DEVELOPMENT OF AN INTEGRATED MODEL FOR SUSTAINABLE AQUACULTURE AND OPTIMIZATION OF FISH PRODUCTION IN RACEWAY SYSTEMS

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By

MOHAMMAD GHOLIZADEH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To My Lovely Family

To Human and Needs for Love, Peace, Spirituality and Sustainable Environment
Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF AN INTEGRATED MODEL FOR SUSTAINABLE AQUACULTURE AND OPTIMIZATION OF FISH PRODUCTION IN RACEWAY SYSTEMS

By

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October 2017

Chairman : Associate Professor Zelina Zaiton Ibrahim, PhD
Faculty : Environmental Studies

Sustainable aquaculture needs effective fish farm management to balance high yield production with low farm effluent, as well as consider changes in available water resources. The aim of this research is to develop a model to simulate fish growth, total farm production, and effluent load estimation for single and multiple stocking events. Modeling is in a spreadsheet format for the most common system of cold-water fish farming in Iran, that is, the raceway system. Model equations were based on the literature and currently available aquaculture models. In addition, new equations, based on mass-balance considerations, and modification of temperature for conditions of fish growth in above optimum temperatures conditions are proposed. Five main modules, that is, Environment, Individual Fish Weight, Water Quality Effluent, Farm, and Analysis, were developed to cover the main processes and parameters in a fish farm. Multiple-model inference was adopted for estimating fish growth. Water quality parameters included dissolved oxygen, total ammonia nitrogen and phosphorous. Effluent load was estimated based on dissolved oxygen depletion, feed requirement, phosphate and total ammonia nitrogen. Single and multi-stocking events as well as use of multiple species is possible in the model. The model was validated to primary and secondary data. Primary data of water temperature and fish weight was used to validate the fish growth in the Individual Fish Weight module. Secondary data from published data sets and results from other current aquaculture models were used to compare with the simulation results of the model developed. The data were for trout, salmon and Seabream fish. The results for fish growth showed very good correlation ($R^2>0.98$) with the measured data of a fish farm at Haraz River, Iran, with mean absolute percentage error (MAPE) of less than 10 percent. Comparison of the model simulation results with other existing models, such as AquaOptima and AquaFarm, also showed very good correlations ($R^2>0.98$) except for estimation of feed requirements with the AquaFarm model results ($R^2=0.87$ and MAPE=24%). In conclusion, the model
developed produced several important results which contribute to improved knowledge for aquaculture modeling. These are the ability to use of a simple tool for complex situations, improved fish growth modeling, proposal for a parameterization of fish growth in temperature conditions which are beyond optimum growth temperature, the possibility to simulate for variable temperature patterns, together with the possibility for fish farm effluent estimation, under single and multiple stocking conditions. The model can be used for planning aquaculture development due to the capability for simulation of multiple scenarios in single integrated aquaculture model. In this way the model will be useful for a wide range of stakeholders as a tool for sustainable management of an aquaculture farm.
Abstrakt tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN MODEL BERSEPADU UNTUK AKUAKULTUR MAPAN DAN PENGOPTIMUM HASIL TERNAKAN DALAM SISTEM PALUNG

