



Open Access Journal

Journal of Sustainable Research in Engineering Vol. 5 (2) 2019, 78-90

Journal homepage: <http://sri.jkuat.ac.ke/ojs/index.php/sri>

ISSN (Online): 2409-1243



# Optimization Model for Recirculating Aquaculture Systems (RASs) for Nile Tilapia in Kenya

Daniel M. Wambua<sup>1\*</sup>, Patrick G. Home<sup>1</sup>, James M. Raude<sup>1</sup>, and Stephen Ondimu<sup>2</sup>

<sup>1</sup>Department of Soil, Water and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, P.O. BOX 62000-00200, Nairobi Kenya.

<sup>2</sup>Department of Agricultural and Biosystems Engineering, Jomo Kenyatta University of Agriculture and Technology, P.O. BOX 62000-00200, Nairobi Kenya.

\* Corresponding author - E-mail: [daniel.wambua@jkuat.ac.ke](mailto:daniel.wambua@jkuat.ac.ke)

**Abstract** Simulation in aquaculture necessitates dynamic modeling that provides a deeper insight into the aquaculture performance. The development towards the use of simulation models in aquaculture has been witnessed in the last few years. Most of the simulation models originate from ecological modeling and applies to through-flow systems. On the other hand, studies on Recirculating Aquaculture Systems (RAS) which consider wastewater treatment, use basic steady-state models of the treatment processes, where the efficiency is set to either a fixed percentage removal or a fixed removal rate. For a farmer, the major target is to improve the efficiency and predictability of intensive aquaculture operations. These improvements are subject to accurate quantification of metabolic rates of the fish coupled with the relationships between water quality and fish growth. Moreover, improvements and refinement of water reuse technologies are inevitable towards the improvement of intensive aquaculture systems. Computer models are effective tools for analyzing water treatment units and fish metabolic response effects on overall system performance. This study aimed at developing a RAS simulation and optimization model to help in predicting water quality and cost optimization of recirculating aquaculture systems. A general standard model development procedure was used in the development of the RAS model. Matrix Laboratory (MATLAB) programming language was used to accomplish the model development task. The data collected on energy consumption, running costs, biofilter efficiency, and flow rates through the connection pipes were used to calibrate and validate the model. From the model evaluation, the Nash-Sutcliffe Efficiency (NSE) values for ammonia, pH, Dissolved Oxygen (DO), Electrical conductivity (EC) and Energy were, -4.26, 0.97, 0.77, 0.59 and 0.94 respectively. Similarly, the coefficient of determination ( $R^2$ ) for ammonia, pH, Dissolved Oxygen (DO), Electrical conductivity (EC) and Energy were, 0.96, 0.89, 0.23, 0.87 and 0.85 respectively. The model also showed that low stocking densities ( $2.3 \text{ kg/m}^3$  to  $5.0 \text{ kg/m}^3$ ) led to longer payback periods as compared to higher stocking densities ( $7.0 \text{ kg/m}^3$  to  $10.0 \text{ kg/m}^3$ ). The model gave a good prediction for most water quality parameters. On profit optimization, most of the good cost scenarios did not coincide with the best water quality conditions. More sub-models to the models to be added to capture aspects of different water treatment and other fish species other than Nile Tilapia.

**Keywords:** Model, Optimization, RAS, Simulation, Water quality

## 1. Introduction

Aquaculture is the raising of aquatic animals or the cultivation of aquatic plants for food. This can be done in

both freshwater and marine systems [1]. Recirculating Aquaculture Systems (RAS) is one of the many types of aquaculture production systems. As the name suggests, a RAS employs the principle of recirculating and reusing



the production water in the aquaculture system. This ensures that there is minimized water usage and therefore reduced water cost as well as reduced water pollution [2]. However, the main challenge in RAS is to remove ammonia from water and create a conducive environment for the fish to thrive while keeping the system profitable at the same time [3].

Up to date, no research in the country has been dedicated to producing standards for RAS system with different stocking densities. As a result, those practicing RAS continue to make huge losses [4]. With no standardization of RAS in Kenya, most of the farmers practicing this intensive system end up developing systems which lead to losses through fish deaths. High flow rates lead to unnecessary expenses on energy and inadequate removal of ammonia and other contaminants [5]. This study aimed at developing a RAS simulation and optimization model that can predict water quality while at the same time guide in predicting the optimum operational cost of the system.

