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

Amy Crockett - Amir Delsouz - John DeGregorio - Alan Muhealden - Daniel Streicher
Agenda

- Context
- Problem/Need Statement
- Design Evaluation
- Design Alternatives
- Simulation and Modeling
- Recommendations
- Project Plan
West and Rhode Rivers (WRR)

- Two sub-estuaries of the Chesapeake Bay
- Contain approximately 53 million cubic meters of water, average depth is 2 meters.
- Watershed covers 78 square kilometers (J. Askvig et al. 2011)
## Current Water Quality of WRR

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>THRESHOLD</th>
<th>WEST RIVER % of samples</th>
<th>RHODE RIVER % of samples</th>
<th>GRADE AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Clarity/Secchi Depth</td>
<td>&gt; 1 m</td>
<td>30%</td>
<td>30%</td>
<td>D</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>&gt; 5 mg/L</td>
<td>73%</td>
<td>92%</td>
<td>A -</td>
</tr>
<tr>
<td>Nutrients (N/P)</td>
<td>&lt; 0.65 mg/L</td>
<td>47%</td>
<td>46%</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.037 mg/L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>&lt; 6.2 μg/L</td>
<td>47%</td>
<td>40%</td>
<td>C -</td>
</tr>
<tr>
<td>Underwater Grasses</td>
<td>&gt; 1.2 km²</td>
<td>0%</td>
<td>0%</td>
<td>F</td>
</tr>
</tbody>
</table>

Eutrophication Process

Excess Nutrients

Algae Bloom

Increased Turbidity

SAV* Growth Prevented

Hypoxic Conditions

Aquatic Species Mortality


* SAV = Sub Aquatic Vegetation

2010 Percent of Samples Meeting Threshold
Blue = West River
Green = Rhode River
Previous Research

• Previous project established three alternatives to decrease turbidity and increase SAV growth

• Recommended the clams as solution

Source: J. Askvig et al 2010 [1]
Outcome of Project

- Clams planted in Rhode River as a pilot project by Smithsonian Environmental Research Center Summer 2011
- All of the clams died: close to survivability limits (Gedan, 2011)

Review and Analysis of Project

- Unlike clams, oysters are known to be more resilient to varying salinity and dissolved oxygen conditions; propose to use oysters in order to improve water quality.
- Due to low probability of reproduction, oysters can also be artificially sustained through aquaculture; propose to use aquaculture program as method of implementation.
Salinity Tolerance

Data taken from Rhode River, site WT8.2

Salinity (1984 - 2011)

\[ y = -0.0002x + 16.096 \]
\[ R^2 = 0.0188 \]

Salinity (ppt) vs. Date (month/year)

Data Source: Maryland Department of Natural Resources
Agenda

• Context
• **Problem/Need Statement**
• Design Evaluation
• Design Alternatives
• Simulation and Modeling
• Recommendations
• Project Plan
Problem/Need Statement

The WRR has seen decreased water quality due to increased nutrients and sediment from runoff and is exacerbated by loss of Sub-Aquatic Vegetation (SAV) and other aquatic resources. Oysters have been proven to remove excess nutrients and sediment and restore the health of the rivers. Currently, the budget climate prevents prolonged government funding to support a sustainable aquaculture system.

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

- Simulation of oyster growth rate within the varying environment of the West and Rhode Rivers.
- Simulation of an oyster aquaculture business plan.
- Simulation of oyster filtration rate on nutrient levels in the West and Rhode Rivers.
- Business plan for implementation
## Primary Stakeholders

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Objectives</th>
<th>Tensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>West and Rhode River Keeper</td>
<td>Supports reducing pollution, enforcing environmental law, promoting restoration, and advocating for better environmental quality.</td>
<td>Monitors water quality and promotes restoration practices, though limited in resources for implementing sustainable plans.</td>
</tr>
<tr>
<td>Maryland Watermen’s Association</td>
<td>Supports harvesting and sale of aquatic species throughout the year.</td>
<td>Main priority is making profit from river.</td>
</tr>
<tr>
<td>Maryland Department of Natural Resources</td>
<td>Supports management of regional watershed, which includes streams, coastal bays, and the Chesapeake Bay.</td>
<td>Limited amount of funding available for restoration projects.</td>
</tr>
<tr>
<td>Local Watershed Residents</td>
<td>Supports recreational use of river and waterfront property use.</td>
<td>Source of waste runoff and nutrient pollution.</td>
</tr>
</tbody>
</table>
Stakeholder Relationship Diagram

Aquaculture Market

Watermen

MDDNR

West and Rhode Rivers

Residents

W/R Riverkeeper

Consumers

Market Revenue

Market Sales

Harvests Resources

Supplies Aquaculture

Supports Aquaculture and Regulates Licenses

Pays Taxes

Waste Runoff

Recreation

Supports Conservation

Supports and Funds

Supports and Monitors

Advocates Policy Change

Reinforcement Loop
Agenda

• Context
• Problem/Need Statement
• Design Evaluation
• Design Alternatives
• Simulation and Modeling
• Recommendations
• Project Plan
Proposed Cage Design (Side View)

