THE FEASIBILITY OF A FLOATING VERTICAL RACEWAY FOR SALMON SMOLT PRODUCTION IN BRITISH COLUMBIA

by

TREV NEUFELD

B.Sc., The University of British Columbia, 1983

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in
THE FACULTY OF GRADUATE STUDIES
(Department of Bio-Resource Engineering)

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
September 1991

Trev Neufeld, 1991
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Bioresource Engineering
The University of British Columbia
Vancouver, Canada

Date 10/11/91
In British Columbia the Floating Vertical Raceway (FVR) system has only recently been introduced as a technique to produce low cost salmonid smolts. A FVR is constructed of synthetic rubber sheeting and may be assembled at, and/or within, an existing off-shore marine net pen. The FVR is filled with freshwater or varying proportions of freshwater/saltwater and thereby floats on the denser saltwater. Mixed results have shown that inconsistent and unreliable designs can prevent successful application of the FVR systems. The design problems are generally associated with stability and turgidity of the raceway.

In this study a computer generated spreadsheet simulation (CGSS) was developed to predict the technical and economic feasibility of 3 FVR scenarios through several production cycles. The program provides a tool to assist producers, investors and banks to assess the technical and economic feasibility of a FVR system.

An analysis of the CGSS behaviour provides valuable insights for prospective operators and farmers. Results indicate that for a FVR with a volume of 100 m$^3$ influent water flow rates of 150, 300 and 600 l/min will incur oxygen deficiencies at 160, 180 and 210 days into a production cycle, respectively. Flow rates higher than 2000 l/min raise the fresh water head order of magnitudes above the observed
heights of 0.01-0.3 m. The added force of this water could cause the investigated liner and outlet screen to fail. A FVR shaped as either a frustrum, hemisphere, paraboloid, or cuboid, adheres to stability criteria. Turgor is maintained for these four shapes as long as the current velocity is not greater than 1.1, 1.6, 1.2 and 1.15 m/s, respectively.

After criteria for technical feasibility were determined, economic feasibility was investigated. To obtain a ten year cash flow, it was assumed that the initial selling price of an Atlantic salmon smolt was $3.50. For one of the three hypothetical farm cases examined, net cash flow remained positive throughout all cycles and a surplus was accumulated. One hypothetical farm failed due to the low number of stocked smolts. The final hypothetical farm maintained a positive cash flow through most cycles but accumulated a deficit due to the large capital costs of PVC piping (45.32%). The lowest production cost of a smolt was $1.37.

Conclusions from test simulations on the CGSS indicate that the FVR system is technically and economically feasible. The spreadsheet developed during this investigation is concluded to be an effective tool to investigate alternative strategies, designs and economies for smolt production within a FVR.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ix</td>
</tr>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0 OBJECTIVES</td>
<td>5</td>
</tr>
<tr>
<td>3.0 LITERATURE REVIEW</td>
<td>7</td>
</tr>
<tr>
<td>3.1 The Freshwater Vertical Raceway (FVR)</td>
<td>7</td>
</tr>
<tr>
<td>3.2 Atlantic Salmon Hatchery Techniques</td>
<td>8</td>
</tr>
<tr>
<td>3.3 Biological Requirements</td>
<td>11</td>
</tr>
<tr>
<td>3.3.1 Growth</td>
<td>11</td>
</tr>
<tr>
<td>3.3.2 Oxygen</td>
<td>15</td>
</tr>
<tr>
<td>3.3.3 Carrying Capacity</td>
<td>16</td>
</tr>
<tr>
<td>3.4 Economic Considerations</td>
<td>18</td>
</tr>
<tr>
<td>3.4.1 Model Review</td>
<td>18</td>
</tr>
<tr>
<td>3.4.2 Smolt Price and Production Costs</td>
<td>18</td>
</tr>
<tr>
<td>3.4.3 Market Potential for Atlantic Salmon</td>
<td>19</td>
</tr>
<tr>
<td>4.0 SPREADSHEET DEVELOPMENT</td>
<td>20</td>
</tr>
<tr>
<td>4.1 Inputs</td>
<td>22</td>
</tr>
<tr>
<td>4.2 Outputs</td>
<td>24</td>
</tr>
<tr>
<td>4.3 Temperature Regime</td>
<td>26</td>
</tr>
<tr>
<td>4.4 Growth and Biomass</td>
<td>26</td>
</tr>
<tr>
<td>4.5 Oxygen Use</td>
<td>27</td>
</tr>
<tr>
<td>4.6 Biophysical Considerations</td>
<td>29</td>
</tr>
<tr>
<td>4.6.1 Difference Between Salt/Fresh Water Datum</td>
<td>29</td>
</tr>
<tr>
<td>4.6.2 Screen Head Loss</td>
<td>31</td>
</tr>
<tr>
<td>4.6.3 Stability</td>
<td>32</td>
</tr>
<tr>
<td>4.6.4 Turgidity</td>
<td>35</td>
</tr>
<tr>
<td>4.7 Economic Considerations</td>
<td>37</td>
</tr>
<tr>
<td>4.7.1 Capital Costs</td>
<td>37</td>
</tr>
<tr>
<td>4.7.1.1 FVR Construction</td>
<td>38</td>
</tr>
<tr>
<td>4.7.1.2 Building and Storage Shed</td>
<td>38</td>
</tr>
<tr>
<td>4.7.1.3 Generator</td>
<td>39</td>
</tr>
<tr>
<td>4.7.1.4 Water Pump</td>
<td>39</td>
</tr>
<tr>
<td>4.7.1.5 PVC Piping</td>
<td>40</td>
</tr>
<tr>
<td>4.7.1.6 Boat and Skiff</td>
<td>40</td>
</tr>
<tr>
<td>4.7.1.7 Diving, Laboratory and Miscellaneous Equipment</td>
<td>40</td>
</tr>
<tr>
<td>4.7.2 Direct Operating Costs</td>
<td>41</td>
</tr>
<tr>
<td>4.7.2.1 Cost of Feed</td>
<td>41</td>
</tr>
<tr>
<td>4.7.2.2 Cost of Eggs</td>
<td>42</td>
</tr>
<tr>
<td>4.7.2.3 Cost of Electricity</td>
<td>42</td>
</tr>
<tr>
<td>4.7.2.4 Cost of Medication and Veterinary</td>
<td>43</td>
</tr>
</tbody>
</table>
4.7.2.5 Cost of Air Fills .................................. 43
4.7.3 Indirect Operating Costs ............................ 43
  4.7.3.1 Mortality Insurance ............................ 43
  4.7.3.2 Financing .................................... 44
  4.7.3.3 Management Cost ............................... 44
  4.7.3.4 Depreciation .................................. 44
  4.7.3.5 Cost of Labour ................................ 44
4.7.4 Net Operating Revenues ............................. 45
4.7.5 Net Cash Flow ..................................... 45
4.7.6 Break-Even Period ................................ 46

5.0 SPREADSHEET VALIDATION AND PARAMETER ESTIMATION ...... 46
  5.1 Growth Rates ...................................... 47
  5.2 Oxygenation and Flow Rate .......................... 48
  5.3 Changes in Head ................................... 51

6.0 SPREADSHEET ANALYSIS .................................. 51
  6.1 Spreadsheet Behaviour ............................... 54
    6.1.1 Influent Flow Rate and Oxygenation ............ 54
    6.1.2 Changes in Head ................................ 56
    6.1.3 Stability and Turgidity ........................ 57
  6.2 Case Studies ....................................... 61
    6.2.1 The Base Farm .................................. 62
    6.2.2 Farm Case 2 .................................... 63
    6.2.3 Farm Case 3 .................................... 69

7.0 CONCLUSIONS ........................................... 75

8.0 FURTHER STUDY AND SUGGESTIONS .......................... 79

BIBLIOGRAPHY ............................................... 81
# TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic Diagram of the Fresh Water Vertical Raceway (FVR) System Illustrating the Position of 3 Datum Points.</td>
</tr>
<tr>
<td>2</td>
<td>Flow Chart Illustrating Typical Timing and Mass for Atlantic Salmon Smolt Production.</td>
</tr>
<tr>
<td>3</td>
<td>A Map of the Computation Areas as They are Located on the Computer Generated Spreadsheet Simulation (CGSS).</td>
</tr>
<tr>
<td>4</td>
<td>A Schematic Diagram Defining the Criteria for Stability for the FVR.</td>
</tr>
<tr>
<td>5</td>
<td>A Comparison Between Equation (5) (Iwama) and Equation (2) (Stauffer) as Growth Models.</td>
</tr>
<tr>
<td>6</td>
<td>A Comparison Between Equation (2) (Stauffer) and Equation (5) (Iwama) with a $G_c$ of 0.675 in Equation (5).</td>
</tr>
<tr>
<td>7</td>
<td>The Amount of Oxygenation Needed Throughout a Typical Production Cycle when the Influent Flow Rate is Limited to 150, 300 and 600 l/min as Predicted by the CGSS.</td>
</tr>
<tr>
<td>8</td>
<td>A Comparison Between the Height of Fresh Water Above the Salt Water Datum (HSD) and the Contributing Portion of which is Attributed to the Screen Friction Loss (SFL).</td>
</tr>
<tr>
<td>9</td>
<td>The Relationship of Unlimited Influent Flow Rate for Increasing Fish Biomass as Predicted by the CGSS.</td>
</tr>
<tr>
<td>10</td>
<td>The Relationship Between Unlimited Influent Flow Rate and the Height Above the Salt Water Datum (HSD) as Predicted by the CGSS.</td>
</tr>
<tr>
<td>11</td>
<td>A Comparison Between the Inertial and Drag Force Differences of 4 FVR Shapes Indicating the Current Velocity Criteria for Liner Turgor.</td>
</tr>
<tr>
<td>12</td>
<td>The Effect of Stocked Smolt Numbers on the Net Cash Flow (NCF) for the Base Farm over 6 Cycles (Mortality = 20%).</td>
</tr>
</tbody>
</table>
Figure 13. The Relationship Between Net Cash Flow and Stocked Smolt Numbers over 6 Production Cycles for the Base Farm. .......... 66

Figure 14. The Relationship Between the Net Cash Flow and the Mortality Rate over 6 Production Cycles for Farm Case 3. ......... 72
LIST OF TABLES

Table I. The Temperature (T) Dependent Coefficients (K, M, and N,) to Determine Oxygen Uptake Rate 16

Table II. The Center of Buoyancy (CB), Center of Gravity (CG) and Metacenter (MC) Defining Stability for Four Different Shapes. 57

Table III. Economic Summary of Base Farm. 64

Table IV. Economic Summary of Farm Case 2. 67

Table V. The Percentage of the Total Cost per Smolt for Direct Operating Costs (DOPCOS) over 3 Production Cycles for Farm Case 2. 68

Table VI. Economic Summary of Farm Case 3. 71

Table VII. Summary of the Start-Up Costs and Percentage of Total Cost per Smolt in the First Production Cycle for Farm Case 3. 73

Table VIII. Summary of Start-Up Costs and Percentage of Total Costs for Smolts in First Production Cycle for Base Farm 2. 74
ACKNOWLEDGEMENTS

I am sincerely thankful to all the people that aided me technically and morally through the course of this thesis preparation. I would especially like to thank my thesis supervisor, Dr. Royann Petrell, for her guidance, patience and humanistic approach to teaching. I would also like to thank Dr. Victor Lo for being a tolerant thesis committee member that always had a smile for encouragement. As well, I would like to thank Dr. Beryl March for her "come to the rescue" edits and examination. Her effort made everything fall together. Dr. George Iwama provided a large impetus for my persistence in aquaculture research and I am therefore greatly indebted. As well, I would like to thank Mr. and Mrs. D. Fromberg for their gracious hospitality and valuable information without which this project would not have been possible.