### 1.1 Simulation and Optimization of RAS

Simulation is the imitation of a process or situation. According to [6] to fully explore the advantages of RASs to its maximum and make the systems commercially successful, the recirculation ratio should be as high as possible. Optimization is the process of finding the most suitable value for a given situation or process based on several constraining conditions [7], [8]. Optimizing by carrying out full-scale experiments alone based on *ad hoc* assumptions is simply too time-consuming. Development of an optimization solution requires a good understanding of the entire system, the processes, and variables. Moreover, simulation in aquaculture necessitates dynamic modeling that provides a deeper insight into the aquaculture performance [9]. This enables the generation of the appropriate objective function(s) and constraints [7]. The development towards the use of simulation models in aquaculture has been witnessed in the last few years [6]. Most of the simulation models originate from ecological modeling and applies to through-flow systems [10]. On the other hand, studies on RASs which consider wastewater treatment, use basic steady-state models of the treatment processes, where the efficiency is set to either a fixed percentage removal or a fixed removal rate [11]. However, since the system is dynamic, according to [6], the dynamics of biology in the treatment processes as well as a more diversified waste description has to be included for realistic simulations.

The complexity of RAS, due to their feedback and multivariable character, implies that nontrivial dynamic

models of all important system components - the fish, feed, bacteria, rearing basins, treatment units among others - are required [12].

### 1.2 Why Modeling of the RAS

The major goals of farmers, researchers, and system designers are to improve the efficiency and predictability of intensive aquaculture operations. These Improvements are subject to accurate quantification of metabolic rates of the fish and the relationships between water quality and fish growth. Moreover, improvements and refinement of water reuse technologies are inevitable towards the improvement of intensive aquaculture systems [10]. Computer models are effective tools for analyzing water treatment units and fish metabolic response effects on overall system performance. With such a model, the performance of several water reuse processes and configurations can be predicted while at the same time simulating water quality, resource requirements, and production capabilities of the systems. The simulation predictions are useful in the design and installation of new systems, evaluation and selection of system components. The simulation results also assist in the implementation of changes to existing systems, and the management of water quality and production schedules in existing farms [8].

### 1.3 Available models

Reference [13] proposed an aquaculture model being developed using a modeling software package (Extend) that allows for the creation of *blocks*, each of which simulates a separate unit operation. Once the blocks are created they are stored in a library from where they can be accessed and connected on the screen to create a model for a particular system configuration. The proposed model can simulate water quality changes and fish biomass production in an aquaculture system over any desired duration as well as account for oxygen and feed consumption, based on assumptions in each block.

The desired simulation period and time-step are chosen and the model is executed. Reference [13] further suggests that time steps used for model execution should be less than one day since most state variables fluctuate daily. The short time steps also prevent possible instability in the numerical integration calculations. The output from this model is then presented in graphs and tables.

The model is dynamic and hence can predict the system changes over time and deterministic in that it has no associated probability distribution since it makes predictions for state variables based on input conditions and model assumptions only. Moreover, all the



components of the model are mechanistic meaning they are based on physical laws.

The water quality variables used in the model include dissolved gases (oxygen, carbon dioxide), solids (suspended solids), dissolved nutrients (total ammonia, combined nitrite and nitrate, total phosphorus), nutrients in suspended solids (nitrogen, phosphorus), organic matter (dissolved, in suspended solids), alkalinity, pH, salinity, and temperature. In addition to these variables, there are the other state variables used in the model which includes fish size, total fish biomass, and oxygen consumption. The blocks in this model include, water supply, flow mixers and splitters, fish culture tank, generic biofilter, trickling biofilter, fine-screen solids removal, settling tank, granular media filter, in-line diffused oxygenation, pure oxygen, air stone, multi-stage low head oxygenation, packed column aerator, chemical addition and output blocks [9]

Reference [13] gives a detailed description of a model different from the one described by [9]. In their model, the RAS is broken into blocks. In the trickling biofilter block, nitrification and BOD removal are calculated using theoretical and empirical formulas developed in earlier studies [13]. Ammonia removal is calculated based on oxygen and ammonia concentrations and diffusion rates, nitrification kinetics, water temperature, media-specific surface area, void ratio and hydraulic loading rate [11].

Reference [14] created a spreadsheet driven program for sizing the water treatment based on expected nitrogen load. Reference [6] proposed and developed a steady-state simulator which comprises of models based on dynamic mass balances with the notations and units following the standards in wastewater treatment. The basic models in the simulator includes the total produced waste of a compound "i" at a time "t", the fish growth model which is a function of the water temperature, model of the total fish mass (kg) in the fish tank and model for the mass growth rate in each tank which is proportional to the digested feed [6]. According to [6], oxygen may be introduced as a liquid added to the tank influent.

Other models developed to help to problem-solve in aquaculture includes FISHSIM which was developed to analyze the financial feasibility and performance of aquaculture production facilities based on the output prices and quantities, variable input costs, survival rates, feed conservation rates and stocking densities [9]. Reference [15] used the modeling tool AQUASIM [16] to build a prediction model, majorly focused on TAN and its removal and calibrated it to measurements taken from replicated experimental systems.