- Oysters placed on river bed:
  - Require a hard substrate (recycled shell) to set on
  - This is costly and scarce
  - Filter only the bottom depths of the water
- Hanging Cage Design:
  - Does not require recycled shell
  - Filters the entire water column

Source: D. Fredriksson et al. 2010 [27]
Proposed Cage Design (Top View)

- **Maximum Capacity**
  - 5 lines/acre
  - 750 trays/acre
  - 2.25 million 3” oysters/acre
Permitting Restrictions

– Must be 300 feet from navigation buoys
– Must be 150 feet from active pound nets
– Must leave channel for boat navigation
– Must have public approval/approval of adjacent landowners
Permitting – West River

Current permits and restrictions make aquaculture in the West River infeasible at this time

MDNR, 2012
Permitting – Rhode River

Use the West River as a control to compare the effects of oyster filtration on the Rhode River

MDNR, 2012
Permitting – Proposed Site at 1 Acre
Agenda

• Context
• Problem/Need Statement
• Design Evaluation
• Design Alternatives
• Simulation and Modeling
• Recommendations
• Project Plan
Design Alternatives

Initial Grow-out Method

1) Remote Setting
   - Larvae

2) Nursery
   - Seed
   - ~2 weeks

3) Spat-on-Shell

Final Product for Sale

Using native Eastern Oysters

A) Half-Shell
B) Shucked

Market Size Oyster

2-3 Years

(Maryland Sea Grant, 2011)
Remote Setting

1 day

Soak Cultch

Costs
Recycled Shell

Obtain Larvae from Hatchery

Costs
Larvae

Combine Larvae in Tank

Costs
Facility Labor Equipment Tank Blower Pump Plumbing Shell-washer Cage

Sort Oysters

Costs
Sorting Machine

Plant Oysters in River

10 days

Final Product

Initial Grow-Out
Design Alternatives

Initial Grow-Out

Nursery

- Place Seed Into Weller
- Downwelling
- Upwelling
- Plant Oysters in River

2 days

Costs
- Micro-cultch
- Wellers
- Water
- Treatment Equipment

Costs
- Algae

Costs
- Bottom mesh cleaned daily
  - Sort by Size & move to bigger mesh
  - Algae

21 days
Design Alternatives

Spat-on-Shell

Obtain Spat on Shell

Costs
Labor
Transportation

Transportation Time

Plant Oysters in River
Design Alternatives

Initial Grow-Out

- Harvest Oysters
- Costs: Labor, Transportation
- 48 Hours

Final Product

- Shuck Oysters
- Costs: Transportation
- Prepare Half Shell Oysters
- Costs: Labor, Marketing Labels

Design Alternatives
Agenda

• Context/Stakeholder Analysis
• Problem/Need Statement
• Design Evaluation
• Design Alternatives
• Simulation and Modeling
• Recommendations
• Project Plan/Budget
Method of Analysis

2DTMM = Two Dimensional Tidal Mixing Model (From Previous Project)
Initial Investment

Investment Parameters

- Max Operating Capacity (in millions of oysters)
- Operating Duration (in years)

Default Simulation

- Max Operating Capacity = 1.0 million oysters
- Operating Duration = 5.0 years
Growth Model

Overview

Assumptions

Inputs

Outputs

Stochastic Environmental Variables

Oyster Biomass

Input

Biometric Variables

Growth Rate

Mortality

Stochastic Variable

Oyster Biomass

Output

Simulation and Modeling
### Growth Model

<table>
<thead>
<tr>
<th>Overview</th>
<th>Assumptions</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
</table>

**Assumptions**

- Oyster mortality due to harvest and disease will be negligible. Only predation and hypoxia will be considered.
- Initial oyster biomass will be based on a log-normal distribution ($\mu=0.65$, $\sigma=0.63$), approximating the mass of the oyster after the initial grow-out phase.
- Oysters will be assumed to be market size once they have reached 76.2 mm in length, or approximately 0.33 kg Carbon.
# Growth Model

## Overview

## Stochastic Environmental Variables

- Values are generated based on a Gaussian distribution.
- $\mu/\sigma$ values based on MDDNR Water Quality Data.
- 12 total distributions (dependent on month)

## January Values. Data from 1984-2011

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Celsius</td>
<td>2.63</td>
<td>2.06</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>mg/L</td>
<td>12.00</td>
<td>0.82</td>
</tr>
<tr>
<td>Salinity</td>
<td>ppt</td>
<td>12.29</td>
<td>0.58</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>mg/L</td>
<td>3.40</td>
<td>1.98</td>
</tr>
<tr>
<td>Particulate Organic Carbon</td>
<td>mg/L</td>
<td>0.95</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Growth Model