Some special thanks are in order. The few words here won't express my gratitude to the following people but I imagine I'll get around to thanking them in a prairie monkey way. My sincere appreciation goes out to Pat Turner (for the insanity), Ken and Suzanne Raison (for being there), Colin Savage (for the sanity rides and unmeasurable technical direction), Marck Hudon (for his steadfastness and proofreading), Mike St. John (for his ol'salt experience and heart), Cindi Minnes (for her caring), Dave Hazlett (for his loyalty), Deanna Simmons (for her positivism), Ray Carrier (for his comradery) and to all of them for the advise, encouragement that comes from good friends even when all they've been hearing is "I've got to work on my thesis!"

Finally, to my Mom, Dad and sister Linda, thanks for being with me in spirit and hang'in in there with me!
1.0 INTRODUCTION

The salmon farmers of British Columbia are producing an increasing amount of Atlantic salmon (Pennell, 1988). The cost effectiveness of rearing Pacific salmon (*Oncorhynchus spp.*) in British Columbia is in question due to slow biological growth rates and market related problems. Alternative species and rearing techniques that lower costs are being sought (Spence, 1989). One such alternative species is the Atlantic salmon, *Salmo salar*, (Blackburn, 1989).

Atlantic salmon attain a saltwater-ready stage (smolt) at 30-70 grams (Hoar, 1989; Frantsi and Justason, 1988). This is 5-60 grams larger than most Pacific salmon smolts. In general, the rearing time for the Atlantic salmon smolt is longer than that of the Pacific salmon smolt (Laird and Needham, 1988). In the 1989-1990 growing season the production of Atlantic salmon smolts in British Columbia nearly doubled (Egan and Kenny, 1990). By 1995 the salmon production is projected to be 25,000 tonnes, approximately a third of which is expected to be Atlantic salmon. The combined effects of these two factors, 1) increased rearing times and 2) a higher proportion of Atlantic salmon stocks, will make present hatchery rearing space inadequate for future industry needs.

To address this rearing space problem an inexpensive freshwater lens system was investigated. The floating vertical raceway (FVR) can be assembled within an off-shore marine net-pen. It is filled with freshwater or varying
proportions of freshwater/saltwater and therefore floats on the denser saltwater (Fig. 1). This offshore facility has been used to rear Pacific salmon from fry to fully smolted stages in Auke Bay, Alaska (Heard and Martin, 1979; Martin and Heard, 1987; Martin and Wertheimer, 1987; Martin and Wertheimer, 1989). The benefits of the raceways are: 1) low construction and maintenance costs; 2) reduced mortality; 3) adaptability to sites that are remote or without suitable area for shore-based raceways; and 4) the ease of providing variable salinity for smoltification and therefore higher smolt survivability (Martin and Heard, 1987). Reliable and consistent utilization of the FVR system is expected to provide needed rearing space and increase the number of fish surviving through the parr-smolt.

The FVR system has only recently been introduced as a rearing system in British Columbia. Local farmers have expressed the view that inappropriate and unreliable designs can prevent successful application of the FVR systems. The design problems are generally associated with stability and turgidity of the raceway. Formulas of fluid statics can be used to predict the parameters that afford stability and turgor under given conditions of head, salinity and current forces (Vennard and Street, 1982).

The purpose of this study was to develop a computer-generated spreadsheet simulation (CGSS) that will be used to technically and economically evaluate different freshwater
Figure 1. Schematic Diagram of the Fresh Water Vertical Raceway (FVR) System Illustrating the Position of 3 Datum Points.
vertical raceway (FVR) systems. Every smolt farm is characterized by the location and can be described by a particular set of site specific parameters, i.e. species grown, number of smolts, temperature regimes, water flow regimes, oxygen availability, FVR dimensions and distances and elevations to freshwater sources. In this study three FVR farm cases were investigated. The CGSS can furthermore be a tool to assist producers, investors and banks in assessment of feasibility and profitability of other types of FVR systems.
2.0 OBJECTIVES

The objectives of this study were:

1) to describe mathematically in terms of biological and physical parameters a floating vertical raceway system to be used to rear Atlantic salmon smolts.

2) to analyze the physical system for those conditions which help maintain stability and turgor in the FVR.

3) to determine the economic feasibility of alternative raceway strategies.

The overall hypothesis is that all types of FVR systems are technically and economically feasible. Two subsets of null and alternative hypotheses can be formulated and stated as:

1) the null hypothesis ($H_0$) is that the physical system is unstable in terms of hydromechanics. The alternative hypothesis ($H_a$) is that the system is stable and
2) the null hypothesis \((H_0)\) is that the FVR system is not economically feasible under a given set of conditions. The alternative hypothesis \((H_a)\) is that the FVR is feasible under the same set of conditions.
3.0 LITERATURE REVIEW

3.1 The Freshwater Vertical Raceway (FVR)

At the Northwest and Alaska Fisheries Centre, in Auke Bay, Alaska, the freshwater lens system was demonstrated to be inexpensive rearing space that increased coho salmon, *Oncorhynchus kisutch*, survivability in seawater (Martin and Heard, 1987; Martin and Wertheimer, 1987; Heard and Martin, 1979). The FVR systems utilized the foreshore space already acquired for the marine grow-out phase of salmon aquaculture. As well, the survivability of the smolts had increased and can be measured by the saltwater challenge (Clarke, 1982; Clarke and Blackburn, 1978), or the number of adult returns (Martin and Wertheimer, 1987).

This vertical raceway (Fig. 1) consists of three primary components: 1) a rubber reinforced plastic liner (Hypalon); 2) a screened circular outlet drain; and 3) a floatation collar that provides a walkway. The inlet pipe delivers freshwater to the cone-shaped structure that, when filled, will be oriented vertically and float upon the denser saltwater. A 0.03-0.1 meter distance is maintained between the saltwater datum and the freshwater datum. A simple mixing device can be attached to the inlet pipe to control the proportion of saltwater/freshwater entering the unit (Heard and Salter, 1978).

Another FVR site is located approximately 80 kilometers northwest of Vancouver, on the south side of Agamemnon
Channel, in the Strait of Georgia. The site has been producing chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon smolts for six years. Stocking densities generally are no higher than the recommended 20 kg/m$^3$ (Martin and Heard, 1987). Coho salmon of a size of 35-50 grams are ready to be transferred to saltwater (smolted) within a 12 month production cycle. Four FVR units are gravity fed by 5, 6.4 cm diameter polyvinyl chloride (PVC) inlet pipes that run approximately 400 meters from a lake at an elevation of 120 meters above sea level. Each inlet pipe has an average flow rate of 150 l/min.

3.2 Atlantic Salmon Hatchery Techniques

The steps of the Atlantic salmon smolt production cycle are listed in Figure 2. Fertilized eggs are moved to trays in hatching troughs in October or November. The incubation and yolk-sac stages are timed so that the young will begin to feed when the water warms to 8-12°C in April. Incubation temperatures as high as 12°C allow the eggs to develop to the first feeding stage in late January/early February, however, temperatures of 8°-10°C are more typical incubation temperatures (Laird and Needham, 1988). Subsequently, first feeding does often not start until March or later.

Production times vary considerably depending on the specific temperature regime of the facility (Laird and Needham, 1988). A 0.1-0.2 gram fry will take from 12-18
months to achieve a smolt mass of 45 grams. Norwegian production times predict an 18 month cycle for Atlantic salmon to reach the seawater ready stage at 45 grams (Bjorndal, 1988; 1990).
Figure 2. Flow Chart Illustrating Typical Timing and Mass for Atlantic Salmon Smolt Production.
3.3 Biological Requirements

3.3.1 Growth

The specific or instantaneous growth rate "g" is defined as:

\[ g = \frac{1}{w} \frac{dw}{dt} \] (1)

where

\[ w = \text{mass of fish (gm)} \]
\[ \frac{dw}{dt} = \text{rate of mass change} \]

after integration, \( w \) can be determined:

\[ w = w_0 e^{gt} \] (1a)

where:

\[ w_0 = \text{initial mass (gm)} \]
\[ w = \text{final mass (gm)} \]
\[ t = \text{time (days)}. \]

Equation (1a) predicts fish growth accurately only under conditions where \( g \) is constant. The parameter "g" is dependent on initial mass \( w_0 \). As the fish mass changes continuously "g" also changes continuously, generally decreasing as the fish ages. Equation (1a) is only valid when the time interval "t" is short, typically one day (Ricker, 1979).
Accurate prediction of production cycles for commercial hatcheries requires that the most significant factors affecting growth should be revealed and controlled. Brett (1979) reviewed the factors that have the most significant influence on the growth of salmonids in hatcheries. The factors included water temperature, ration level, diet, species, race and sexual maturity. The consensus is that temperature is one of the most important factors affecting salmonid growth rate (Brett, 1979; Ricker, 1979; Iwama and Tautz, 1981; Brett, Clarke, and Shelbourne, 1982).

