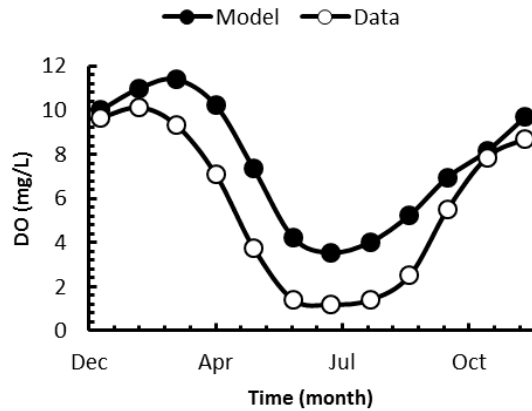


Fig. 4. Dissolved Oxygen values calculated for one year versus observed values.

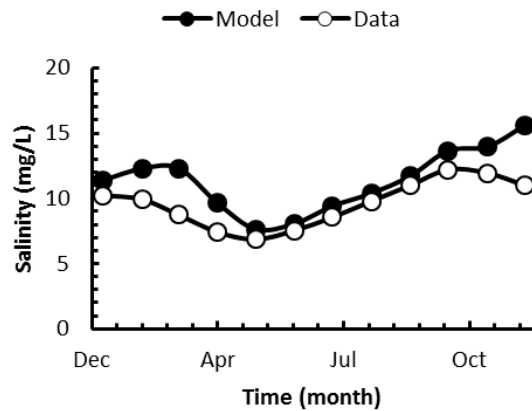


Fig. 5. Salinity values calculated for one year versus observed values.

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

A two-dimensional tidal mixing model was adapted from a previous study [1] to predict the amount of nutrients and TSS removed from the WRR by the design alternatives, which act as sinks in the model. 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. Note that the transitions from cells 7-8 and 7-9 occur simultaneously. The nutrient concentrations and sink rates in the model are recalculated after each time step and at the end of each tide cycle; these variables are then stored and used in the next tide cycle iteration. These transitions can be seen in the cell breakdown shown in Fig. 6; the data points listed (WT8.2/CB4.1W) are water quality monitoring stations from which nutrient data was measured. The selected site location for this study is in cell one. This location was selected due to current restrictions in aquaculture leases in the West and Rhode Rivers.

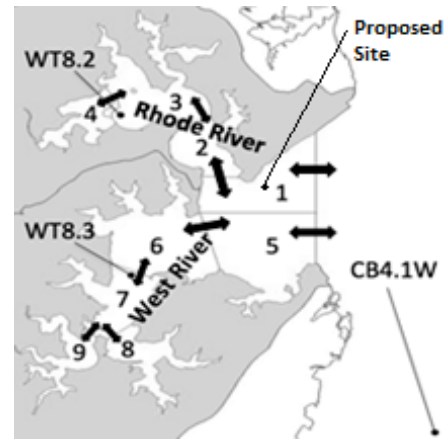


Fig. 6. 2DTMM Cell Breakdown – The proposed aquaculture site would be placed in cell 1. Tidal flow occurs between each cell as labeled on the figure.

D. Business Model

The business model is used to calculate the financial aspects of the aquaculture business including the initial investment, costs, revenues, loan payments, and the net present value of the investment. The cost of buying the oysters and shell is assumed to be funded by a loan taken from the MDDNR. The loan is for five years with the first three years interest only and 40% forgiveness at the start of the fourth year. The initial cost of equipment capital will be an upfront investment from the watermen or can be a loan taken from a separate bank.

As the growth model runs, the output is used to determine costs and revenues in the business model. The planting of oysters will be broken up over the five years in order to result in revenue yearly after the first oysters have initially grown out and been sold. For example, if one million oysters are desired, 200,000 will be planted each season.

The oysters are harvested and are assumed to be sold the same season they reach market size. The oysters that have been sold are also replaced the same season in addition to the numbers which are planted on a seasonal basis. Table II illustrates the costs for each alternative for one year for 200,000 oysters.