Oleh

MOHAMMAD GHOLIZADEH

Oktober 2017

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Akuakultur yang mapan memerlukan pengurusan ladang ikan yang berkesan untuk mengimbangi pengeluaran hasil yang tinggi dengan efluen ladang yang rendah, serta mempertimbangkan perubahan sumber air yang sedia ada. Tujuan penyelidikan ini adalah untuk membangunkan satu model untuk mensimulasikan pertumbuhan ikan, jumlah pengeluaran ladang, dan anggaran beban efluen bagi pengunaan stok tunggal dan berbilang. Pemodelan dilakukan dalam format hamparan untuk sistem penternakan ikan air sejuk yang paling umum di Iran, iaitu, sistem aliran palung. Persamaan model berdasarkan literatur dan model akuakultur yang sedia ada sekarang. Di samping itu, persamaan baharu, berdasarkan pertimbangan imbangan jisim, dan pengubahsuaian suhu bagi keadaan pertumbuhan ikan di dalam keadaan yang melebihi suhu optimum adalah dicadangkan. Lima modul utama, ia itu, Persekitaran, Berat Ikan Individu, Efluen Kualiti Air, Ladang, dan Analisis, telah dibangunkan untuk merangkumi proses dan parameter utama dalam ladang ikan. Inferens pelbagai model telah digunakan untuk menganggar pertumbuhan ikan. Parameter kualiti air termasuk oksigen terlarut, jumlah ammonia nitrogen dan fosforus. Beban efluen dianggarkan berdasarkan pengurangan oksigen terlarut, keperluan makanan, fosfat dan jumlah amonia nitrogen. Pengunaan stok tunggal dan berbilang serta penggunaan pelbagai spesies boleh dilakukan dalam model. Model ini telah disahkan kepada data primer dan sekunder. Data primer suhu air dan berat ikan digunakan untuk mengesahkan pertumbuhan ikan dalam modul Berat Ikan Individu. Data sekunder dari set data yang diterbitkan dan hasil daripada model akuakultur semasa yang lain digunakan untuk dibanding dengan hasil simulasi model yang dibangunkan. Data ini adalah untuk ikan trout, ikan salmon dan Seabream. Keputusan untuk pertumbuhan ikan menunjukkan korelasi yang sangat baik (R² > 0.98) dengan data yang ukur dari ladang ikan di Sungai Haraz, Iran, dengan peratusan purata ralat mutlak (MAPE) kurang daripada 10 peratus. Perbandingan hasil simulasi model dengan model sedia ada yang lain, seperti AquaOptima dan AquaFarm, juga menunjukkan korelasi yang
sangat baik ($R^2>0.98$) kecuali untuk anggaran keperluan bahan makanan dengan hasil model AquaFarm ($R^2 = 0.87$ dan MAPE = 24%). Sebagai kesimpulan, model yang dibangunkan menghasilkan beberapa hasil penting yang menyumbang kepada penambahan pengetahuan untuk pemodelan akuakultur. Ini adalah keupayaan untuk penggunaan perkakas mudah untuk situasi kompleks, pemodelan pertumbuhan ikan yang lebih baik, cadangan untuk parameterisasi pertumbuhan ikan dalam keadaan suhu yang melebihi suhu pertumbuhan yang optimum, kemungkinan untuk mensimulasikan untuk corak suhu berubah-ubah, bersama dengan kebolehan untuk melakukan anggaran efluen ladang ikan, di bawah keadaan stok tunggal dan berbilang. Model ini boleh digunakan untuk perancangan pembangunan akuakultur kerana kemampuan untuk melakukan simulasi pelbagai senario dengan menggunakan model akuakultur bersepadu tunggal. Dengan cara ini model ini akan berguna untuk pelbagai pihak yang berkepentingan sebagai alat untuk pengurusan mapan ladang akuakultur.
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I certify that a Thesis Examination Committee has met on 9 October 2017 to conduct the final examination of Mohammad Gholizadeh on his thesis entitled "Development of an Integrated Model for Sustainable Aquaculture and Optimization of Fish Production in Raceway Systems" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>vi</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xviii</td>
</tr>
</tbody>
</table>

## CHAPTER

### 1 INTRODUCTION

1.1 Background 1
1.2 Problem Statement 1
1.3 Objectives 5
1.4 Thesis Outline 5

### 2 LITERATURE REVIEW

2.1 Introduction 6
2.2 Sustainability in Aquaculture 6
2.3 Modeling and Simulation in Aquaculture 8
   2.3.1 Purpose of Models 8
   2.3.2 Development of Aquaculture Farm Models 10
   2.3.3 Deterministic versus Probabilistic Simulation 11
   2.3.4 Spreadsheet Modelling 12
2.4 Fish Growth Models 13
   2.4.1 Introduction 13
   2.4.2 Linear Fish Length Growth 14
   2.4.3 Von Bertalanffy Growth 14
   2.4.4 Specific Growth Rate 15
   2.4.5 Daily Growth Rate 16
   2.4.6 Daily Growth Coefficient 17
   2.4.7 Growing Degree-Days 17
   2.4.8 Thermal Growth Coefficient 18
   2.4.9 Lupatsch Model 19
   2.4.10 Hernandez Model 20
   2.4.11 Bioenergetics Growth Model 20
   2.4.12 Temperature Modification 21
2.5 Feed Model 21
   2.5.1 Introduction 21
   2.5.2 Food Conversion Efficiency 22
   2.5.3 Feed Conversion Table 22
2.5.4 Factorial Approach
2.6 Effluent and Waste Estimate Model
  2.6.1 Introduction
  2.6.2 Total Ammonia Nitrogen
  2.6.3 Un-Ionized Ammonia
  2.6.4 Phosphorous
  2.6.5 Biochemical Oxygen Demand
  2.6.6 Total Suspended Solids
  2.6.7 Dissolved Oxygen Consumption Rate
  2.6.8 Minimum Oxygen Levels
2.7 Carrying Capacity
2.8 Gaps in Aquaculture Modeling