Most recently, [17] developed LibRAS which is an improved version of FISHSIM developed by [9]. His model concentrated on several water treatment topologies which ranged from a fully open system to a closed RAS system with a Moving bed biofilm reactor. However, the model developed in this study adopts as a simplistic approach tied to feeding, and the generation of metabolic wastes to predict a RAS performance. From the three aspects of feeding, aeration and waste generation, the RAS water quality and energy requirements can be predicted with a fairly good degree of accuracy and with limited data.

#### 1.4 Modeling process

According to [18], with the ever-growing knowledge in information technology and the galloping financial constraints in the aquaculture industry, models can be developed for a variety of uses in RAS. Such models are developed using an algorithm. Reference [18] presents a step by step procedure for model development. The steps proposed in their modeling procedure include problem identification, problem definition, algorithm development, computer model development, computer model verification, computer model validation which lead to a verified and validated computer model.

The two most commonly used models for RAS systems are the empirical growth models and the physical growth models [13], [19]. The main difference between the two models is that an empirical model is a model based on a statistical analysis of a specific data set while a physical model, sometimes called an analytical model, is a model based on physical, chemical, or biological laws that describe how a system works [9]. On the other hand, the empirical model is based on the site-specific data of the phenomenon under study.

System functioning issues such as head losses, pump sizes, and tank circulation can be modeled, evaluated and optimized. Therefore a model can be developed for every single problem facing aquaculture today as long as the cause-effect relationship can be identified and expressed in a formula. However, the main challenges are to identify the most important parameters to use in model development, verification, and validation [10].

## 2 Methodology

A physical computer model was developed using the procedure described by [18] Matrix Laboratory (MATLAB) programming language was used to accomplish the model development task. The data collected on energy consumption, running costs, biofilter efficiency, and flow rates through the connection pipes



were used to calibrate and validate the model. Later, the model was used to simulate the operation and performance of various scales of RAS.

2.1 RAS computer simulation model development

2.1.1 The Engineering, biology, chemistry, and economics of RASs

A RAS is a multidimensional and a multidisciplinary system which brings together aspects of engineering, chemistry biology and economics together just to mention a few. The main components of a RAS include the production tank, the pump, aerators, the biofilter, and a piping system. In engineering, RAS employs hydraulic designs in its different components such as piping, pumps, and aerators. To move water around the system, a pump which uses energy has to be used. Similarly, aeration or oxygenation require energy to be accomplished. Biology and chemistry come in handy especially in water treatment and regulation of the water quality to provide a conducive environment of the plant or animal life in the RAS water. The biofilter is the heart of the RAS system since it provides for the removal of wastes before the water is taken back into the system in this study, the Nile tilapia (*Oreochromis niloticus*) is the fish of interest. The Nile tilapia is a fish which thrives best in warm water environments and is one of the most preferred species in warm water aquaculture across the world. The fish can grow into table size of 300g to 500g in a span of 5 to 8 months with appropriate feeding.

RASs being used for food production cannot leave the aspect of economics out, as a result running an economical and profitable RAS to produce food is a very important aspect in RAS design. Energy for pumping and aeration together with feeding make up the largest portion in the cost of running a RAS.

2.2 The RAS modeling

In this study, a physical growth model touching on the cost of installation and operation was developed and used to simulate and optimize RAS performance. Physical growth models (model based on physical, chemical, or biological laws and theories) were used to allow for the computer model's applicability within the country and beyond. Matrix laboratory (MATLAB) was used to accomplish the model development task. Design monographs were then prepared and published for use by the larger Kenyan community.

The developed model was used to determine maximum attainable profits while at the same time minimizing the costs of feed, energy, and fingerling.

The objective function for the optimization is as presented in (1)

$$\text{Maximize profit } (\delta) = (P_q \times Q_f) \times P_{ay} - ((C_e + C_f + C_s + C_{om}) \times t) \times P_{ay} + (C_i) \tag{1}$$

Where:

$\delta$  = is profit in KES

$P_q$  = the price per kg of the harvested fish (KES.600)

$Q_f$  = the quantity of the harvested fish (Kg)

$C_e$  = the cost of electricity (KES)

The unit cost of electricity = KES.13.50/kWh

$C_f$  = the cost of feed (KES)

Cost of feed per kg (KES 200 ± 50/kg (variable)) and,

$C_s$  = the cost of fish during stocking (KES)

$C_i$  = cost of installation of the RAS structures (production tanks, pumps aerators pipework, biofilter)

$C_{om}$  – operation and maintenance cost (assumed at 15% of the installation cost)

$P_{cy}$  – Number of production cycles (Number) whereby the duration of the production cycle is taken like 6 months

$t$  = the age of the fish (days)

Unit cost of fish at introduction (fingerlings) = KES140/fish (variable)

The optimization constraints are as presented in (2). Equation (2) constraints profit to at least 10% of the total revenue [20], [21].

$$\frac{((P_q \times Q_f) \times P_{cy} - ((C_e + C_f + C_s + C_{om}) \times P_{cy} + (C_i))}{P_q \times Q_f) \times P_{cy}} \geq 0.1 \tag{2}$$

For profitability of the enterprise, the total revenues should be greater than the total costs for a given crop and can be computed using (3).

$$(P_q \times Q_f) \times P_{cy} \geq (C_e + C_f + C_s + C_{om}) \times P_{cy} + C_i \tag{3}$$

The constraint variables,  $P_q$ ,  $Q_f$ ,  $C_e$ ,  $C_f$ ,  $C_s$ ,  $C_i$  &  $C_{om}$  should be greater than 0.