Stauffer (1973) developed an equation to predict fish growth in hatcheries based on data provided by an analysis of coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) growth. The researcher concluded that water temperature, fish mass and ration level had the most important predictable influence on fish growth. In a hatchery system ration level can be assumed to be maximum; therefore, the biology of a hatchery system can be based on the temperature-dependent growth of fish (Gates, MacDonald and Pollard, 1980). The equation that Stauffer developed

\[ w = (w_0^8 + ABt)^{1/8} \]  

where

\[ w = \text{final fish mass (gm)} \]
\[ w_0 = \text{initial fish mass (gm)} \]
\[
B = \frac{1}{3}
\]

\[
A = \text{a polynomial function of temperature}
\]

\[
t = \text{time (days)}
\]

is used for Washington State hatcheries (McLean, 1980) and as the basis for a pond management program developed for Island Science in Oregon (Thomsen, 1991).

Iwama and Tautz (1981) developed a simple temperature-dependent growth model for predicting salmonid mass. The data supported the idea that the instantaneous growth rate "g" was discretely related to temperature. They showed that various salmonid growth models could be reduced to the general form

\[
W_T^b = W_0^b + G_s t
\]  

(3)

where

\[
b = \text{a fitted exponent of weight}
\]

\[
t = \text{time (days)}
\]

\[
G_s = \text{growth slope} = \frac{T}{1000}
\]

\[
W_T = \text{weight at time } t \text{ (gm)}
\]

\[
W_0 = \text{weight at time } 0 \text{ (gm)}
\]

The growth slope \( G_s \) is a function of ration size (a constant maximum under culture conditions) and a linear function of temperature. The exponent \( b \) is relatively insensitive to change and therefore allowed the model to take the form of
\[ WT^{0.33} = W_0^{0.33} + \frac{T}{1000}t \]  \hspace{1cm} (4)

where

\[ T = \text{temperature (°C)} \]

and \( W^{0.33} \) vs. time is linear, and \( G_s \) is equivalent to \( \frac{T}{1000} \) and is linear with temperature over most temperatures used to rear salmonids (4°C-18°C).

Equations (3) and (4) were developed and are used for Pacific salmon hatcheries. Neither of these models specifically address Atlantic salmon growth and fish display a considerable interspecific range of growth rates. A paucity of Atlantic salmon growth models in the Canadian aquaculture industry exist (Saunders, 1991). Saunders and Harmon (1990) and Duston and Saunders (1989) have empirical data on juvenile Atlantic salmon growth but the period studied does not range through the full hatchery cycle. Storebakken and Austreng (1987) generated regression equations to define instantaneous growth rates for Atlantic salmon; however, the study only covered the first 6 months of the hatchery cycle.

To account for Atlantic salmon (and other species) growth rates, Iwama and Fidler (1989) added a variable growth coefficient \( G_c \) to equation 2. The equation took the form

\[ WT^{0.33} = W_0^{0.33} + G_c \left( \frac{T}{1000} \right)t \]  \hspace{1cm} (5)
The simplicity and flexibility of this model makes it appropriate for routine hatchery purposes.

3.3.2 Oxygen

Since the oxygen content of water is very low compared to that of air, growth and survival of fish can be limited by the influent oxygen concentration (Meade, 1975). For salmonids the minimum required water oxygen concentration should not fall below 6 mg/l (Laird and Needham, 1988). The farmer has two options to ensure that the fish are provided with adequate oxygen: 1) have available sufficient flow rate and/or 2) add supplemental oxygen, i.e. oxygenation (Laird and Needham, 1988).

Liao (1971) developed an equation to predict oxygen requirements for salmonids. Liao related oxygen consumption "RO" to fish mass and water temperature such that:

\[
RO = K(1.8 \cdot \text{ITEMP} + 32)^N \cdot \text{IWEI}^M
\]  

(6)

where:

\[\begin{align*}
\text{RO} &= \text{oxygen consumption (mg/kg/hr)} \\
\text{IWEI} &= \text{initial mass (gm)} \\
\text{ITEMP} &= \text{initial temperature (°C)}
\end{align*}\]

and the constants K, N and M are given in Table 1.
Table I. The Temperature (T) Dependent Coefficients (K, M, and N,) to Determine Oxygen Uptake Rate

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>T &lt;= 10°C</td>
<td>9.828E-04</td>
<td>-0.194</td>
<td>3.20</td>
</tr>
<tr>
<td>T &gt; 10°C</td>
<td>6.689E-04</td>
<td>-0.194</td>
<td>2.12</td>
</tr>
</tbody>
</table>

This formula has been utilized extensively to determine oxygen requirements for coho and chinook salmon. Cook and Canton (1988) developed a spreadsheet program that can be used in conjunction with equation (6) to calculate percent oxygen saturation of the water.

3.3.3 Carrying Capacity

The carrying capacity is a function of fish biomass and the water's capacity to carry oxygen. The facilities oxygen capacity will limit the number of smolts produced. Most farms will have a freshwater limit, a related oxygen limit and therefore a smolt (fish biomass) production limit.

Weber (1970) demonstrated that knowing the oxygen consumption rate (Eq. 3) and the oxygen saturation allows the prediction of the average daily pond effluent oxygen concentration. Weber also determined effluent oxygen concentration as a function of carrying capacity. McLean
(1980) rearranged Weber's equation to solve for carrying capacity at a given effluent oxygen concentration. McLean's equation is as follows:

\[
L = \frac{28500 \times O_2 SAT - 60X_0 \times (T + 32.035)}{R_0 \times (T + 32.035)}
\]  

(7)

where:

\[
L = \text{carrying capacity (kg/l/min)}
\]

\[
O_2 SAT = \text{percent oxygen saturation}
\]

\[
X_0 = \text{effluent oxygen concentration (mg/l)}
\]

\[
T = \text{temperature (°C)}
\]

\[
R_0 = \text{oxygen consumption rate (mg/kg/hr)}
\]
3.4 Economic Considerations

3.4.1 Model Review

Egan, Egan and Wright (1989); Lee (1988); Combs (1986) and MacGregor (1986) have developed spreadsheet models for financial analysis of the post-hatchery phase of salmon farming in British Columbia. Other spreadsheet models have been produced by private consulting companies such as Scantech Resources Limited, Entech Environmental Consultants and Envirocon Limited (Lee, 1988).

The above models simulate the economics of a post-hatchery fish farm system. The objective of these models was to determine economic feasibility and provide a financial analysis of a standard post-hatchery fish farm. Typical investment measures used by these models were cash flow, internal rate of return, net present value, breakdown of input costs and break-even price. The main emphasis was on economic indicators and investment evaluation. None of the reviewed models considered either the economic or technical feasibility of a hatchery system.

3.4.2 Smolt Price and Production Costs

The selling price of a 50-60 gram Atlantic salmon smolt in B.C. was $3.50 as of February, 1991 (Ministry of Agriculture and Fisheries, 1991). This price varied within that month from $3.25-$3.75 per smolt. The production costs for an Atlantic salmon smolt in B.C. have ranged from $2.00-
$3.00 (Kenny, 1991). Bjorndal (1990) listed the production cost of an Atlantic salmon smolt in Norway to vary between $1.22-$1.88. Bjorndal (1990) also noted the Scottish Atlantic salmon production cost was $1.60 per smolt.

The B.C. smolt production costs are considerably higher than in Europe. As production cost breakdowns were not available for the hatchery stage of the production cycle, it is difficult to determine the cause of the cost differential.

3.4.3 Market Potential for Atlantic Salmon

In 1978 the Canadian government sponsored a feasibility study on the commercial culture of Atlantic salmon at Deer Island, New Brunswick (Sutterlin et al., 1981). Since then the private sector has continued to develop the industry in eastern Canada. By 1987 Atlantic salmon were being commercially farmed in British Columbia. In 1990 15% of the farmed salmon in B.C. were Atlantic salmon (Egan and Kenny, 1990).

By 1995 the salmon aquaculture production in British Columbia is projected to be 25,000 metric tonnes (MT). An increasing proportion of this production will be Atlantic salmon. By the year 2000 it has been projected that Atlantic salmon and chinook will be raised in equal numbers in British Columbia (Needham, 1990).

Between 1955 and 1981 the price of Atlantic salmon, deflated by the consumer price index, has increased by about
54% (Kabir and Ridler, 1984). The increased demand for Atlantic salmon in B.C. is reflected in the selling price of the Atlantic smolt. As of February, 1991 the cost of an Atlantic salmon smolt was $3.50 (Ministry of Agriculture and Fisheries, 1991).

These increasing figures support a strong domestic market demand for farmed Atlantic salmon. Both demand and price for Atlantic salmon within Canada suggest that the domestic market should grow by 4.2% annually (Ridler and Kabir, 1988).

4.0 SPREADSHEET DEVELOPMENT

Mathematical analogs of aquaculture systems have three uses: planning and research; identification and control; and finally economic analysis (Fridley, 1986). Three general categories of modelling are available to the investigator to integrate relationships: simulation and validation, mathematical programming and spreadsheet analysis. The microcomputer spreadsheet is an easy medium for communication between researchers, technicians, business and banking personnel and the producer (Leung and Rowland, 1989) and was therefore chosen to simulate and analyze a FVR. A map of the Quattro Pro spreadsheet that was developed over the course of this study is depicted in Figure 3. A person familiar with spreadsheets will be able to fully manipulate variables and parameters to query a typical farm case.
Figure 3. A Map of the Computation Areas as They are Located on the Computer Generated Spreadsheet Simulation (CGSS).

- **Input**
  - Temp
  - Growth and Biomass
  - Oxygen Use
  - Stability and Turgidity
  - O2 Saturation
  - Specific Density and Weight for Salt and Freshwater

- **Economics**
  - Capitol Costs
  - Operating Costs
  - Revenue
  - Net Farm Income
Generally, a computer-generated spreadsheet (CGSS) is initiated from a set of variable inputs. A series of computations, restricted by system assumptions and parameters, are then made. The assumptions and parameters have been resolved from the literature, actual FVR site measurements and model estimation. The results of the computations are displayed as outputs in the areas represented in Figure 3.