3 METHODOLOGY AND MODEL DEVELOPMENT
  3.1 Methodological Framework
  3.2 Model Equations
  3.3 Model Conceptual Framework
  3.4 Implementation Limitations
  3.5 Optimization
  3.6 Environment Module
    3.6.1 Introduction and Module Assumptions
    3.6.2 Water Temperature Prediction
  3.7 Individual Fish Weight Module
    3.7.1 Introduction and Assumption of Module
    3.7.2 Description of Individual Fish Weight Module
      3.7.2.1 Introduction
      3.7.2.2 Daily Growth Length Coefficient
      3.7.2.3 Thermal Growth Coefficient
      3.7.2.4 Lupatsch Feed Model
    3.7.3 Dissolved Oxygen Consumption Rate
    3.7.4 Feed Rate
  3.8 Water Quality Effluent Module
    3.8.1 Introduction
    3.8.2 Calculation Criterion
    3.8.3 Dissolved Oxygen Depletion
    3.8.4 Dissolved Oxygen Concentration in Effluent Water
    3.8.5 Total Ammonia Nitrogen
    3.8.6 Unionized Ammonia
    3.8.7 Phosphorous
    3.8.8 Biochemical Oxygen Demand
    3.8.9 Total Suspended Solid
  3.9 Farm Module
    3.9.1 Introduction
    3.9.2 Biomass Calculation
    3.9.3 Harvesting Date Criterion
  3.10 Analysis Module
    3.10.1 Introduction
3.10.2 Multi-Stocking Calculations 64
3.10.3 Dissolved Oxygen 64
   3.10.3.1 Dissolved Oxygen Carrying Capacity 64
   3.10.3.2 Minimum Dissolved Oxygen 65
   3.10.3.3 Dissolved Oxygen After Weir 66
3.10.4 Total Daily Load 67
3.11 Model Validation and Calibration Approach 69
   3.11.1 Introduction 69
   3.11.2 Validation 69
   3.11.3 Calibration Approach 70
   3.11.4 Sensitivity Analysis Method 70
   3.11.5 Implementation Limitation 71
3.12 Data Sets Used 71

4 RESULTS AND DISCUSSION 74
4.1 Introduction 74
4.2 Sensitivity Analysis 75
4.3 Verification and Validation 77
   4.3.1 Introduction 77
   4.3.2 Integrated Fish Farm Production and Effluent Simulation 77
4.4 Assumptions and Limitations 77
   4.4.1 Introduction 77
   4.4.2 Water 78
   4.4.3 Fish 78
   4.4.4 Culture System 78
4.5 Growth and Production in Single-Stocking Farm 78
   4.5.1 Introduction 78
   4.5.2 Simulation With Sinusoidal Temperature Variation 79
   4.5.3 Trout Growth Simulation with Variable Temperature 81
   4.5.4 Trout Production and Feed Requirement with Constant Temperature 84
   4.5.5 Haraz Farm Data for Fish Growth 88
4.6 Integrated Farm Production and Effluent Discharge 90
   4.6.1 Introduction 90
   4.6.2 Dissolved Oxygen Depletion Simulation 91
   4.6.3 Integrated Farm Production and Effluent Simulation 92
4.7 Integrated Fish Production and Effluent in Multi-stocking Farm 97
   4.7.1 Introduction 97
   4.7.2 Salmon Production with Constant Temperature 97
   4.7.3 Gilthead Sea-bream Production with Constant Temperature 99
   4.7.4 Gilthead Sea Bream Production with Sinusoidal Temperature and Stocking Rate 101
4.8 Use of AIM for Fish Farm Sustainability 103
   4.8.1 More Efficient Resource Use 103
   4.8.2 Adaptation to Climate Change 103
5 CONCLUSION 105
5.1 Introduction 105
5.2 Findings 105
5.3 Modeling Fish Farm Sustainability 106
5.4 Model Strengths and Weakness 107
5.5 Conclusion 108
5.6 Potential Future Research 110