TABLE II
COST OF ALTERNATIVES

Cost	Remote Setting	Nursery	Spat-on-Shell
Oysters & Shell	\$516	\$3,600	\$1,600
Annual Grow-out Labor	\$23,110	\$14,300	\$0
Annual Cleaning	\$720	\$1,920	\$2,570
Equipment Capital	\$23,313	\$23,313	\$23,313
Annual Cages & Setup	\$8,020	\$8,020	\$8,020
Total Costs	\$55,679	\$51,153	\$35,503

VI. RESULTS

A. Growth Model Results

The results of the growth model are shown in Fig 6. The cumulative distribution function shows there is a 79%

probability of oysters reaching market size within three years. Due to the stochastic nature of the Rhode River's salinity and dissolved oxygen levels, the risk of no market size oysters within 3 years is 21%, where there will be no revenue from harvesting the oysters. The effect of the growth model can be seen in Fig. 9, which is a graph of the average expected ROI in the fifth year.

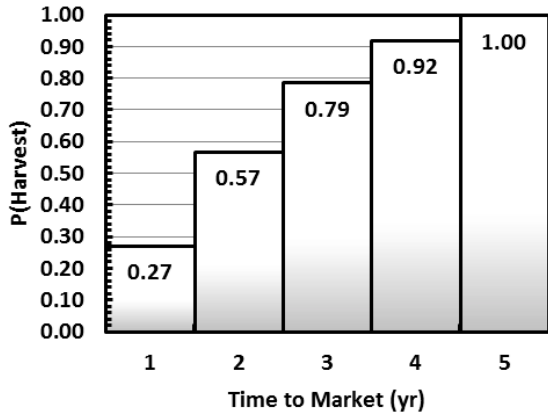


Fig. 7. Cumulative Probability of time for oysters to reach market size by three years with a 79% frequency

B. 2DTMM Model Results

The results of the 2DTMM model are shown in Fig. 8. The model was first run with an aquaculture system of 1 million oysters and the second being an aquaculture system of 10 million oysters. The percent amount of TSS removed from the West and Rhode Rivers was calculated over the length of 5 years. The output indicates up to a 1.66% reduction and 10.36% reduction in the Rhode River for a 1 million and 10 million oyster system, respectively. Due to placement of the oysters in cell one, the percent reduction was negligible in the West River.

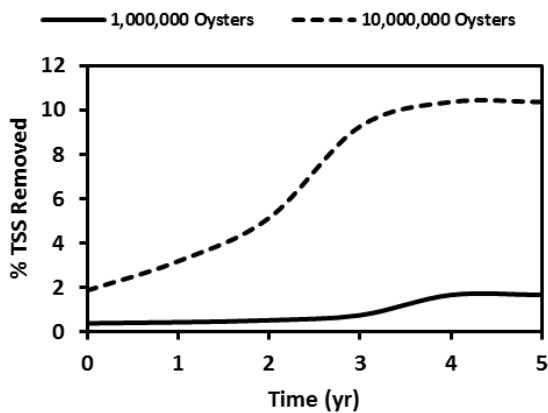


Fig. 8. 2DTMM model output. Rhode River levels shown only.

C. Business Model Results

The business model shows remote setting, sold as half-shell, result in the highest ROI in five years. All of the alternatives sold as half-shell result in a positive ROI in five

years. The alternatives sold as shucked do not return a positive ROI until run at a scale of 500,000 oysters or more. The price of shucked oysters would need to increase to at least 0.30 dollars to be on a comparable level of ROI as the half-shell method. The ROI for remote setting for 0.1 million oysters is 0.90 and increases to an upper limit with an ROI of 5.48 at ten million oysters.

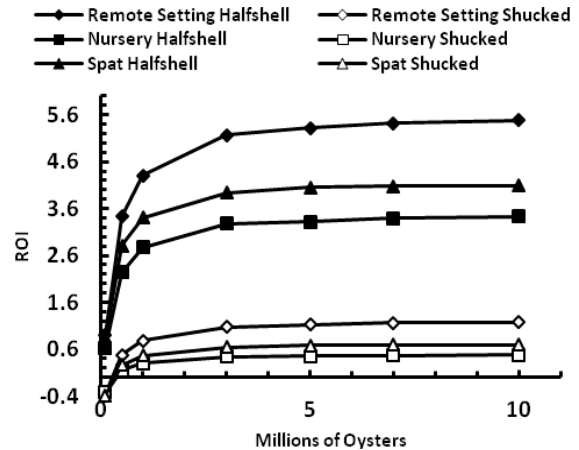


Fig. 9. Average ROI in 5 Years for Each Alternative over varied amounts of oysters

D. Business Model Sensitivity Analysis

The variables which have the greatest effect on the ROI are the selling price of the oysters and the price of the vertical cages. A 30% change in the selling price results in an approximately 35% increase or decrease in the ROI. Even with a decrease in selling price, the ROI is still positive. A decrease in the cage price results in a 27% increase in ROI.