The CGSS was developed on the following assumptions:

1) a 12-18 month production cycle
2) a final stocking density of 20 kg/m³
3) satiation/maximum ration feeding
4) electricity is obtained from B.C. Hydro grid
5) bottled oxygen through a diffusion stone is used for oxygenation

4.1 Inputs

The CGSS can be used to determine and assess the biological, technical and economical feasibility of an FVR production system given a set of variable inputs. These inputs include:

1) **temperature regime** - in terms of the average monthly temperature (°C);
2) **growth coefficient** \( (G_c) \) - 0.675 as determined for Atlantic salmon (see section 5.1);
3) initial smolt number - which can range from 1-120,000 smolts;

4) initial smolt mass - which is actually the alevin or fry mass when it is first introduced into the FVR unit usually between 0.05-0.2 grams);

5) decimal fraction mortality rate - which is the expected mortality rate of the fish over the entire smolt production cycle i.e. 0.20;

6) dimensions of FVR - given in meters as the diameter, the depth from the outlet screen to the saltwater datum, and, in the case of a hemisphere, the radius, of the unit;

7) current velocity - which is the expected velocity of the seawater at the site i.e. 0.5 m/s;

8) influent oxygen concentration - which is the amount of oxygen in the source water (mg/l);

9) salt and freshwater salinity - which are values given in parts per thousand (%) of the salinity inside and outside of the FVR;

10) flow rate - which is the volume per unit time of the inlet water supply (l/min);

11) gravity flow or pump (G/P) - which gives the user the choice of evaluating costs with (P), or without (G) an electric pump (see below);

12) oxygenation (Y/N) - which again provides the user with the choice of evaluating the costs with (Y), or without (N) supplemental oxygen.
13) **elevation above water source** - which determines the portion of the pumping costs that accounts for lifting water from a source height (m);

14) **distance from water source** - which determines the portion of the pumping costs that accounts for moving water through a PVC pipe from the water source (m).

The inputs provided above will be used within the equations described within this section. The computations are performed and subsequent output values are determined.

### 4.3 Outputs

With the inputs and computations the CGSS calculates the following outputs:

1) **monthly biomass estimates** - where individual smolt mass is expressed in grams (g) and total crop biomass is expressed in kilograms (kg);

2) **respiration and oxygenation** - where fish respiration is expressed in milligrams of oxygen per kilogram of fish every hour (mg/kg/hr) and supplemental oxygen is expressed similarly;

3) **carrying capacity** - i.e. the potential mass of fish that can be sustained by the oxygen content in the culture water expressed in kilograms of fish for every litre of water per minute (kg/l/min);
4) **volume and specific weight** - that is the volume in cubic meters \((m^3)\) of water of the FVR and the specific weight of salt and freshwater in Newtons for every cubic meter \((N/m^3)\);

5) **the number of FVR units** - as the biomass increases within each unit the stocking density increases. When the stocking density reaches 20 kg\(/m^3\) the CGSS assumes another unit will be added to the facility in order to accommodate this increasing biomass. The price of all the units are assumed to be accounted for in the capital costs;

6) **stability and turgidity** - of four different shapes (frustrum, cuboid, hemisphere and paraboloid) of FVR - where stability is based on criteria explained below and turgidity dependent on the force, in Newtons, applied on the inner and outer surfaces of the liner;

7) **capital and operating costs** - that largely depend on economic assumptions stated below;

8) **total revenues and net farm income** - that are determined mostly by harvest value;

9) **break-even period** - that reflects when the farm revenues can offset the total investment.

The following sections are included to illustrate how the CGSS was developed.
4.3 Temperature Regime

As described above, temperature is the main environmental factor affecting growth (see section 3.3.1). It is important to use a temperature regime that accurately reflects the situation of the hatchery system. The spreadsheet in this investigation utilized average monthly temperatures that were obtained from the Agamemnon FVR site. Any regime may, however, be substituted to suit the particular site in question.

4.4 Growth and Biomass

Equation (5) was used with initial smolt mass and the growth coefficient to determine the final smolt mass. Mass was determined for 30 day (monthly) increments. This mass was then used as the initial mass for the next monthly calculation. A mortality calculation is included to obtain total numbers of fish for each monthly increment. Values of fish mass and total fish numbers were multiplied to obtain total fish biomass.

Feed amounts were then calculated. The feed amounts depend on Moore-Clarke feeding charts (Moore-Clarke, 1991). The percentage of body mass fed to the fish per day is dependent on size of fish and temperature. It will vary from 0.9-7.0 %/day.
4.5 Oxygen Use

Equations (6) and (7) are used in succession to determine the oxygen consumption (mg/kg/hr) and carrying capacity (kg/l/min). Total oxygen consumed (mg/hr) is also computed.

The flow rate, \( Q \) (l/min), can then be determined as it corresponds to the carrying capacity. The flow rate is obtained by dividing the total biomass of fish by the carrying capacity as

\[ Q = \frac{\text{WEI}}{L} \]  

(8)

where

\[ Q = \text{flow (l/min)} \]
\[ \text{WEI = total biomass of fish (kg)} \]
\[ L = \text{carrying capacity (kg/l/min)} \]

To mitigate the effects of inadequate water flow, as mentioned in section 3.3.3, it is possible to supplement the existing oxygen with compressed oxygen (Kepenyes, 1984). Compressed oxygen is inexpensive and convenient for remote sites. The supplement rate is a function of flow, influent and effluent oxygen concentrations, volume and stocking density such that:

\[ R_A = \frac{(\text{SD} \times V \times R_0) - Q(X_s - X_o)}{\text{SD} \times V} \]  

(9)

where
\[ R_A = \text{oxygenation rate} (\text{mg/kg/hr}) \]
\[ \text{SD} = \text{stocking density} (\text{kg/m}^3) \]
\[ V = \text{volume of vertical raceway} (\text{m}^3) \]
\[ X_s = \text{influent oxygen concentration} (\text{mg/l}) \]
\[ Q = \text{flow rate} (\text{m}^3/\text{hr}) \]

The rate at which the oxygen is transferred into a soluble form is also considered. It is assumed that a diffusing stone introduces compressed oxygen into the FVR at a rate \( R_A \) multiplied by the oxygen absorption efficiency. The absorption efficiency is defined by the amount of oxygen absorbed by the water divided by the oxygen added to the water and is used to account for the mechanisms involved in oxygen transfer. Oxygen is transferred from the bubbles of a stone diffuser to the water by diffusion across the liquid film. The two-film theory of gas transfer applies to this situation (Tchobanoglous, 1979). Oxygen diffuses into the water as the bubble rises, the oxygen concentration in the bubble and the concentration gradient between water and gas decreases as the bubble rises. Submergence depth of the diffuser stone increases oxygen absorption with increasing depth. It is assumed that the oxygen absorption efficiency of the diffusing stone is 30\% (Tchobanoglous, 1979).
4.6 Biophysical Considerations

4.6.1 Difference Between Salt/Fresh Water Datum

The fundamental approach to predict head changes in a body of liquid (the FVR) is to utilize the mass balance flow rate equation and two usages of Bernoulli's equation. From the principle of mass balance and assuming the liquid is of constant density,

\[ \rho Q = \rho A_1 V_1 = \rho A_2 V_2 \]  \hspace{1cm} (10)

where

- \( \rho \) = density of water (kg/m\(^3\))
- \( Q \) = input flow rate (l/sec)
- \( A_1 \) = cross-sectional area at top of raceway (m\(^2\))
- \( V_1 \) = velocity at the surface of the raceway (m/s)
- \( A_2 \) = cross-sectional area at bottom of raceway (m\(^2\))
- \( V_2 \) = velocity at the bottom of the raceway (m/s)

The velocity at the bottom of the tank is calculated using equation 6 and \( Q \), the input flow rate. Two usages of Bernoulli's equation will be used to calculate the head (m) above the freshwater datum. The procedure follows. The general form of Bernoulli's equation for 2 points within a control volume is:

\[ \frac{P_1}{\gamma_1} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g} + z_2 + \Delta H \]  \hspace{1cm} (11)
where

\[ P_1 = \text{Pressure at point 1 (Pa)} \]
\[ P_2 = \text{Pressure at point 2 (Pa)} \]
\[ \gamma_1 = \text{Specific weight of liquid at point 1 (N/m}^3\text{)} \]
\[ \gamma_2 = \text{Specific weight of liquid at point 2 (N/m}^3\text{)} \]
\[ g = \text{acceleration due to gravity (m/s}^2\text{)} \]
\[ z_1 = \text{depth at point 1 (m)} \]
\[ z_2 = \text{depth at point 2 (m)} \]
\[ \Delta H = \text{frictional head loss (m)} \]

One usage of Bernoulli's equation is used to find the pressure at the outlet screen depth, \( P_2 \). In this case, the freshwater datum is, \( z_1=0 \), \( V_2 \) is determined from Equation (6), \( \gamma_1 = \gamma_2 = \gamma_f \) (freshwater) and \( P_1 = 0 \). The depth, \( z_2 \), equals the known design length of the FVR, TL. The pressure \( P_2 \) is solved for as follows:

\[ P_2 = (\gamma_f*(V_1^2-V_2^2))/2g - \Delta H\gamma_f - TL\gamma_f \]  \hspace{1cm} (12)

where \( \Delta H \) = the combined friction losses due to pressure loss across the screen and liner wall friction.

The second usage of Bernoulli's equations uses \( P_2 \) from equation (12) to solve for \( h \), the distance between the salt and fresh water datum. In this case the saltwater datum is \( z_1 = 0 \), \( z_2 = H \), where \( H = TL-h \), \( \gamma_1 = \gamma_2 = \gamma_s \) (saltwater) and \( P_1 = 0 \).
The parameter $P_2$ is substituted into equation (13), and the equation is rearranged to solve for $h$,

$$h = \frac{\left(\gamma_s (V_f^2 - V_s^2)/2g\right) - \Delta H \gamma_f - TL (\gamma_s - \gamma_f)}{\gamma_s}$$

(14)

The specific weights of waters of different salinities are estimated with the International Equation of State of Sea Water (Pond and Pickard, 1989)

4.6.2 Screen Head Loss

The screen at the bottom of the vertical raceway causes friction loss that will diminish the effective area of the outlet. This reflects as a frictional head loss, $\Delta H$, predicted by the following equation (Beveridge, 1987):

$$\Delta H = C \frac{V^2}{2g}$$

(15)

where

$C$ = discharge coefficient

$V$ = velocity at screen

The discharge coefficient, $C$, is a function of velocity and screen mesh size. This coefficient is empirically calculated.
(Beveridge, 1987) and is therefore specific to a given situation. The \(H\) measurements from the Agamemnon site and from Heard and Martin (1978) were used to estimate \(C\) (see section 5.3).

### 4.6.3 Stability

For a body such as the floating vertical raceway, stability is important. Stability means that a body will return to the original position after being rotated about a vertical or horizontal axis by wave or current forces.