Overview

Assumptions

Inputs

Outputs

Biometric Variables

- Fraction Ingested – % TSS used for oyster growth.
- Basal Metabolic – Passive respiration (% biomass/day)
- Respiratory Fraction – Active respiration (% assimilated)
- Assimilation Efficiency – % TSS used completely
- Mortality Rate – Total mortality (% biomass/day)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction Ingested</td>
<td>IF</td>
<td>0.0 ≤ IF ≤ 1.0</td>
</tr>
<tr>
<td>Basal Metabolic</td>
<td>BM</td>
<td>d^(-1)</td>
</tr>
<tr>
<td>Respiratory Fraction</td>
<td>RF</td>
<td>0.0 ≤ RF ≤ 1.0</td>
</tr>
<tr>
<td>Assimilation Efficiency</td>
<td>α</td>
<td>0.0 ≤ α ≤ 1.0</td>
</tr>
<tr>
<td>Mortality Rate</td>
<td>β</td>
<td>d^(-1)</td>
</tr>
</tbody>
</table>

Values determined through previous research (C. Cerco, 2007)
Growth Model

Oyster Biomass

- Total weight of oysters measured in kg Carbon

\[ \frac{\Delta O}{dt} = (\alpha \times Fr \times POC \times IF(1-RF) \times O) - (BM \times O - \beta \times O) \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oyster Biomass</td>
<td>O</td>
</tr>
<tr>
<td>Particulate Organic Carbon</td>
<td>POC</td>
</tr>
<tr>
<td>Filtration Rate</td>
<td>FR</td>
</tr>
<tr>
<td>Fraction Ingested</td>
<td>IF</td>
</tr>
<tr>
<td>Basal Metabolic</td>
<td>BM</td>
</tr>
<tr>
<td>Respiratory Fraction</td>
<td>RF</td>
</tr>
<tr>
<td>Assimilation Efficiency</td>
<td>(\alpha)</td>
</tr>
<tr>
<td>Mortality Rate</td>
<td>(\beta)</td>
</tr>
</tbody>
</table>

Filtration Rate

- \( Fr = f(WT) \times f(TSS) \times f(S) \times f(DO) \times Fr_{max} \)
- \( Fr_{max} = 0.55 \text{ m}^3 \text{ g}^{-1} \text{ oyster carbon d}^{-1} \)

\[
\begin{align*}
f(WT) &= \exp(-0.015 \times (T-27)^2) \\
f(S) &= 0.5 \times (1 + \tanh(S - 7.5)) \\
f(DO) &= \left(1 + \exp \left(3.67 \times (1.0 - DO)\right)\right)^{1} \\
f(TSS) &= 0.1 \text{ when } TSS < 5 \text{ g m}^{-3} \\
      &= 1.0 \text{ when } 5 \text{ g m}^{-3} < TSS < 25 \text{ g m}^{-3} \\
      &= 0.2 \text{ when } 25 \text{ g m}^{-3} < TSS < 100 \text{ g m}^{-3} \\
      &= 0.1 \text{ when } TSS > 100 \text{ g m}^{-3}
\end{align*}
\]

Growth Model

Overview
Assumptions
Inputs
Outputs

Model Validation

• Model environmental variable output compared to data taken at the Rhode River over the past 26 years.
• Error was found to be 18.2% for Salinity and 26.7% DO.

Salinity Values

<table>
<thead>
<tr>
<th>Time (month)</th>
<th>Salinity (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
</tr>
</tbody>
</table>

DO Values

<table>
<thead>
<tr>
<th>Time (month)</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
</tr>
</tbody>
</table>

Simulation and Modeling
Growth Model

Model Output

P(3” Oyster within 3 years) = 0.79
2D Tidal Mixing Model [1]

Overview

Assumptions

Inputs

Outputs

Oyster Biomass

Tidal Flow

Cell Attributes

N,P,TSS Load

Input

Cell Placement

N,P,TSS Removed

Output

Source: J. Askvig et al 2010 [1]
### Assumptions

- The water column being modeled is thoroughly mixed. (based on data taken by team at WRR, September/October 2011).
- Filtration rates will be uniform for the entire cell.
- Wind shear will be negligible.
- Tide flow into each cell occurs instantaneously.
- Environmental variable concentrations are assumed to be uniform throughout each cell.
## Cell Attributes

<table>
<thead>
<tr>
<th>Cell</th>
<th>Surface Area (m^2)</th>
<th>Average Depth (m)</th>
<th>Volume (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,099,012</td>
<td>3.05</td>
<td>9,445,789</td>
</tr>
<tr>
<td>2</td>
<td>3,024,895</td>
<td>2.44</td>
<td>7,375,904</td>
</tr>
<tr>
<td>3</td>
<td>2,322,522</td>
<td>2.13</td>
<td>4,955,333</td>
</tr>
<tr>
<td>4</td>
<td>1,251,301</td>
<td>1.22</td>
<td>1,525,586</td>
</tr>
<tr>
<td>5</td>
<td>4,211,924</td>
<td>2.75</td>
<td>11,582,791</td>
</tr>
<tr>
<td>6</td>
<td>4,603,933</td>
<td>2.13</td>
<td>9,822,951</td>
</tr>
<tr>
<td>7</td>
<td>2,526,922</td>
<td>1.83</td>
<td>4,621,235</td>
</tr>
<tr>
<td>8</td>
<td>1,493,339</td>
<td>1.22</td>
<td>1,820,679</td>
</tr>
<tr>
<td>9</td>
<td>1,390,849</td>
<td>1.17</td>
<td>1,627,293</td>
</tr>
<tr>
<td></td>
<td><strong>Total Volume</strong></td>
<td></td>
<td><strong>52,777,561</strong></td>
</tr>
</tbody>
</table>