REFERENCES 111
BIODATA OF STUDENT 124
LIST OF PUBLICATIONS 125
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Experts consulted on aquaculture issues in Iran between 2005 and 2010</td>
</tr>
<tr>
<td>2.1</td>
<td>Different growth models</td>
</tr>
<tr>
<td>2.2</td>
<td>BOD and TSS concentration of flow-through trout farm effluents</td>
</tr>
<tr>
<td>2.3</td>
<td>BOD concentrations, and feeding levels</td>
</tr>
<tr>
<td>2.4</td>
<td>Summary of models specifications</td>
</tr>
<tr>
<td>3.1</td>
<td>Equations used in model development</td>
</tr>
<tr>
<td>3.2</td>
<td>Statistical techniques for comparison of model results</td>
</tr>
<tr>
<td>3.3</td>
<td>Data sets used in this study</td>
</tr>
<tr>
<td>3.4</td>
<td>Data of fish farm at Haraz River, Iran</td>
</tr>
<tr>
<td>4.1</td>
<td>Summary of model simulation and validation data sets used</td>
</tr>
<tr>
<td>4.2</td>
<td>Summary of sensitivity analysis of model variables</td>
</tr>
<tr>
<td>4.3</td>
<td>Conditions for simulation of growth in a single-stocking farm</td>
</tr>
<tr>
<td>4.4</td>
<td>Statistical comparison of AIM results with Akhan et al. (2010) data set for fish-length and fish-weight</td>
</tr>
<tr>
<td>4.5</td>
<td>Statistical comparison of AIM results with AquaOptima (2006) for feed rate and feed requirement</td>
</tr>
<tr>
<td>4.6</td>
<td>Statistical comparison of simulation results for fish growth with variable temperature.</td>
</tr>
<tr>
<td>4.7</td>
<td>Farm production simulation in a single-stocking farm</td>
</tr>
<tr>
<td>4.8</td>
<td>Statistical comparison of AIM results with AquaOptima (2006) for $DO_{rate}$ and $DO_{depletion}$</td>
</tr>
<tr>
<td>4.9</td>
<td>Statistical comparison of AIM results with AquaFarm (2009) for TGC+DGL, Lupatech, Feed Rate and TAN</td>
</tr>
<tr>
<td>4.10</td>
<td>Summary of simulation conditions for multi-stocking farm</td>
</tr>
<tr>
<td>4.11</td>
<td>Statistical comparison of AIM results with Colt et al. (2009a)s</td>
</tr>
<tr>
<td>4.12</td>
<td>Model output for increased water temperatures</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The overall structure of the modules used to model the environmental impacts of fish farm</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>A sample of food conversion efficiency diagram</td>
<td>22</td>
</tr>
<tr>
<td>2.3</td>
<td>Possible decision tree for the implementation of effluent nutrient reduction strategies in trout farms, dependent on the feeding level</td>
<td>29</td>
</tr>
<tr>
<td>3.1</td>
<td>The overall methodology framework of research</td>
<td>35</td>
</tr>
<tr>
<td>3.2</td>
<td>A simplified conceptual framework of the model, input and output variables, and calculation modules.</td>
<td>39</td>
</tr>
<tr>
<td>3.3</td>
<td>Decomposition scheme of the aquaculture integrated model (AIM)</td>
<td>40</td>
</tr>
<tr>
<td>3.4</td>
<td>Parameters in the Environment module</td>
<td>42</td>
</tr>
<tr>
<td>3.5</td>
<td>Dissolved oxygen in water</td>
<td>43</td>
</tr>
<tr>
<td>3.6</td>
<td>Water temperature (T_w) correlation in Haraz River (This study)</td>
<td>44</td>
</tr>
<tr>
<td>3.7</td>
<td>The parameters of the Individual Fish module</td>
<td>45</td>
</tr>
<tr>
<td>3.8</td>
<td>Oxygen consumption per individual fish, for constant temperatures, 5, 10, 15 and 25 °C. Based on the data set of Klontz, 1991.</td>
<td>49</td>
</tr>
<tr>
<td>3.9</td>
<td>Feed and Pollutant in Fish</td>
<td>49</td>
</tr>
<tr>
<td>3.10</td>
<td>Feed rate of Barramundi fish, based on Lupatsch equation FR1t for various temperature, 10, 15, 20 and 24 °C as a function of IFW.</td>
<td>50</td>
</tr>
<tr>
<td>3.11</td>
<td>Comparison of AIM feedrate and Klontz dataset for salmon fish</td>
<td>52</td>
</tr>
<tr>
<td>3.12</td>
<td>Illustration of water temperature modification equation effect</td>
<td>53</td>
</tr>
<tr>
<td>3.13</td>
<td>A simplified conceptual framework of the Water Quality Effluent module</td>
<td>54</td>
</tr>
<tr>
<td>3.14</td>
<td>NH3 and waterquality.</td>
<td>58</td>
</tr>
<tr>
<td>3.15</td>
<td>BOD as a function of feeding level</td>
<td>59</td>
</tr>
<tr>
<td>3.16</td>
<td>BOD in the model as a function of biomass and feed</td>
<td>60</td>
</tr>
</tbody>
</table>
3.17 TSS load in the model as a function of feed 61
3.18 Simplified conceptual framework of the Farm module 62
3.19 Simplified conceptual framework of the Analysis module 63
3.20 Minimum dissolved oxygen for Shasta trout 66
3.21 Weir in serial raceways 66
3.22 Estimation of dissolved oxygen saturation (Sa) after weir 68
4.1 Sensitivity analysis of production variable, based on OFAT method 76
4.2 Fish growth simulation results of AIM with AquaFarm 80
4.3 Fish growth correlation between AIM and AquaFarm 81
4.4 Length-weight relationship based on the Akhan et al. (2010) data set (open circles). 82
4.5 Length-weight relationship based on the Akhan et al. (2010) data set (open circles). 82