A floating body is in equilibrium with the center of gravity (CG) above the center of buoyancy (CB) on a vertical axis. If a force causes the body to rotate slightly, although the location of the center of gravity remains fixed, the location of the center of buoyancy shifts because the displaced volume of fluid has changed (Fig. 4). The buoyant force and the weight of the body create a couple that tends to produce a righting moment that returns the body to the original position.

This definition of stability can also be made with reference to the point of intersection of the vertical axis and the line of action of the buoyant force. This point of intersection is known as the metacenter (MC). A floating body is stable if CG is below MC and unstable if CG is above MC.

The first step to determine if a freshwater inverted cone, or another shape, would be stable while floating in
Figure 4. A Schematic Diagram Defining the Criteria for Stability for the FVR.
saltwater is to determine the submerged depth of the cone, \( H = TL - h \) (see section 4.6.1). CG is the centroid of the cone and can be determined as

\[
CG = \frac{(H + h)}{4}
\]

Similarly CB can be determined as the centroid of the cone that is submerged to depth D in saltwater as

\[
CB = \frac{H}{4}
\]

The determination as to whether the center of gravity is below or above the metacenter can be made quantitatively by using the following equation to determine the distance from CB to MC:

\[
MB = \frac{I}{V_d}
\]

where

\[
MB = \text{distance from CB to MC}
\]

\[
I = \text{moment of inertia}
\]

\[
V_d = \text{volume of fluid displaced}
\]

For an inverted cone the moment of inertia is given by

\[
I = DIAP*H^3/36
\]
and the volume of fluid displaced by

\[ V_d = \frac{1}{3} (\pi \text{DIAP}^2 \cdot \frac{D}{4}) \]  \hspace{1cm} (20)

where DIAP is an input of the top diameter of the cone.

Iterations used during the determination of stability are performed on a hemisphere, cuboid and paraboloid to determine the relative stability of each.

4.6.4 Turgidity

Drag forces due to currents of sufficient magnitude can affect the turgidity of the vertical raceway. The FVR is turgid if the sum of the forces acting on the outside of the liner \( (F_s) \), the pressure drag, is equal to the sum of the forces acting on the inside of the liner \( (F_f) \). If \( F_f < F_s \), or \( F_f > F_s \), then the liner is not turgid. When a current of magnitude \( F \) is applied to the FVR then \( F_s \) increases. The force, \( F \), applied to the vertical raceway can be determined by:

\[ F = f_o \sigma V^2 A / 2g \]  \hspace{1cm} (21)

where

\[ f_o = 0.074R^{-0.2} \]
\[ \sigma = \text{density (kg/m}^3\text{)} \]
\[ V = \text{velocity (m/sec)} \]
\[ A = \text{projected area normal to direction of flow} \]
The Reynold's number, \( R \), for a body of revolution, that is a paraboloid, hemisphere, cuboid or frustrum, can be obtained from the relationship

\[
R = \frac{DV}{\nu} \quad (22)
\]

where

\[
D = \text{diameter of body}
\]

\[
\nu = \text{kinematic viscosity}
\]

The pressure or form drag \( F_s \) is directly proportional to the projected area of the body normal to the direction of water flow (Eq. 21). Three FVR shapes, or forms, were chosen besides the frustrum to represent a cross section of form drags (the cuboid being the shape with the greatest form drag and the hemisphere being the shape with the least form drag). Each of these different forms would be expected to maintain turgidity under different current velocities.

The current force outside of the liner \( F_s \) must now be measured against the inertial, static force inside of the vertical raceway \( F_i \) to determine if turgor is maintained. The force \( F_i \) is equivalent to the force applied by the freshwater head determined by adding \( V_d \), from equation (20), and \( \Delta H \), from equation (10), and then multiplying this sum by the specific weight of freshwater (Pond and Pickard, 1989).
4.7 Economic Considerations

To determine if a FVR system is economically feasible a breakdown of input costs is first established. Subsequently, the net cash flow (NCF) and therefore the break-even period can be determined.

The following calculations are needed to determine the NCF: 1) the total start up costs for the FVR system, the capital costs; 2) the costs of operating the farm, that is the direct and indirect operating costs and; 3) the revenue obtained by selling the smolts, the total revenue. The break-even period is resolved when the NCF is positive and when a surplus is accumulating. Factors contributing to the NCF and break-even period will be explained in this section.

An inflation rate of 4% per year is taken into consideration. As well a tax rate is set at 33% of the net operating revenue. It is assumed that if the net operating revenue is negative that no tax or tax credit will be imposed.

4.7.1 Capital Costs

The capital costs are the initial costs to start up a FVR operation. These costs do not include the costs associated with the routine operation of smolt growout. Capital costs include costs of: liner, floats and mooring, building and storage shed, generator, motor and pump, a skiff, PVC piping, boat, diving equipment, lab equipment and miscellaneous tools.
4.7.1.1 FVR Construction

The cost of the FVR construction is a function of 3 factors: liner cost; floating collar cost and mooring. The floating collar is considered to be a typical aluminum framed structure common in the industry. A typical cost for each float and walkway system is $5000 (Fromberg, 1991). The mooring charges are assumed to be $5000 to start up the farm and then $1500 for each individual FVR unit (Egan, Egan and Wright, 1989). The cost of liner construction is dependent on surface area. The dimensions are obtained as inputs (see section 4.1). The materials used for construction are typically a 1.14 mm thick Hypalon or Shelterite liner. The cost of the material is quite variable. Suppliers in the U.S. provide the best price of $8.81/m² while Canadian suppliers may be as high as $45.21/m². The higher cost has been used in the spreadsheet.

The liner and mooring have no salvage value. The life expectancy of the liner, floats and mooring are 3, 10 and 10 years, respectively.

4.7.1.2 Building and Storage Shed

The building and storage shed are necessary to accommodate employees, equipment and feed. The building price has been set at $13,725 (Lee, 1988) although it should be noted that building costs are highly variable depending on material and design. Fromberg (1991) used wood framing and
polyethylene sheets to construct a feed shed at $1,920. The two costs are assumed in the CGSS.

The salvage value and expected life expectancy of the building is $3000.00 and 15 years. The respective values for the storage shed are $400.00 and 10 years.

4.7.1.3 Generator

Although the FVR sites in this study are assumed to be on the B.C. Hydro power grid the farm must be prepared for power failures. A five kilowatt diesel generator has accordingly been included with a price set at $6,000 (Ministry of Agriculture and Fisheries, 1989).

The generator has no salvage value and expected life expectancy of 10 years.

4.7.1.4 Water Pump

A water pump is necessary in situations where gravity-assisted flow is not available. A water pump with a capacity of 700-1000 l/min has been included at a cost of $3126 (Ministry of Agriculture and Fisheries, 1991). A typical pump efficiency of 0.75 is assumed (Wheaton, 1985).

The pump has no salvage value and an expected life span of 3 years.
4.7.1.5 PVC Piping

Each FVR unit has two 6.4 cm PVC pipes directing the input water flow. The cost of this pipe is $9.88 per meter (Ministry of Agriculture and Fisheries, 1991). The amount of pipe needed is determined from the inputs, distance from source and elevation from source (see section 4.1).

The PVC is assumed to have no salvage value and a life expectancy of 5 years.

4.7.1.6 Boat and Skiff

Both a crew work boat and an aluminum skiff are necessary to perform routine operations and maintenance on any marine farm. The cost of a 12 ft aluminum boat is set at $2,433. The price of a larger 18 ft aluminum skiff would be $12,623 (Ministry of Agriculture and Fisheries, 1991).

The salvage value and expected life expectancy of the boat is $300.00 and 10 years. The respective values for the skiff are $1262.00 and 10 years.

4.7.1.7 Diving, Laboratory and Miscellaneous Equipment

Diving equipment allows compulsory inspection and maintenance of all underwater facilities. The cost of two dry suits and accompanying equipment is set at $3,299. Basic laboratory equipment to maintain health and water quality are expected. The cost of this equipment is set at $5,000 (Lee,
Miscellaneous equipment such as dip nets, power tools and hand tools are necessary for routine operation of the farm. An average cost for these are $2,950 (Lee, 1988).

None of the above items has a fixed salvage price. The expected life spans of the items are 3, 5 and 10 years, respectively.

4.7.2 Direct Operating Costs

The factors that contribute to direct operating costs are: feed, eggs, electricity, oxygen, veterinary supplies, SCUBA air fills.

4.7.2.1 Cost of Feed

The actual cost of feed can vary greatly especially under conditions where hand-feeding accounts for fish response (Malamus, 1991). For the purposes of projections, however, it is assumed that the feed amounts will follow Moore-Clarke feeding charts as stated in section 4.4. The cost of feed (FEED) can then be determined as

\[ \text{FEED} = \text{cost/kg feed} \times \text{total feed consumed (kg)} \]

The cost of feed is set at $1.25/kg (Ministry of Agriculture and Fisheries, 1991).
4.7.2.2 Cost of Eggs

The cost of eggs is assumed to be $400.00 dollars per litre of eggs (Bjorndal, 1990). Each liter of Atlantic salmon eggs contains approximately 4000 individual eggs.

4.7.2.3 Cost of Electricity

The cost of electricity (ELEC) is based on the sum of all the pumping costs for each month (t) of the production cycle as follows:

\[ ELEC = \$ / \text{KWhr} \times \sum_{t=0}^{18} \text{POW} \tag{23} \]

where, in this case \( t=18 \) and,

\[ \text{POW} = \frac{Q \gamma H_i}{MPEFF} \]

\( H_i = \) total of head losses (m)

\( MPEFF = \) motor/pump efficiency (0.75)

\( Q = \) water flow l/hr

\( \gamma = \) specific weight of water (N/m\(^3\))

The price of electricity is fixed at $.057/KWhr and it is assumed that the motor and pump efficiency are both 0.75 (Wheaton, 1985).
4.7.2.4 Cost of Medication and Veterinary Service

Lee (1988) determined the average costs for fish medication and veterinary service at eight different B.C. farm sites. This cost is thus fixed at $.08/kg of fish at harvest.

4.7.2.5 Cost of Air Fills

In this study at least one dive per week is assumed to be necessary to maintain and inspect the FVR. The price of an air fill is set at $5.00. For the entire production cycle air fill cost will be fixed at $360.

4.7.3 Indirect Operating Costs

Indirect costs arise from work that is beneficial to the farm or not directly attributable to smolt production. Included in the indirect operating costs are: mortality insurance, financing cost, depreciation, labour and maintenance and testing.