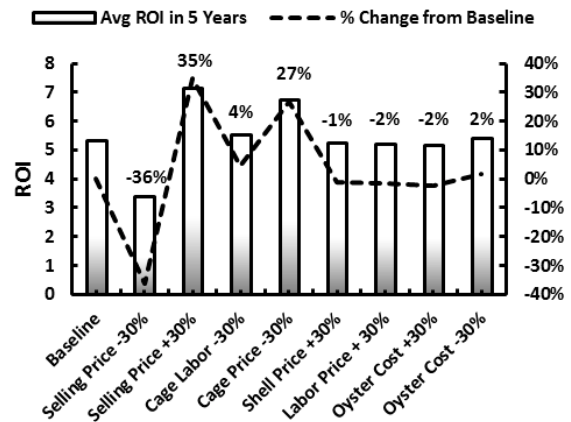


Fig. 10. Average ROI in 5 Years for Remote Setting sold as Half-Shell - Baseline year has half-shell sold for 0.60 cents per oyster. All variations are done at 30% increase or decrease of the baseline price.

E. Utility Function

The three components of the utility are the return on investment, availability of shell, and public approval. The return on investment accounts for the financial aspect of the project. The availability of shell is essential because shell is scarce and sometimes difficult to obtain. In these years,

remote setting and spat-on-shell will be most adversely affected. The nursery phase is more resilient to change as it requires crushed shell and uses much less shell. Public approval is essential because all adjacent landowners must approve of a project before a permit will be awarded. The nursery phase requires equipment visible on the shoreline and remote setting uses land based operations, but spat-on-shell require no additional equipment besides the floating cages in the river. The weights for the utility were determined through discussion with aquaculture experts and our project sponsor, the West/Rhode Riverkeeper, Inc.

$$U(x) = 0.25 \cdot Pa + 0.75 \cdot Su \quad (7)$$

$$Su = 0.60 \cdot Roi + 0.40 \cdot Sa \quad (8)$$

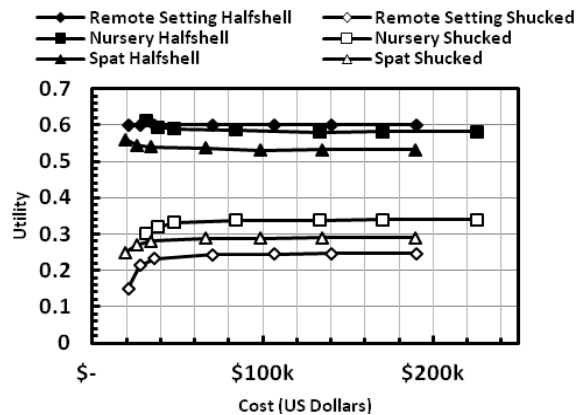


Fig. 11. Cost vs. Utility Analysis

The results from the utility function show remote setting sold as half-shell as the best alternative. Remote setting always results in the highest ROI over the six alternatives. However, if the weight on public approval drops two percent or availability of shell increases five percent the nursery option becomes the recommended alternative for all costs. If public approval increases to above forty percent, the spat-on-shell alternative becomes the proposed solution.

VII. DISCUSSION AND RECOMMENDATIONS

Based on the current analysis of oyster growth in the West and Rhode Rivers and business operation finances, an oyster aquaculture business is a financially self-sustaining operation to help reduce the excess nutrients in the Rivers. An aquaculture operation is feasible for all of the alternatives above 0.5 million oysters. The amount of total suspended solids removed is ten times greater with ten million oysters than with one million oysters.

It is recommended a remote setting stage oyster aquaculture system be implemented in the West and Rhode Rivers to increase the water quality while providing a financially self-sustaining business for local watermen if sold as half-shell. While any operation above 0.5 million oysters will increase the water quality, ten million oysters will result in the largest impact on water quality and highest ROI within five years.

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