4.6 Length-growth simulation results of AIM versus Akhan et al. (2010) data set. 83
4.7 Weight-growth simulation results of AIM compared with Akhan et al. (2010) 83
4.8 AIM fish length and weight simulation results of AIM versus Akhan et al. (2010) dataset 84
4.9 Production simulation of AIM with AquaOptima 85
4.10 Comparison between fish weight and biomass for AIM and AquaOptima 86
4.11 Simulation results of AIM and AquaOptima output 87
4.12 Correlation of feed simulation results of AIM with AquaOptima (2006) 88
4.13 Fish growth simulation on Haraz fish farm 89
4.14 Correlation of TGC and Tm on fish growth 90
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.15</td>
<td>Fish dissolved oxygen consumption, simulation results of AIM and AquaOptima (2006)</td>
</tr>
<tr>
<td>4.16</td>
<td>Correlation of daily dissolved oxygen between AIM and AquaOptima (2006)</td>
</tr>
<tr>
<td>4.17</td>
<td>Simulation results of AIM with AquaFarm (Ernst et al., 2000) for sinusoidal temperature conditions</td>
</tr>
<tr>
<td>4.18</td>
<td>TAN simulation results of AIM and</td>
</tr>
<tr>
<td>4.19</td>
<td>Comparing AIM with AquaFarm</td>
</tr>
<tr>
<td>4.20</td>
<td>Comparison of TAN results from AIM with AquaFarm</td>
</tr>
<tr>
<td>4.21</td>
<td>Integrated IFW, Feed Rate and TAN simulation results of AIM and AquaFarm</td>
</tr>
<tr>
<td>4.22</td>
<td>Simulation results of AIM with Colt et al. (2009)</td>
</tr>
<tr>
<td>4.23</td>
<td>Scatter plot of AIM and Colt et al. (2009a) results</td>
</tr>
<tr>
<td>4.24</td>
<td>Cumulative fish production for AIM and Seginer &amp; Halachmi (2008)</td>
</tr>
<tr>
<td>4.25</td>
<td>Scatter plot of AIM and Seginer &amp; Halachmi (2008) results</td>
</tr>
<tr>
<td>4.26</td>
<td>Stocking rate pattern for Seginer &amp; Halachmi (2008) and AIM</td>
</tr>
<tr>
<td>4.27</td>
<td>Fish production simulation for Seginer &amp; Halachmi (2008) and AIM</td>
</tr>
<tr>
<td>4.28</td>
<td>Yield production of AIM and Seginer &amp; Halachmi (2008)</td>
</tr>
</tbody>
</table>
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIO</td>
<td>Biomass</td>
</tr>
<tr>
<td>BIOE</td>
<td>Bioenergetics Function</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>CAGR</td>
<td>Constant Absolute Weight Growth Rate</td>
</tr>
<tr>
<td>CSGR</td>
<td>Constant Special Weight Growth Rate</td>
</tr>
<tr>
<td>DGC</td>
<td>Daily Growth Coefficient</td>
</tr>
<tr>
<td>DGR</td>
<td>Daily Growth Rate</td>
</tr>
<tr>
<td>DSGR</td>
<td>Double-Logarithmic Specific Growth Rate</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>DOCC</td>
<td>Dissolved oxygen carrying capacity</td>
</tr>
<tr>
<td>ELV</td>
<td>Water Resource Elevation</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protect Agency</td>
</tr>
<tr>
<td>FCE</td>
<td>Feed Conversion Efficiency</td>
</tr>
<tr>
<td>FCR</td>
<td>Food Conversion Ratio</td>
</tr>
<tr>
<td>FFI</td>
<td>Fish Feeding Index</td>
</tr>
<tr>
<td>FGI</td>
<td>Fish Growth Index</td>
</tr>
<tr>
<td>FMR</td>
<td>Fish Metabolic Rate</td>
</tr>
<tr>
<td>FTS</td>
<td>Flow Through System</td>
</tr>
<tr>
<td>FR</td>
<td>Feed Rate</td>
</tr>
<tr>
<td>Fw</td>
<td>Feed waste</td>
</tr>
<tr>
<td>Feed G</td>
<td>Absorbed Phosphorous</td>
</tr>
<tr>
<td>GCM</td>
<td>Growth Curve Modeling</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>GRP</td>
<td>Growth Rate Potential</td>
</tr>
<tr>
<td>GDD</td>
<td>Growing Degree-Days</td>
</tr>
<tr>
<td>IFG</td>
<td>Individual Fish Growth</td>
</tr>
<tr>
<td>IFW</td>
<td>Individual Fish Weight (g)</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LWR</td>
<td>Length-Weight Relationship</td>
</tr>
<tr>
<td>NEL</td>
<td>No-Effect Limit</td>
</tr>
<tr>
<td>NH₃</td>
<td>Ammonia</td>
</tr>
<tr>
<td>NPU</td>
<td>Net Protein Unit</td>
</tr>
<tr>
<td>NSFₜ</td>
<td>Count of Survived Fish at each Time step</td>
</tr>
<tr>
<td>pKₘ</td>
<td>Acidity constant</td>
</tr>
<tr>
<td>PP</td>
<td>Particulate Phosphorous (kg.day⁻¹)</td>
</tr>
<tr>
<td>PRAS</td>
<td>Partition Recirculating Aquaculture System</td>
</tr>
<tr>
<td>RAS</td>
<td>Recirculating Aquaculture System</td>
</tr>
<tr>
<td>SA</td>
<td>Sensitivity Analysis</td>
</tr>
<tr>
<td>SA-OFAT</td>
<td>Sensitivity Analysis One factor at the time</td>
</tr>
<tr>
<td>SGR</td>
<td>Specific Growth Rate</td>
</tr>
<tr>
<td>SS</td>
<td>Suspended Solid</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solid</td>
</tr>
<tr>
<td>TAN</td>
<td>Total Ammonia Nitrogen (kg/day)</td>
</tr>
<tr>
<td>TDL</td>
<td>Total Daily Load of each water quality parameter</td>
</tr>
<tr>
<td>TGC</td>
<td>Thermal-unit Growth Coefficient</td>
</tr>
<tr>
<td>TP</td>
<td>Total Phosphorous (kg.day⁻¹)</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic VBA Application</td>
</tr>
<tr>
<td>VBGF</td>
<td>Von Bertalanffy growth function</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background