Source: J. Askvig et al. 2011 [1]
2D Tidal Mixing Model

Overview
Assumptions
Inputs
Outputs

Tidal Flow

\[ V_n = \text{Volume of Cell } n \]
\[ T_n = \text{Tide volume of Cell } n \]
\[ N_n = \text{Nitrogen concentration of Cell } n \]

\[ F = \text{River volume} \]
\[ B_n = \text{Bay Concentration of Nitrogen} \]
\[ R_n = \text{River Concentration of Nitrogen} \]

Cell 1 to Cell 2:
\[ N_2 = \frac{(N_2 \cdot V_2 + N_1 \cdot T_2)}{(V_2 + T_2)} \]
\[ N_1 = \frac{(N_1 \cdot (V_1 + T_1) + B_n \cdot T_1 - N_1 \cdot T_2)}{(V_1 + T_1)} \]

Cell 2 to Cell 3:
\[ N_3 = \frac{(N_3 \cdot V_3 + N_2 \cdot T_3)}{(V_3 + T_3)} \]
\[ N_2 = \frac{(N_2 \cdot (V_2 + T_2) + N_1 \cdot T_3 - N_2 \cdot T_3)}{(V_2 + T_2)} \]
\[ N_1 = \frac{(N_1 \cdot (V_1 + T_1) + B_n \cdot T_3 - N_1 \cdot T_3)}{(V_1 + T_1)} \]

Cell 3 to Cell 4:
\[ N_4 = \frac{(N_4 \cdot V_4 + N_3 \cdot T_4)}{(V_4 + T_4)} \]
\[ N_3 = \frac{(N_3 \cdot (V_3 + T_3) + N_3 \cdot T_4 - N_3 \cdot T_4)}{(V_3 + T_3)} \]
\[ N_2 = \frac{(N_2 \cdot (V_2 + T_2) + N_1 \cdot T_3 - N_2 \cdot T_4)}{(V_2 + T_2)} \]

Assume complete mixing and a new \( N_2 \) mg/L

Source: VIMS, 1993
Business Model

Overview
Assumptions
Inputs
Outputs

Operation Costs
Oyster Selling Price
Time
Demand for Oysters
Growth of Oysters

Revenue - Cost

Yearly Cash Flows
Probability of Profit

Simulation and Modeling
## Business Model

<table>
<thead>
<tr>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Will receive MDNR loan for oysters and shell</td>
</tr>
<tr>
<td>• Interest only for three years</td>
</tr>
<tr>
<td>• 40% forgiven at beginning of fourth year</td>
</tr>
<tr>
<td>• Last two years at 5% interest</td>
</tr>
<tr>
<td>• Total capacity of aquaculture business will be split by five and planted in fifths annually to increase probability of profits each year</td>
</tr>
<tr>
<td>• i.e.) If total capacity desired is one million oysters, each year 200,000 will planted</td>
</tr>
<tr>
<td>• All of the oysters at market size at the beginning of a season will be harvested, sold, and replaced by new oysters in the water</td>
</tr>
<tr>
<td>• Discount rate equals 2%</td>
</tr>
</tbody>
</table>
## Business Model

**Costs per 200,000 Oysters/year (up to 1,000,000 cap)**

<table>
<thead>
<tr>
<th></th>
<th>Remote Setting</th>
<th>Nursery</th>
<th>Spat-on-Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grow-out Labor (recurring yearly)</td>
<td>$516</td>
<td>$3,600</td>
<td>$1600</td>
</tr>
<tr>
<td>Grow-out Equipment (capital)</td>
<td>$23,110</td>
<td>$14,300</td>
<td>$0</td>
</tr>
<tr>
<td>Oysters and Shell (recurring yearly)</td>
<td>$720</td>
<td>$1,920</td>
<td>$2,570</td>
</tr>
<tr>
<td>Cages and Setup (recurring yearly for 5 years)</td>
<td>$23,313</td>
<td>$23,313</td>
<td>$23,313</td>
</tr>
<tr>
<td>Cleaning (Recurring yearly)</td>
<td>$8,020</td>
<td>$8,020</td>
<td>$8,020</td>
</tr>
</tbody>
</table>
Business Model