4.7.3.1 Mortality Insurance

The premiums for mortality insurance are based on the expected harvest value multiplied by an insurance rate of .04 (Lee, 1988).
4.7.3.2 Financing

Interest will accrue on the start-up cost, or capital cost, at an annual rate that can be set by the user. For this study the interest rate is arbitrarily set at 15% per annum.

4.7.3.3 Management Cost

The management cost is the salary of the owner/operator of the fish farm. This amount will be arbitrarily set at $55,000.00.

4.7.3.4 Depreciation

Depreciation is calculated simply as the straight-line method which is an inverse function of the lifespan of the equipment (Lee, 1988) such that:

\[
D = \frac{IC - SV}{LY}
\]

where

\[
D = \text{Depreciation cost}
\]
\[
IC = \text{Initial cost}
\]
\[
SV = \text{Salvage value}
\]
\[
LY = \text{Expected life of equipment (years)}
\]

4.7.3.5 Cost of Labour

The cost of labour is based on 1 labourer with a monthly wage of $1,500 (Ministry of Agriculture and Fisheries, 1989).
The labour includes job functions such as stocking, feeding, harvesting and transporting of fish.

4.7.4 Net Operating Revenues

The Net Operating Revenue (NOR) is determined by the product of number of smolts sold and the value per smolt (total revenue) minus the total cost within a cycle. The number and size of smolts produced is calculated by the biological system (see section 4.2).

The value of the smolt is typically set by the market. Currently 50-60 gram Atlantic salmon smolts sell for $3.50 per smolt (Ministry of Agriculture and Fisheries, 1991).

4.7.5 Net Cash Flow

The Net Cash Flow (NCF) of a hatchery system can be calculated by subtracting the costs of production from the total revenue from the sale of smolts (Allen et. al., 1984; Bjorndal, 1988 and Bjorndal, 1990). The cost of lost opportunities, i.e. interest on operating and capital costs and operator labour and management, is considered in this calculation (Ministry of Agriculture and Fisheries, 1989). Hatchery systems that variably affect these component costs will directly alter the NCF (Schueller and Krutz, 1989).
4.7.6 Break-Even Period

The break-even period is the cycle in which the NCF is positive and a surplus of cash is established. The total revenue will consistently exceed the total costs of farm operation and start-up.

5.0 SPREADSHEET VALIDATION AND PARAMETER ESTIMATION

Simulated experiments performed on the CGSS were first conducted to compare to the actual data accumulated from and at the two aforementioned FVR farm sites. This is the process of validation. More specifically the physical characteristics that define the FVR system (i.e. the height of fresh water above the salt water datum) are compared to the computed values. This specific process is parameter estimation.

Fish growth, oxygenation and flow rate, changes in the freshwater height above the saltwater datum (HSD), and stability and turgidity of the FVR were investigated and compared to actual data. These investigations generated output and parameter estimations that further resolved the simulated FVR system. The results from these initial investigations were used as revised inputs.

The CGSS was provided with a growth coefficient and production cycle that emulated Atlantic salmon growth rates, otherwise it was given inputs that reflected the Agammemnon farm site. These were:
1) **temperature regime** - averaged monthly temperatures of the FVR in Agamemnon Channel

2) **growth coefficient** \((G_c)\) - 0.675

3) **initial smolt number** - 50,000

4) **initial smolt mass** - 0.2 g

5) **length of production cycle** - 18 months

6) **decimal fraction mortality rate** - 0.20

7) **dimensions of a frustrum FVR** - top diameter 6.2 m, bottom diameter 4.2 m, depth 4.75 m

8) **current speed** - 0.5 m/s

9) **influent oxygen concentration** - 11 mg/l

10) **oxygenation** (Yes)

11) **salt and freshwater salinity** - 24 ppt, 0 ppt, respectively

12) **distance from water source** - 1400 m

13) **elevation of source** - 130 m

14) **flow rate** - 300 l/min

15) **gravity flow or pump** (Gravity)

### 5.1 Growth Rates

Two Pacific salmon growth models (Eq. 2 and Eq. 5) were compared to determine which would better validate Atlantic salmon growth rates. Through iteration, Equation 5 provided the best fit Atlantic salmon growth if \(G_c\) was 0.675.
Equation (2) was compared to equation (5) in Figure 5. Both models have a very similar growth curve that have an exponential expression with increasing time. Both Equation (2) and (5) were developed from *Oncorhynchus* spp. growth data. However, adjusting the growth coefficient, as suggested by Iwama and Fidler (1989), allowed Equation (5) to more closely fit Atlantic salmon growth rates.

An adjustment of the growth coefficient to 0.675 in equation (5) closely approximated Atlantic salmon growth rates of 45 grams in twelve months, 365 days, (Laird and Needham, 1989) and in 70 grams (Bjorndal, 1990) in fifteen months, 450 days (Fig. 6). Equation (2) significantly overestimated fish mass with respect to a 12-15 month (365-450 days) Atlantic salmon growth period.

5.2 Oxygenation and Flow Rate

At the Agammenon FVR site supplemental oxygen had been used to maintain the oxygen saturation of the culture water. Influent flow rates, Q, were limited to 150 and 300 l/min. CGSS tests were performed to determine the oxygen needs for a simulated Agammemnon FVR unit at the influent water flow rates of 150 and 300 l/min. When the parameter "Q" is limited to actual flows the CGSS validated the need for supplementary oxygen (Fig. 7).
Figure 5. A Comparison Between Equation (5) (Iwama) and Equation (2) (Stauffer) as Growth Models.
Figure 6. A Comparison Between Equation (2) (Stauffer) and Equation (5) (Iwama) Growth Models with a $G_c$ of 0.675 in Equation (5).
5.3 Changes in Head

The predicted HSD varied between 0.094-0.097 m. It was not significantly different than the HSD at the Agamemnon FVR site (0.105 m) and fell within the range of the documented HSD, 0.03-0.10 m (Martin and Heard, 1987).

Screen friction loss (SFL) was expected but the extent of the friction was uncertain. The actual HSD (h in Eq. 9) at the Agamemnon FVR site was used in the CGSS to calculate SFL (∆H) and the screen drag coefficient C (see Eq. 7 and Eq. 10).

The parameter C was determined to be 9.28E05. At a flow rate of 150 l/min the screen friction component of HSD is approximately 0.006 m and is relatively unvarying with respect to the HSD (Fig. 8). The force against the screen and liner associated with this height is 1041 N.

6.0 SPREADSHEET ANALYSIS

From validated and estimated model parameters determined in the previous section the technical and economic output of the CGSS was analyzed. Design criteria for technical feasibility are determined from the spreadsheet behaviour. The economic feasibility is determined through the analysis of farm case studies.

6.1 Spreadsheet Behaviour

Inputs of the CGSS were varied to determine how this variation effects system outputs. By analyzing the output of this variation it is possible to generate preliminary FVR
Figure 7. The Amount of Oxygenation Needed Throughout a Typical Production Cycle when the Influent Flow Rate is Limited to 150, 300, and 600 l/min as Predicted by the CGSS.
Figure 8. A Comparison Between the Height of Fresh Water Above the Salt Water Datum (HSD) and the Contributing Portion of which is Attributed to the Screen Friction Loss (SFL).
design criteria. Influent flow rate and current velocity are two inputs that may affect the FVR operation in terms of supplemental oxygen and stability and turgor.

6.1.1 Influent Flow Rate and Oxygenation

A CGSS test run allowed the influent flow rate to change with the increasing respiration needs of the growing fish. Generally the flow rates increased with increasing fish biomass (Fig. 9). The relationship between increasing biomass and flow rate is sigmoidal. This is partially an artifact of the yearly temperature regime. The initial maximum is an additive result of the increased fish respiration and depressed solubility of oxygen in water during the warmer summer months. The sharp positive slope in the latter stages of the graph reflects an increasing flow demand by the smolt crop as they move into a second summer of growth.

Spreadsheet tests to quantify fish oxygen needs were run at three influent water flow rates, 150, 300 and 600 l/min (Fig. 7). At an influent flow rate of 150 l/min oxygenation is needed 160 days into the cycle. Oxygen needs increase into the first summer to 5.0E05 mg/kghr. The need then decreases slightly over the winter and subsequently increases to 2.0E06 mg/kghr as the water temperature increases in the second season. The test at a flow rate of 300 l/min parallels the 150 l/min profile with proportionately less oxygen needs. This test indicated that oxygenation was required 180 days
Figure 9. The Relationship of Unlimited Influent Flow Rate for Increasing Fish Biomass as Predicted by the CGSS.
into the production cycle. At an influent flow rate of 600 l/min oxygenation appears to be needed for a two month period coinciding with the warmer summer waters and then not again until day 420 when the total crop biomass begins to increase quickly and warmer water temperatures reoccur. The negative values in Figure 9 are an artifact of the computation and should be interpreted as zero oxygenation requirements.

These test runs indicated that specific oxygenation strategies should be expected under different flow conditions. Current farmers have had losses due to the inability to quickly respond to oxygen deficiencies.

6.1.2 Changes in Head

The height above the saltwater datum (HSD) of the freshwater in the FVR simulation varies between 0.094 and 0.097 m over the production cycle for a FVR unit volume of 100 m$^3$ (Fig. 8). The sinusoidal shape of Fig. 8 reflects the effects of temperature on the density of freshwater and saltwater.

The HSD is theoretically the result of 3 components: fluid velocity, frictional forces and relative specific weight (Eq. 9). The friction forces can be from two sources: liner friction and screen friction. At a water flow rate of 150 l/min the velocities through the FVR unit, at the inlet and outlet areas, are very low, 1.79E-4 m/s and 2.63E-4 m/s respectively. Consequently the velocity component of head and
the liner friction can be considered negligible under such flow regimes.

Tests runs were performed with the CGSS to investigate the effects on the HSD if water flow rates were increased (Fig. 10). At a flow rate of 1000 l/min a HSD of 0.10 m was predicted as confirmed by Martin and Heard (1987). At higher flow rates the HSD increased with more positive slopes to 2.2 m at 7800 l/min. If such flow rates were to be used in a FVR unit the screen and surrounding liner would have to be designed to support the forces associated with such a HSD.

6.1.3 Stability and Turgidity

The values of CG, CB and MC (Table II) show that CG remains between CB and MC thereby satisfying the criteria for stability (see section 4.5.3). Under sheltered conditions typical of most fish farm conditions in B.C. any of the four shapes considered could provide stable equilibrium.