Aquaculture fish farming is one of the main sources of food. Aquaculture production with a yearly average rate of 9% is one of the world’s fastest growing industries (Timmons & Ebeling, 2012). Every decade aquaculture production has doubled (Fitwi, et al., 2012). Technological advances have led to these growth (Kumar & Engle, 2016). Aquaculture now provides almost half of all fish for human consumption (FAO, 2016). Fish farmers need to have a good production plan and high health fish (Ghorbani & Mirakabad, 2010). This includes high yield production and high income with less inputs of resources. However, it is evident that water quantity and quality are one of the main resources in a fish farm. Water sources are limited in many countries; however, the fish farmers need to have higher production even if they cannot increase their water resource. Farmers and fisheries try to have high production even in dry seasons. The effluents of fish farms will negatively impact on water quality parameters (Kohanestani, et al., 2013). On the other hand, the water authority approach, such as in Iran (Torabi, 2010), is to decrease water demand and effluent discharge. For sustainable aquaculture, there needs to be a good approach for farm production management. There should be a balance between higher yield production, for higher income, but with less farm effluent to the environment.

A fish production plan may be achieved experimentally, manually, or mathematically, by modeling, for instance, the pollutant load or changes in water quality. These can be achieved by computing the carrying capacity of the water resources and the maximum amount of fish that can be reared in the farms. Nowadays, computer software, such as spreadsheet programs and mathematics, are used as common tools in a modeling of fish production. For instance, scientists and aquaculture farmers have to consider aquaculture effluent impact on receiving waters. They can apply computer programs for water quantity and quality, water availability and water temperature (Handisyde, Ross, & Allison, 2006).

1.2 Problem Statement

Salmonidaes are one of the most important cold water cultured fishes in the world. In Iran, farming of this species started in 1960. Now, Iran is one of the important Salmonidaes producers in the world (Adeli, & Baghaei, 2013), especially trout fish. The improvement of the aquaculture production plans is important for the Iranian Government because of the local potential for the aquaculture, and the high request by the consumer (Adeli, & Shabanpour, 2007).
Between 2005 through 2010 the issues about aquaculture sustainability, the need of fish farmers and production management modeling, related to the ecology and environment, was discussed informally with key persons and experts in Iran, as listed in Table 1.1. These discussions were made during aquaculture and environment conferences and in the offices of the mentioned experts. From these discussions the main points raised were:

- The need for the aquaculture sustainability approach;
- The need of modeling in trout farm management on flow though system in Iran;
- Modeling of the yield and carrying capacity of springs and rivers with fluctuations in water flow and temperature;
- Modeling of the effluent of fish farms; and
- Modeling for fish farm management based on multi-stocking and multi species for scenario planning.