Overview | Assumptions | Inputs | Outputs
--- | --- | --- | ---

Average ROI in 5 Years

- Remote Setting HalfShell
- Remote Setting Shucked
- Nursery Half Shell
- Nursery Shucked
- Spat-on-Shell Half Shell
- Spat-on-Shell Shucked

ROI in 5 Years vs. Number of Oysters Planted (in Millions)
Business Model

Overview | Assumptions | Inputs | Outputs

Sensitivity of ROI in 5 Years

5 Million Oysters – Remote Setting Half-Shell

Simulation and Modeling
Business Model

Overview | Assumptions | Inputs | Outputs
---|---|---|---

Frequency of ROI

Year 3 – 5 Million Oysters

Average ROI in 3 Years

<table>
<thead>
<tr>
<th>Setting</th>
<th>ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote Setting</td>
<td>2.1</td>
</tr>
<tr>
<td>Nursery</td>
<td>1.3</td>
</tr>
<tr>
<td>SOS</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Simulation and Modeling
Business Model

Overview  Assumptions  Inputs  Outputs

Frequency of ROI

Year 5 – 5 Million Oysters

Average ROI in 5 Years

Remote Setting 4.9
Nursery 3.0
SOS 3.3

Simulation and Modeling
Utility Function

Value Hierarchy

Aquaculture System Objective Function

Maximize Public Approval
0.25

Maximize Sustainability
0.75

Return on Investment
0.6

Availability of Shell
0.4

Weights determined in conjunction with W/R Riverkeeper and SERC (Askvig et al, 2010)
Cost vs. Utility

- Remote Setting Half Shell has the highest ROI over all capacities
- If Public Approval decreases 2% or more Nursery has highest utility
- If Availability of Shell increases 5% or more Nursery has highest utility
- If Public Approval increases 40% or more Spat-on-Shell has the highest utility
Agenda

• Context/Stakeholder Analysis
• Problem/Need Statement
• Design Evaluation
• Design Alternatives
• Simulation and Modeling
• Recommendations
• Project Plan/Budget
Recommendations

• It is recommended an oyster aquaculture system be implemented in the West and Rhode Rivers.
• While any amount of oysters will help decrease the turbidity of the river, 10 million oysters is recommended to maximize the effects of filtration.
• Due to the sensitivity of the weights on the utility function remote setting or nursery operations are recommended for obtaining oysters with the decision made by the watermen based on location, local public approval, and personal preference.
• It is recommended oysters be cleaned and packaged to be sold in the half shell market.
Agenda

• Context/Stakeholder Analysis
• Problem/Need Statement
• Design Alternatives
• Simulation and Modeling
• Sensitivity Analysis
• Recommendations
• Project Plan/Budget
Work Breakdown Structure (WBS)

1.0 Management
  1.1 Work Breakdown Structure
  1.2 Meeting Minutes
  1.3 Budget

2.0 Research
  2.1 Concept of Operations
  2.2 Oyster
  2.3 Legal
  2.4 Environment
  2.5 Business
  2.6 Field Research

3.0 Design
  3.1 Requirements
  3.2 Value Hierarchy
  3.3 Business Proposal

4.0 Modeling
  4.1 Oyster Growth Model
  4.2 Business Model
  4.3 2DTMM Model

5.0 Analysis
  5.1 Trade-off Analysis
  5.2 Growth Model Analysis
  5.3 Cost-Benefit Analysis
  5.4 Long-Term Plan

6.0 Report
  6.1 Papers
  6.2 PowerPoint Presentations
  6.3 Posters
Project Schedule

<table>
<thead>
<tr>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Scope</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Requirements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design Alternatives</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Model Research</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Utility Weights</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Model V/V</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Final</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Model Building</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abstract</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Proposal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Poster</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Competition Prep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Earned Value Management

Estimated Budget

Cost Spent ($) vs. Week Number

- Planned Value
- Actual Cost
- Earned Value

Planned Cost: $89,220
Actual Cost: $60,405
Earned Value: $89,744
CPI: 1.01
SPI: 1.49
This project has developed methods to clean the WRR which we can pursue with state agencies and watermen to clean the waters as well as benefit the investors financially. – Feedback from Chris Trumbauer, WR Riverkeeper.
References


[6] Dr. Donohue, verbal communication


References


[22] K. Gedan, Smithsonian Environmental Research Center, Presentation, November 2011.