Table II. The Center of Buoyancy (CB), Center of Gravity (CG), and Metacenter (MC) Defining Stability for Four Different Shapes.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Center</th>
<th>Frustum</th>
<th>Cuboid</th>
<th>Hemisphere</th>
<th>Parabola</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB (m)</td>
<td>2.333</td>
<td>2.455</td>
<td>3.069</td>
<td>3.274</td>
<td></td>
</tr>
<tr>
<td>CG (m)</td>
<td>2.376</td>
<td>2.546</td>
<td>3.125</td>
<td>3.333</td>
<td></td>
</tr>
<tr>
<td>MC (m)</td>
<td>4.341</td>
<td>3.066</td>
<td>8.018</td>
<td>6.360</td>
<td></td>
</tr>
</tbody>
</table>
Figure 10. The Relationship Between Unlimited Influent Flow Rate and the Height Above the Salt Water Datum (HSD) as Predicted by the CGSS.
The forces exerted on either side of a frustrum were calculated over the production cycle. The greater force on the inside is accounted for by the freshwater head. This force maintains the turgidity of the liner. Figure 11 is the results of a simulation that illustrates the relationship between the difference of the inertial forces of different shaped FVR units and the associated drag force exerted on these different shapes by a set of current velocities. The top diameter of the units were set at 6 meters and the depth of the units 5 meters. Analysis of the profiles indicate that a frustrum will begin lose turgidity at current speeds of 1.1 m/s, a cuboid at 1.15 m/s, a paraboloid at 1.2 m/s and a hemisphere at nearly 1.6 m/s. With the stated dimensions and at greater respective current velocities additional mooring mass would be required to maintain FVR turgor. The decreasing slope with increasing current velocities reflects the drag coefficients dependency on the square of the current velocity (Eq. 21).

The fact that the FVR turgidity can be predicted by the CGSS has important site selection implications. For instance, a frustrum shaped liner in areas with current velocities greater than 1.1 m/s would be unsuitable. Many areas on the British Columbia coastline have regular current velocities greater than 1.1 m/s (Thomson, 1981).
Figure 11. A Comparison Between the Inertial and Drag Force Differences of 4 FVR Shapes Indicating the Current Velocity Criteria for Liner Turgor.
6.2 Case Studies

The CGSS parameters and technical design criteria were elucidated from: 1) the Agamemnon FVR site; 2) the Alaskan FVR (Martin and Heard, 1987); 3) spreadsheet validation; and 4) spreadsheet behaviour. With this information farm case studies were analyzed for economic feasibility.

The base case investigated was a variation of the Agamemnon FVR site. The second and third cases were variants of this base farm that are considered representative for other potential farm sites in British Columbia.

Economic assumptions that hold common to all cases are:

1) an initial smolt price of $3.50 declining by 5% in every subsequent production cycle
2) FVR rubberized liner cost of $45.21 /m²
3) building and shed cost of $16,450.00
4) float and mooring cost per unit of $6,500.00
5) water pump cost of $3126.00
6) feed cost of $1.25 /kg
7) labour cost of $36,000.00 /year
8) an electricity cost of $0.0276 /KWhr
9) a start-up loan at an interest of 15% /year
10) straight-line depreciation
11) lease and license fees of $1025.00 /year
6.2.1 The Base Farm

The base farm was analyzed using the technical inputs as listed in section 5.0 and economic inputs as listed above. Table III is the economic output from the base farm simulation. The Net Cash Flow (NCF) is negative for all but the first production cycle. This is so because the selling price of the Atlantic smolt is set at $3.50 in the first harvest cycle and is assumed to decline in value by 5% for every subsequent production cycle. As well, not enough smolt revenue is obtained to offset the costs incurred for capital and operating costs for this farm scenario.

The only revenue source is the sale of smolts. The spreadsheet was used to determine the relationship between NCF and the initial number of smolts assuming a 20% mortality rate (Fig. 13). For 50,000 smolts the NCF goes negative in the second cycle and continues to decrease through further production cycles. Both the stocking of 75,000 and 100,000 smolts maintains a positive NCF. The general decline in all the cases is due to both the decreasing selling price of the Atlantic smolt and the affects of inflation.

The relationship between NCF and the number of smolts started was also considered (Fig. 14). Total payback, as indicated by positive cash flow, is highly dependent on the number of smolts started. A general trend toward sooner payback periods appears as the number of smolt-starts increase. Any smolt starts between 50,000 and 100,000 allow
payback to be achieved within the first cycle. By the sixth cycle at least 80,000 smolts must be started to achieve payback of the initial investment.

6.2.2 Farm Case 2

All economic assumptions are as stated in section 6.2 above and, with the exception of the following input changes, technical assumptions are as stated in section 5.0:

1) initial numbers- 100,000 fish
2) distance from water source- 1000 m
3) elevation of source- -5 m
4) length of production cycle- 15 months
5) gravity flow or pump- (pump)

This scenario brought the initial number of smolts to 100,000 in order to create a positive NCF as suggested by the previous simulation. The water source now, however, was to be pumped to the FVR to test the effect of pumping costs.

The NCF remains positive through six cycles (Table IV). The electricity cost of pumping water for three cycles is 0.36%, 0.37% and 0.38% of the total costs, respectively (Table V). Furthermore, oxygenation costs are considerably lower at .05% of total costs for the same three cycles (Table V). In comparison to other costs such as PVC, feed and labour, electricity and oxygen costs are insignificant.
<table>
<thead>
<tr>
<th>PROFORM</th>
<th>CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>(+) TOTAL REVENUES</td>
<td>$139,999.88</td>
</tr>
<tr>
<td>DOP/IDOP COSTS</td>
<td>$136,484.42</td>
</tr>
<tr>
<td>DEPRECIATION</td>
<td>$22,864.00</td>
</tr>
<tr>
<td>(-) TOTAL COSTS</td>
<td>$159,348.42</td>
</tr>
<tr>
<td>(=) NET OPER REVENUE</td>
<td>($19,348.54)</td>
</tr>
<tr>
<td>(-) TAXES</td>
<td>$0.00</td>
</tr>
<tr>
<td>(=) INCOME AFTER TAXES</td>
<td>($19,348.54)</td>
</tr>
<tr>
<td>(+) DEPRECIATION</td>
<td>$22,864.00</td>
</tr>
<tr>
<td>(=) NET CASH FLOW</td>
<td>$3,515.46</td>
</tr>
<tr>
<td>CUM SURPLUS/DEFICI</td>
<td>($142,437.54)</td>
</tr>
</tbody>
</table>

Table III. Economic Summary of Base Farm.
Figure 12. The Effect of Stocked Smolt Numbers on the Net Cash Flow (NCF) for the Base Farm over 6 Cycles (Mortality = 20%).
Figure 13. The Relationship Between Net Cash Flow and Stocked Smolt Numbers over 6 Production Cycles for the Base Farm.
<table>
<thead>
<tr>
<th>PROFORM</th>
<th>CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+)TOTAL REVENUES</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$279,999.76</td>
</tr>
<tr>
<td>DOP/IDOP COSTS</td>
<td>$141,815.89</td>
</tr>
<tr>
<td>DEPRECIATION</td>
<td>$19,702.40</td>
</tr>
<tr>
<td>(-)TOTAL COSTS</td>
<td>$161,518.29</td>
</tr>
<tr>
<td>(=)NET OPER REVENUE</td>
<td>$118,481.47</td>
</tr>
<tr>
<td>(-)TAXES</td>
<td>$39,098.89</td>
</tr>
<tr>
<td>(=)INCOME AFTER TAXES</td>
<td>$79,382.59</td>
</tr>
<tr>
<td>(+)DEPRECIATION</td>
<td>$19,702.40</td>
</tr>
<tr>
<td>(=)NET CASH FLOW</td>
<td>$99,084.99</td>
</tr>
<tr>
<td>CUM SURPLUS/DEFIC</td>
<td>($126,629.54)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table IV. Economic Summary of Farm Case 2.
Table V. The Percentage of the Total Cost per Smolt for Direct Operating Costs (DOPCOS) over 3 Production Cycles for Farm Case 2.

<table>
<thead>
<tr>
<th>Direct Operating Costs (%)</th>
<th>Production Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Feed Delivery</td>
<td>0.61</td>
</tr>
<tr>
<td>Feed</td>
<td>8.42</td>
</tr>
<tr>
<td>Eggs</td>
<td>6.19</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.36</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.05</td>
</tr>
<tr>
<td>Fuel</td>
<td>1.98</td>
</tr>
<tr>
<td>Veterinary</td>
<td>0.17</td>
</tr>
<tr>
<td>Air Fills</td>
<td>0.22</td>
</tr>
</tbody>
</table>
6.2.3 Farm Case 3

All assumptions are as stated in section 5.5.2 above with the exception of the following changes:

1) Mortality rate of 40%
2) Shape- Paraboloid
3) distance from water source- 2000 m
4) elevation of source- -10 m

The mortality rate has a direct effect on the number of harvested smolts. More importantly, because of the higher economic investment, increased or unforeseen mortalities in later growth stages can significantly affect NCF. Bjorndal (1988) makes an economic analysis of the affects of changing mortality rates and unforeseen mortality. The effect of mortality rate on NCF was similarly emphasized in this simulation, however the CGSS can not account for periodic, or unforeseen mortality.

At a rate of 40% only 60,000 smolts will go to market for a harvest value of $209,999.52 in the first cycle (Table VI). The NCF remains positive for the first three cycles but then accumulates a deficit of $819.72 in the fourth cycle. Although the NCF is usually positive not enough income is obtained to offset the accumulated deficit (Table VI).

A simulation was run to determine the relationship between mortality rate and NCF (Fig. 14). A general linear decrease of NCF with increasing mortality rate for all cycles was found. The NCF does remain positive for the first three
cycles even when the mortality rate reaches 50%. However, for the fourth through sixth cycle NCF is negative if the mortality rate increases past 40%.

The shape of the FVR unit was changed to a paraboloid that has a surface to volume ratio approximately 6 times higher than that of the frustrum. The total cost of the liner material for a paraboloid is $23,919.94 (Table VII), whereas the cost of the frustrum liner in the farm case 2 is only $3,147.54 (Table VIII). Clearly the relatively large the surface area of the paraboloid contributes significantly to the capital costs.