A recent FAO study report (Hasan, 2013) also identified the need to optimize feed production and on-farm feed management practices in aquaculture. The FAO (2016) stated that the "implications of feed type, formulation and feed management practices on the environmental footprint and economics of the farming operation are important issues that farmers need to consider when planning their activities". They also recommended that there must be simple tools for the farmer to monitor farm production indices such as feed conversion efficiency and growth rate.
Table 1.1: Experts consulted on aquaculture issues in Iran between 2005 and 2010

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Last Name</th>
<th>First Name</th>
<th>Position (in 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engr.</td>
<td>Aryannejad</td>
<td>Mohsen</td>
<td>Director, Cold Water Group, IFO</td>
</tr>
<tr>
<td>2</td>
<td>Engr.</td>
<td>Bahmanyary</td>
<td>Hussein</td>
<td>Ex Director, Bushehr Providence, IFO</td>
</tr>
<tr>
<td>3</td>
<td>Engr.</td>
<td>Esmaeely</td>
<td>Mohammad Ebrahim</td>
<td>President, Abzian Asia Aquaculture Consultant Co.</td>
</tr>
<tr>
<td>4</td>
<td>Engr.</td>
<td>Hassani</td>
<td>Mohammad Reza</td>
<td>Manager, Peyab Novin Aquaculture Consultant Engineers.</td>
</tr>
<tr>
<td>5</td>
<td>Dr.</td>
<td>Hosseinzadeh</td>
<td>Homayun</td>
<td>Director, Aquaculture Department, IFRO</td>
</tr>
<tr>
<td>6</td>
<td>Engr.</td>
<td>Jedi Rangraz</td>
<td>Mohammad</td>
<td>Ex Director, Tehran Providence, IFO</td>
</tr>
<tr>
<td>7</td>
<td>Engr.</td>
<td>Jamalzadeh</td>
<td>Faryborz</td>
<td>Ex Director, Coastline Office, Iran Department of Environment</td>
</tr>
<tr>
<td>8</td>
<td>Dr.</td>
<td>kolkaki</td>
<td>Shahpour</td>
<td>Director, Capture Fisheries, IFO</td>
</tr>
<tr>
<td>9</td>
<td>Engr.</td>
<td>Mokarami</td>
<td>Ghobad</td>
<td>Aquaculture Experts in IFO</td>
</tr>
<tr>
<td>10</td>
<td>Dr.</td>
<td>Nabizadeh</td>
<td>Arash</td>
<td>Iran Aquaculture Association</td>
</tr>
<tr>
<td>11</td>
<td>Engr.</td>
<td>Norbakhsh</td>
<td>Ali Reza</td>
<td>Ex Director, Aquacultural Engineering Department, IFO</td>
</tr>
<tr>
<td>12</td>
<td>Dr.</td>
<td>Partabayan</td>
<td>Massod</td>
<td>Trout Farmer; Best Iranian Trout Famer in 2003</td>
</tr>
<tr>
<td>13</td>
<td>Dr.</td>
<td>Pirali</td>
<td>Ali</td>
<td>Director, Charmahal Providence Technology Park</td>
</tr>
<tr>
<td>14</td>
<td>Dr.</td>
<td>Pourgholam</td>
<td>Reza</td>
<td>Ex Head, Caspian Research Center, IFRO</td>
</tr>
<tr>
<td>15</td>
<td>Assoc Prof.</td>
<td>Rafiee</td>
<td>Reza</td>
<td>Head, Fisheries Department, Tehran University</td>
</tr>
<tr>
<td>16</td>
<td>Engr.</td>
<td>Roshanro</td>
<td>Ahmad</td>
<td>Aquaculture Experts in Azarbayjan Providence, IFO</td>
</tr>
<tr>
<td>17</td>
<td>Dr.</td>
<td>Salehi</td>
<td>Hassan</td>
<td>Iran Agriculture Deputy Minister; President, IFO</td>
</tr>
<tr>
<td>18</td>
<td>Dr.</td>
<td>Shakouri</td>
<td>Mehdi</td>
<td>Ex. Director, Aquaculture Department, IFO</td>
</tr>
<tr>
<td>19</td>
<td>Dr.</td>
<td>Shariifpour</td>
<td>Issa</td>
<td>Aquatic Health Expert in IFO</td>
</tr>
<tr>
<td>20</td>
<td>Prof.</td>
<td>Soltani</td>
<td>Mehdi</td>
<td>Ex Head, Fish Health Department, Tehran University</td>
</tr>
<tr>
<td>21</td>
<td>Dr.</td>
<td>Torabi</td>
<td>Sedigheh</td>
<td>Head, Water Allocation Group, Ministry of Water and Power</td>
</tr>
<tr>
<td>22</td>
<td>Dr.</td>
<td>Yazdani Jahromi</td>
<td>Yazdani Jahromi</td>
<td>Private Sector Aquaculture Consultant</td>
</tr>
<tr>
<td>23</td>
<td>Engr.</td>
<td>Zolfaghari</td>
<td>Karim</td>
<td>Director, Agriculture Department, Tehran Province</td>
</tr>
<tr>
<td>24</td>
<td>Dr.</td>
<td>Zorrieh Zahara</td>
<td>Seyed Ebrahim Jalil</td>
<td>Head, Aquatic Health, IFRO</td>
</tr>
</tbody>
</table>