[25] Don Webster, Email Communication, 2012

[26] J. Quigley, Chesapeake Bay Oyster Company, Email Communication, 2012


# Appendix I - Our Field Data

<table>
<thead>
<tr>
<th>Station</th>
<th>Depth (feet)</th>
<th>Temp (C)</th>
<th>Specific Conductance (uS)</th>
<th>salinity (ppt)</th>
<th>Dissolved Oxygen %</th>
<th>DO mg/L</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>w6</td>
<td>2</td>
<td>23.5</td>
<td>5.78</td>
<td>3.13</td>
<td>91</td>
<td>7.6</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>23.6</td>
<td>5.8</td>
<td>3.14</td>
<td>90.7</td>
<td>7.62</td>
<td>8.25</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23.7</td>
<td>5.85</td>
<td>3.17</td>
<td>90.3</td>
<td>7.51</td>
<td>8.32</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>23.7</td>
<td>5.85</td>
<td>3.17</td>
<td>92.1</td>
<td>7.63</td>
<td>8.34</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>23.3</td>
<td>5.84</td>
<td>3.17</td>
<td>91.1</td>
<td>7.63</td>
<td>8.35</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>23.1</td>
<td>5.78</td>
<td>3.13</td>
<td>93.6</td>
<td>7.9</td>
<td>8.37</td>
</tr>
<tr>
<td>w20</td>
<td>2</td>
<td>22.9</td>
<td>5.88</td>
<td>3.19</td>
<td>91.4</td>
<td>7.65</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>23</td>
<td>5.89</td>
<td>3.2</td>
<td>91.4</td>
<td>7.67</td>
<td>8.16</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23</td>
<td>5.91</td>
<td>3.12</td>
<td>87.6</td>
<td>7.23</td>
<td>8.14</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>23</td>
<td>5.92</td>
<td>3.22</td>
<td>86.1</td>
<td>7.23</td>
<td>8.11</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>23</td>
<td>5.91</td>
<td>3.22</td>
<td>86.6</td>
<td>7.13</td>
<td>8.07</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>22.9</td>
<td>5.95</td>
<td>3.23</td>
<td>82.9</td>
<td>6.99</td>
<td>8.03</td>
</tr>
<tr>
<td>AVG</td>
<td>23.23</td>
<td>5.86</td>
<td>3.17</td>
<td>89.57</td>
<td>7.48</td>
<td>8.21</td>
<td></td>
</tr>
</tbody>
</table>

Taken September 16, 2011
## Appendix I - Our Field Data

West/Rhode River Sample 10/14/11

<table>
<thead>
<tr>
<th>Station</th>
<th>Depth (ft)</th>
<th>Temp (°C)</th>
<th>Salinity (ppt)</th>
<th>DO (%)</th>
<th>DO (mg/L)</th>
<th>pH</th>
<th>SC (μS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W06</td>
<td>2</td>
<td>19.7</td>
<td>4.02</td>
<td>99</td>
<td>8.83</td>
<td>8.3</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>19.71</td>
<td>4.02</td>
<td>97.1</td>
<td>8.67</td>
<td>8.28</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>19.71</td>
<td>4.05</td>
<td>96.4</td>
<td>8.61</td>
<td>8.27</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>19.71</td>
<td>4.04</td>
<td>96</td>
<td>8.56</td>
<td>8.26</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>19.7</td>
<td>4.34</td>
<td>95</td>
<td>8.38</td>
<td>8.16</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>W20</td>
<td>2</td>
<td>19.75</td>
<td>3.85</td>
<td>99.1</td>
<td>8.82</td>
<td>8.39</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>19.74</td>
<td>3.86</td>
<td>97.4</td>
<td>8.7</td>
<td>8.35</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>19.74</td>
<td>3.85</td>
<td>97.1</td>
<td>8.68</td>
<td>8.34</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>19.74</td>
<td>3.85</td>
<td>97.1</td>
<td>8.67</td>
<td>8.33</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>19.74</td>
<td>3.86</td>
<td>97.1</td>
<td>8.68</td>
<td>8.32</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>CYC</td>
<td>1</td>
<td>20.03</td>
<td>4.17</td>
<td>90.3</td>
<td>8.05</td>
<td>8.66</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>19.88</td>
<td>4.23</td>
<td>90.2</td>
<td>7.94</td>
<td>8.63</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>19.76</td>
<td>4.01</td>
<td>95.98</td>
<td>8.55</td>
<td>8.36</td>
<td>N/A</td>
</tr>
<tr>
<td>Std</td>
<td></td>
<td>0.10</td>
<td>0.17</td>
<td>2.90</td>
<td>0.28</td>
<td>0.15</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Appendix II - Charts

Rhode River Secci Depth (1984 - 2011)

\[ y = -4 \times 10^{-5}x + 2.0926 \]
\[ R^2 = 0.0803 \]
Appendix II - Charts

2010 VIMS Model – Secchi Depth Improvement
Appendix III - Definitions

Turbidity

- Having sediment and/or foreign particles stirred up or suspended in water (haziness)
- Contributions to turbidity in WRR
  - Excess nutrients and sediments that flow into the rivers through the tide
  - Run off from surrounding land (Local residents, farms, construction)
  - Suspended Solids (ie: algae)
    - Reduce dissolved oxygen level, killing off other life in river.
Appendix III - Definitions

Salinity

- Salt content of the water (measured in parts per thousand (ppt))
  - Salt water flows into the Chesapeake from the Atlantic Ocean.
  - Fresh water flows into the Chesapeake from the Susquehanna River, creeks and rain.
  - Eastern Oysters (Crassostrea virginica) require at least 7.5 ppt to be filtering effectively [2]
Appendix IV – Etc.