In farm case 3 both the distance from the water source and the elevation from the water source was increased to 2000 m and 10 m, respectively. Even with these increases the electricity for pumping costs was still insignificant. Polyvinyl chloride piping, on the other hand, at 45.32% of the capital costs (Table VII), is a concern. The distance from the water source may affect the feasibility of the farm as a result of PVC costs.
<table>
<thead>
<tr>
<th>PROFORM</th>
<th>CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>(+)TOTAL REVENUES</td>
<td>$209,999.52</td>
</tr>
<tr>
<td>DOP/IDOP COSTS</td>
<td>$146,810.20</td>
</tr>
<tr>
<td>DEPRECIATION</td>
<td>$27,606.40</td>
</tr>
<tr>
<td>(-)TOTAL COSTS</td>
<td>$174,416.60</td>
</tr>
<tr>
<td>(=)NET OPER REVENUE</td>
<td>$35,582.92</td>
</tr>
<tr>
<td>(-)TAXES</td>
<td>$11,742.36</td>
</tr>
<tr>
<td>(=)INCOME AFTER TAXES</td>
<td>$23,840.56</td>
</tr>
<tr>
<td>(+)DEPRECIATION</td>
<td>$27,606.40</td>
</tr>
<tr>
<td>(=)NET CASH FLOW</td>
<td>$51,446.96</td>
</tr>
<tr>
<td>CUM SURPLUS/DEFICI</td>
<td>($186,921.94)</td>
</tr>
</tbody>
</table>
Figure 14. The Relationship Between the Net Cash Flow and the Mortality Rate over 6 Production Cycles for Farm Case 3.
Table VII. Summary of the Start-Up Costs and Percentage of Total Cost per Smolt in the First Production Cycle for Farm Case 3.

<table>
<thead>
<tr>
<th>TOTAL COSTS</th>
<th>Start-Up Costs</th>
<th>% TC 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>$13,725.00</td>
<td>7.87</td>
</tr>
<tr>
<td>Liner</td>
<td>$23,919.94</td>
<td>13.71</td>
</tr>
<tr>
<td>Float</td>
<td>$10,000.00</td>
<td>5.73</td>
</tr>
<tr>
<td>Mooring</td>
<td>$13,000.00</td>
<td>7.45</td>
</tr>
<tr>
<td>Storage Shed</td>
<td>$1,920.00</td>
<td>1.10</td>
</tr>
<tr>
<td>Diving Equipment</td>
<td>$3,299.00</td>
<td>1.89</td>
</tr>
<tr>
<td>Lab Equipment</td>
<td>$5,000.00</td>
<td>2.87</td>
</tr>
<tr>
<td>Tools</td>
<td>$2,950.00</td>
<td>1.69</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>$6,000.00</td>
<td>3.44</td>
</tr>
<tr>
<td>Water Pump</td>
<td>$3,126.00</td>
<td>1.79</td>
</tr>
<tr>
<td>Aluminum Skiff</td>
<td>$12,623.00</td>
<td>7.24</td>
</tr>
<tr>
<td>Work Boat</td>
<td>$2,433.00</td>
<td>1.39</td>
</tr>
<tr>
<td>PVC Piping</td>
<td>$79,040.00</td>
<td>45.32</td>
</tr>
<tr>
<td>Boat Motors</td>
<td>$9,886.00</td>
<td>5.67</td>
</tr>
</tbody>
</table>
Table VIII. Summary of Start-Up Costs and Percentage of Total Costs for Smolts in First Production Cycle for Base Farm 2.

<table>
<thead>
<tr>
<th>TOTAL COSTS</th>
<th>Start-Up Costs</th>
<th>% TC 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>$13,725.00</td>
<td>8.50</td>
</tr>
<tr>
<td>Liner</td>
<td>$3,147.54</td>
<td>1.95</td>
</tr>
<tr>
<td>Float</td>
<td>$10,000.00</td>
<td>6.19</td>
</tr>
<tr>
<td>Mooring</td>
<td>$13,000.00</td>
<td>8.05</td>
</tr>
<tr>
<td>Storage Shed</td>
<td>$1,920.00</td>
<td>1.19</td>
</tr>
<tr>
<td>Diving Equipment</td>
<td>$3,299.00</td>
<td>2.04</td>
</tr>
<tr>
<td>Lab Equipment</td>
<td>$5,000.00</td>
<td>3.10</td>
</tr>
<tr>
<td>Tools</td>
<td>$2,950.00</td>
<td>1.83</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>$6,000.00</td>
<td>3.71</td>
</tr>
<tr>
<td>Water Pump</td>
<td>$3,126.00</td>
<td>1.94</td>
</tr>
<tr>
<td>Aluminum Skiff</td>
<td>$12,623.00</td>
<td>7.82</td>
</tr>
<tr>
<td>Work Boat</td>
<td>$2,433.00</td>
<td>1.51</td>
</tr>
<tr>
<td>PVC Piping</td>
<td>$39,520.00</td>
<td>24.47</td>
</tr>
<tr>
<td>Boat Motors</td>
<td>$9,886.00</td>
<td>6.12</td>
</tr>
</tbody>
</table>
7.0 CONCLUSIONS

A CGSS of a floating vertical raceway for Atlantic salmon smolt production was developed during the course of this study. The spreadsheet mathematically described the FVR in terms of biological, physical and economic parameters. Fresh water vertical raceway simulations were validated with data from two actual FVR sites. The CGSS was analyzed to determine conditions that would provide a technically and economically feasible smolt production unit that would utilize existing marine rearing space.

Tests validated the conclusion that flow rates typical of one local FVR farm, 150, 300 and 600 l/min, will result in oxygen deficiencies during the production cycle. These oxygen deficiencies occur most regularly during the warmer summer months, 160, 180 and 210 days into the production cycle, respectively. By anticipating oxygen-deficient periods the farmer will have time to obtain and apply supplemental oxygen.

A range of influent flow rates were analyzed to determine the effect on the fresh water head, or height above salt water datum (HSD). For actual influent flow rates the HSD predictions were consistent with the Agamemnon and Alaskan FVR sites, approximately 0.10 m. However, influent flow rates of 2000-7800 l/min increase the HSD from 0.2-2.2 m. An increasing proportion of this HSD is attributed to friction at the outlet screen which may cause the screen and liner to fail.
The spreadsheet simulation demonstrated that a FVR shaped as either a frustrum, hemisphere, paraboloid, or cuboid, is stable with respect to criteria defined by the relationship between the metacenter, center of buoyancy and center of gravity. For the four shapes investigated the center of gravity remains between the center of buoyancy and the metacenter.

Turgor, defined as an equality between the current drag forces exerted on the FVR and the inertial forces of the FVR, will be maintained for all four shapes provided the current velocities are not too large. If the current velocity is not greater than 1.1 m/s a frustrum will remain turgid. The same is true for a hemisphere, paraboloid and cuboid if current velocities are not greater than 1.6, 1.2 and 1.15 m/s, respectively.

With design criteria determined from the CGSS and actual farm sites, three hypothetical farm cases were tested and analyzed to determine economic feasibility. The net cash flow of the base farm remains negative after the first production cycle break-even. This farm case, however, assumed that only 50,000 smolts were started for a facility that took the responsibility for complete start-up costs. Farm case 2 and smolt starts of 100,000 obtained a consistent positive NCF. Positive NCF is highly dependent on the number of smolts sold. Farm case 3 for the most part retains a positive NCF but income never gains on the accumulating deficit. The 2 km
distance from the fresh water source, and therefore the PVC piping cost (45.32%) is an important factor affecting this deficit.

The smolt production cost ranged from $1.37-$5.89. The cost of $1.37 was achieved with a smolt stocking of 100,000, a 20% rate and a 15 month production cycle, i.e. farm case 2.

For all three base farms the electricity costs of pumping (0.25-0.87%) and oxygenation costs (0.01-0.07%) contributed little to the total costs as compared to labour (12.02-32.79%) and feed costs (5.58-12.39%).

It can be concluded that the spreadsheet developed during this study is an effective tool to investigate alternatives of FVR production strategy, design and economy. In summary, these conclusions can be drawn:

1. Oxygen deficiency becomes a concern during the production cycle.
2. The CGSS enables the farmer to predict when supplemental oxygen is required to maintain fish oxygen demands.
3. At flow rates of 150, 300 and 600 l/min, screen head loss is insignificant.
4. At higher flow rates, 2000-7800 l/min, the frictional forces at the outlet screen may stress the screen and surrounding liner, causing liner failure.
5. Under typical production conditions the four shapes considered will provide hydromechanical stability.
6. For the conditions considered, a current velocity greater than 1.1 m/s requires additional mooring weight to maintain FVR turgor, depending on the shape of the liner.

7. The NFC is positive and maintains a cumulative surplus only for farm case 2, i.e. 100,000 smolts, 20% mortality rate and a 15 month production cycle. NFC is affected most by the lack of smolt revenue in farm case 1 and by the cost of PVC piping (45.32%) in farm case 3.

8. The lowest smolt production cost was $1.37 achieved within farm case 2.

9. In relation to the cost of feed and labour, electricity and supplemental oxygen costs are insignificant.
8.0 FURTHER STUDY AND SUGGESTIONS

The CGSS developed during this study is the only simulation known to date that integrates basic engineering with the technical and economic feasibility of locally applied aquaculture technologies. This study is necessarily limited in scope to specific investigations of the aspects of one of these technologies. The aquaculture industry would benefit from continued study in the application of spreadsheet simulations to basic engineering problems in aquaculture technology.

More specifically this study provides a basic tool that can further investigate alternative FVR farm sites, technology and economy. Some of the investigations that may be considered are:

1) developing a more resolute simulation for oxygen prediction and control;
2) determining the stability and turgor criteria during the smoltification process when salinities in and out of the FVR are more similar;
3) quantifying and comparing the elastic limits of the liner and outlet screen to the hydraulic forces being applied by the influent flow;
4) investigating alternatives to water supply systems i.e. PVC pipe sizes, pumping configurations etc.
5) applying the CGSS to other salmonid species to determine the economic feasibility within the FVR;
6) applying an optimization function that relates the technical and economic aspects of this simulation;
7) a survey from the commercial hatcheries of the break-down of the smolt production costs that can then used to augment and revise this simulation to reflect hatchery costs more accurately.
8) the addition of a more resolute cash flow analysis to study quarterly periods.
9) the addition of an investment analysis routine.
BIBLIOGRAPHY


A Computer-Based Model Approach. Department of Fisheries and Oceans, Economic and Commercial Analysis Division Report No. 54.