Note: IFO - Iranian Fisheries Organization; IFRO - Iranian Fisheries Research Organization

Aquatic health experts also believe that a fish simulation model for water quality monitoring helps to prevent fish disease risk and there are several models of fish growth and effluent, and of aquaculture production simulation. For instance, there is POND DSS (Bolte, Nath, & Ernst, 2000), AquaFarm (Ernst et al., 2000), RTDSS (Wang & Song, 2006) and multiple stock spreadsheet model by Colt, Schuur, Cryer, & Miles (2009).
Colt et al. (2009a) calculated carry capacity by developing a computer program in using FORTRAN language. Ernst, Bolte, & Nath (2000) developed computer software to simulate the operation and facility of the fish farm. Wang & Song (2006) simulated raceway trout farm by using spreadsheet software. Colt et al. (2009b) also applied spreadsheet software to study salmon hatchery planning. All of them reported good results in case of using a computer program as a tool. By introducing carrying capacity models for aquaculture development model the environmental impact effects can be reduced (Ross et al., 2013; White, Phillips, & Beveridge, 2013).

From the literature on aquaculture fish farm models, as mentioned above and presented in Chapter 2, there are some gaps that were identified. Currently, all of the above studies and models are for constant temperature condition. In the AquaOptima, (2006) model, any fluctuation of temperature is needed to be carried out manually. Previous models are for a single stocking and single a species. None include options for multi-stocking and multi-species condition. Several of the experts in Table 1. 1, that is Dr. Nabizadeh from Iran Aquaculture Association, Prof. Soltani, Ex-Head of the Fish Health Department, Tehran University, and Dr Zorrieh Zahara, Head of the Aquatic Health, Iranian Fisheries Research Organization suggested that that this type of simulation model for multi-stocking and multi-species can be useful. Jamalzadeh-Fallah, former Director of the Coastline Office, Iran Department of Environment, also supported that a model for multi-stocking for assessing fish farm impact on the environment is still needed for sustainability assessment. A study carried on recirculating aquaculture system (Kumar & Engle, 214) concluded that feeding and stocking strategies can affect the farm profits made. The recent paper by Valenti et al. (2018) on aquaculture sustainability also stress the environmental parameters of natural resource use and effluents from farms.

A recent review by (Anyadike, et al., 2017) of aquaculture production models found that none of the existing model could be used to model the effects of different management scenario or consider the fish species that they were interested in. They made the conclusion that there was a serious need to develop models that can predict the effects of environment on the performance of fish species in order to help the farmers for different management scenarios.

Currently, there are no models that can run an integrated simulation of fish growth, farm production, and effluent resulting from multi-stocking, multi-species and multi-growth farm condition, which is closer to the real condition for aquaculture farmers. This is also one of the points raised by the Iranian experts consulted. For stakeholders, such as fish farmer, environmental decision maker, fishery and environmental student and researcher, it is a gap in knowledge for promoting sustainable aquaculture.
1.3 Objectives

The aim of this research is to develop a model to simulate fish growth, total farm production, and effluent load estimation for single and multiple stocking events. The focus is on the trout farms with flow-through systems (FTS). The specific objectives are, to:

1. Develop a model for FTS fish farm management by applying multiple-models for fish growth in a spreadsheet format;
2. Develop a simulation model for effluent load estimation from an FTS fish farm; and to
3. Integrate the simulation of fish farm production management by incorporating effluent, multi-stocking and multi-species conditions.

1.4 Thesis Outline

The following chapter, Chapter 2, presents the review of the literature on fish growth, fish production simulation, and fish effluent modeling. Chapter 3 presents an overview of the methodology approach, and the framework for the development of an integrated aquaculture model for fish farm production and effluent simulation. Each module of the model includes the effective parameters, variables, functions, and procedures. The validation and calibration approach, dataset types, and implementation limitations are described in this chapter. In Chapter 4, the model validation results and comparison to similar models is discussed. In Chapter 5, the conclusion and achievements are presented.
REFERENCES


AquaOptima. (2006). *AquaOptima production plan.* Internal report. Permission to use by courtesy of AquaOptima AS, Norway, via email on July 5 2012 from Mr Idar Schei, CEO (idar.schei@aquaoptima.com)


111