Cage Equations

• Floatation = Dry body weight * \[1 – (\delta_{\text{fluid}}/\delta_{\text{body}})\]
• Resistance force = \(\frac{1}{2} \times C_d \times A \times \delta \times v^2\)
• Rope Sizing
  – Length: \(n = j \times h\)
  – Tension: \(T_{m-a} = (T_h^2 + T_v^2)^{0.5}\)
  – Rope Diameter: \(d = (T_{\text{max}} \times F_s)^{0.5} / C_r\)
• Buoy Sizing
  – \(V_b = [W / [(\delta_{sw} – \delta_b) \times g]] \times F_s\)
• Anchor System Sizing
  – \(V_{\text{anchor}} = W_{\text{dry}} / \delta_{\text{anchor}} \times g\)
  – \(W_{\text{sub}} = (T_{m-a} \times \cos \Phi / \mu) + T_{m-a} \times \sin \Phi\)
Appendix IV – Etc.

Cage Assemblies Longline Culture System

• Mooring-Anchor System
  – Stabilizes the system against the effects of both vertical and horizontal stresses

• Floatation System
  – Maintains suspension of the culture system

• Growing System
  – Used to contain and grow oysters

• Design Principles
  – Buoyancy Force
    • Floatation or Gravity Force on an Immersed Body
  – Resistance Force
  – Tension between all lines
Appendix V: Oyster Lifecycle

Data Source = Maryland Sea Grant, 2011
## Appendix VI: Potential Risks

<table>
<thead>
<tr>
<th>Risks</th>
<th>Mitigation Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theft (poaching)</td>
<td>Build relations with adjacent watershed residents to have community monitoring</td>
</tr>
<tr>
<td>Catastrophic weather (effecting equipment)</td>
<td>Reduce profit (rainy day fund)</td>
</tr>
<tr>
<td>Catastrophic weather (effecting oyster growth)</td>
<td>Reduce profit (rainy day fund), replace oyster biomass</td>
</tr>
<tr>
<td>Disease</td>
<td>Monthly cleaning for preventive care, harvest before 7 years</td>
</tr>
<tr>
<td>Change in market demand</td>
<td>Sensitivity shows we will still have positive ROI with 30% demand decrease</td>
</tr>
<tr>
<td>Lack of available shell</td>
<td>Accounted for in utility, may reduce profit.</td>
</tr>
<tr>
<td>Low public approval</td>
<td>Community outreach program early in permitting process</td>
</tr>
<tr>
<td>Injury to workers</td>
<td>Covered in liability insurance</td>
</tr>
</tbody>
</table>
Appendix VII: Average NPV in 5 Years

- Remote Setting Half-Shell
- Remote Setting Shucked
- Nursery Half-Shell
- Nursery Shucked
- Spat-on-Shell Half-Shell
- Spat-on-Shell Shucked

Number of Oysters (in Millions) vs. NPV in 5 Years
# Appendix VIII – Remote Setting Inventory Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST ($)</th>
<th>UNIT</th>
<th>Cost Per Million ($)</th>
<th>CAPACITY</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled Shell</td>
<td>1.50</td>
<td>bushel</td>
<td>1,000.50</td>
<td>500 shells per bushel, 333,500 shells per million set</td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Larvae</td>
<td>260.00</td>
<td>million</td>
<td>2,600.00</td>
<td>Need 10 times the number of oysters desired to account for only 10% setting rate</td>
<td>Parker et. al, 2011, Oyster Recovery Partnership</td>
</tr>
<tr>
<td>Heater</td>
<td>600.00</td>
<td></td>
<td>600.00</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Tank</td>
<td>1,500.00</td>
<td>per tank</td>
<td>1,500.00</td>
<td>3,000 gal.</td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Blower</td>
<td>625.00</td>
<td>per blower</td>
<td>625.00</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Pump</td>
<td>575.00</td>
<td>per pump</td>
<td>575.00</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Plumbing</td>
<td>400.00</td>
<td></td>
<td>400.00</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Shell-washer</td>
<td>2,050.00</td>
<td>per unit</td>
<td>2,050.00</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Sorting Machine</td>
<td>10,000.00</td>
<td>per machine</td>
<td>10,000.00</td>
<td></td>
<td>Chesapeake Bay Oyster Company</td>
</tr>
<tr>
<td>Food</td>
<td>150.00</td>
<td>per 1 million</td>
<td>150.00</td>
<td></td>
<td>Congrove, 2009</td>
</tr>
</tbody>
</table>
### Appendix IX – Remote Setting Operations Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>Cost Per Million</th>
<th>CAPACITY</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Unskilled</td>
<td>8</td>
<td>per hour</td>
<td>2080</td>
<td>260 hours per 1 million</td>
<td>Parker et. al, 2011 and Wieland, 2007</td>
</tr>
<tr>
<td>Labor Skilled</td>
<td>500</td>
<td>per set</td>
<td>500</td>
<td>Set price per set</td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Facility Rental</td>
<td>120</td>
<td>per month</td>
<td></td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Blower Electric</td>
<td>2.16</td>
<td>per day</td>
<td>21.6</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Pump Electric</td>
<td>13.25</td>
<td>per day</td>
<td>132.5</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
<tr>
<td>Heater Electric</td>
<td>72</td>
<td>per day</td>
<td>720</td>
<td></td>
<td>Parker et. al, 2011</td>
</tr>
</tbody>
</table>
# Appendix X – Nursery Inventory & Operations Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>Cost per Million</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed</td>
<td>$9.10</td>
<td>per 1 thousand</td>
<td></td>
<td>$9,100.00</td>
<td>Oyster Recovery Partnership</td>
</tr>
<tr>
<td>Micro-cultch Shell</td>
<td>$500</td>
<td>per 1 million</td>
<td></td>
<td>$500</td>
<td>Don Webster</td>
</tr>
<tr>
<td>Floating Upweller</td>
<td>$7,200</td>
<td>per 2 million</td>
<td></td>
<td>$7,200</td>
<td>Chesapeake Bay Gold Oysters</td>
</tr>
<tr>
<td>Bucket Upweller</td>
<td>$5,200</td>
<td>per 2 million</td>
<td></td>
<td>$5,200</td>
<td>Chesapeake Bay Gold Oysters</td>
</tr>
<tr>
<td>Algae (Food)</td>
<td>$150</td>
<td>per 1 million</td>
<td></td>
<td>$150</td>
<td>Congrove, 2009</td>
</tr>
<tr>
<td>Pump Electric</td>
<td>$13.25</td>
<td>per day for 23 Days</td>
<td></td>
<td>$304.75</td>
<td>Parker et. al, 2011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor (Sorting)</td>
<td>$8</td>
<td>per 1 million</td>
<td>2250 hours per 1 million</td>
<td>Wieland, 2007</td>
</tr>
</tbody>
</table>
Appendix XI – Spat-on-Shell Inventory & Operations Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spat on Shell</td>
<td>$12.85</td>
<td>per thousand</td>
<td>$12,850.00</td>
<td>Oyster Recovery Partnership</td>
</tr>
<tr>
<td>Labor (Transportation)</td>
<td>$8</td>
<td>1000 hours per 1 million</td>
<td>$8,000</td>
<td>Wieland, 2007</td>
</tr>
</tbody>
</table>
# Appendix XII – Cage System Inventory & Operations Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>Cost per Acre</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triple-stack Tray</td>
<td>$120</td>
<td>per cage</td>
<td>3000 oysters</td>
<td>$90,000</td>
<td>Chesapeake Bay Oyster Company</td>
</tr>
<tr>
<td>Concrete Deadweight</td>
<td>$25</td>
<td>per cage</td>
<td>1337 lbs</td>
<td>$90,000</td>
<td><a href="http://www.concretenetwork.com/concrete/howmuch/calculator.htm">http://www.concretenetwork.com/concrete/howmuch/calculator.htm</a></td>
</tr>
<tr>
<td>Sink Line</td>
<td>$1,091</td>
<td>1 million</td>
<td>1</td>
<td>$90,000</td>
<td>Wieland, 2008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>COST PER MILLION</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor (Placement)</td>
<td>$8</td>
<td>per hour, 0.5 hours with four workers per cage</td>
<td>One time set up cost</td>
<td>5,344</td>
<td>Estimated based on other labor cited in Wieland, 2008</td>
</tr>
<tr>
<td>Labor (Cleaning)</td>
<td>$8</td>
<td>per hour, 0.25 hours with 1 watermen</td>
<td>Monthly</td>
<td>668</td>
<td>Estimated based on other labor cited in Wieland, 2008</td>
</tr>
</tbody>
</table>
## Appendix XIII – All System Costs

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
<th>UNIT</th>
<th>CAPACITY</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>$165</td>
<td>per month</td>
<td></td>
<td>OysterNPV_Final</td>
</tr>
<tr>
<td>Boat Maintenance</td>
<td>$1,832</td>
<td>per 1 million</td>
<td></td>
<td>Wieland, 2008</td>
</tr>
<tr>
<td></td>
<td>$51</td>
<td>per day</td>
<td></td>
<td>Wieland, 2008</td>
</tr>
<tr>
<td>Insurance</td>
<td>$500</td>
<td>minimum</td>
<td></td>
<td>Daniel Grosse TerrAqua Environmental Science Policy</td>
</tr>
<tr>
<td></td>
<td>$1,000.00</td>
<td>Above 200K sold per year</td>
<td></td>
<td>Daniel Grosse TerrAqua Environmental Science Policy</td>
</tr>
<tr>
<td></td>
<td>$2,500.00</td>
<td>Above 400K sold per year</td>
<td></td>
<td>Daniel Grosse TerrAqua Environmental Science Policy</td>
</tr>
</tbody>
</table>