The equations used for the development of the RAS computer model was as follows:

The energy consumed by the pump ( $P_p$ ) in one day was computed as presented in (4).

$$\text{Energy } (P_p) = \frac{W\rho ghQ}{60,000 \times 1000} \times 24 \tag{4}$$

Where:



W = A modification factor (s/Nm)  
 Pp = the energy (kWh)  
 ρ = the density of the fluid (1000kg/m<sup>3</sup>)  
 g = acceleration due to gravity (9.81N/kg)  
 h = the height to which the fluid is being raised (m)  
 Q = the discharge in (L/min)

The energy consumed by the pump for an entire production cycle was calculated as the product of Pp and the length of the production period in days. The systems oxygen demand was computed based on the systems prevailing stocking density, specific oxygen consumption and production water volume. Mathematically, this is presented in (5).

$$OD = SD \times SOC \times \frac{V}{1000} \quad (5)$$

Where:

OD = Oxygen demand (mg O<sub>2</sub>/hr)  
 SD = Stocking density (kg/m<sup>3</sup>)  
 SOC = Specific oxygen consumption (mg O<sub>2</sub>/kg fish.hr)  
 V = is the volume of the production tanks (L)

From the computed oxygen demand, the amount of energy consumed by the aerators was calculated using (6).

$$P_A = 0.001 \times OD \times AER \times \frac{SAE}{100} \times 24hr \quad (6)$$

Where:

P<sub>A</sub> = energy required for aeration (kWh)  
 OD = Oxygen demand (mg O<sub>2</sub>/hr).  
 AER = Aerators energy rating (watts/mg O<sub>2</sub>)  
 SAE = Specific aeration efficiency as a percentage (%)  
 0.001 converts energy from watts into kilowatts

The oxygen concentration (DO) of the production water is computed using (7)

$$DO = F \times \frac{\text{Oxygen demand}}{60 \times Q} \quad (7)$$

Where:

DO (mg/L)  
 Oxygen Demand (mg O<sub>2</sub>/hr)  
 F = constant of proportionality  
 Q = flow rate (L/min)

The total cost of energy for running the RAS system is as presented in (1.8).

$$C_e = (P_p + P_A) \times \text{Unit cost of Energy KES, per day} \times t \quad (8)$$

Where:

C<sub>e</sub> = Cost of energy (KES)  
 t = number of days from stocking to the harvesting (days)

The amount of energy utilized by the RAS in a day (C<sub>e day</sub>) was calculated by dividing the total amount of energy consumed by the system during a production cycle (C<sub>e</sub>) by the number of days from stocking to the harvesting.

The number of fish to be stocked was calculated as using (9).

$$\text{NoF} = \left( \frac{SD}{\text{Unit weight of fish}} \times \frac{V}{1000} \right) \quad (9)$$

Where:

NoF = Number of fish to be stocked (Number)  
 SD = the stocking density in (kg/m<sup>3</sup>)  
 V = the volume of the production tank (Litres)  
 Unit weight of fish (kg)

The cost of stocking (C<sub>s</sub>) was computed as presented in (10)

$$C_s = \text{NoF} \times \text{price per fish} \quad (10)$$

The cost of stocking per day (C<sub>s day</sub>) is obtained by dividing the cost of stocking (C<sub>s</sub>) by the number of days from stocking to harvesting (t)

The weight gain of the fish is a function of the water temperature (22°C - 31°C), initial fish weight and the stocking density (which is influenced by the ammonia and oxygen concentration and the fish appetite and amount of feed fed) [10].

The fish weight at a given time was calculated from (11);

$$Q_f = 0.9 \times \text{NoF} \times A \times SD \times e^{kt} \quad (11)$$

Where:

NoF = Number of fish to be stocked (Number)  
 0.9 = a survival rate  
 t = the age of the fish (days)  
 A = is the initial body weight of the fish (kg)  
 SD = 0.261

SD is the stocking density growth coefficient that will be obtained through calibration using experimental data. An approximate value to this coefficient is 0.261[22].



"k" is the temperature-dependent growth coefficient which ranges from 0.0259 at 22°C through 0.0416 at 28°C to 0.0374 at 30°C [23], [24].

The amount of feed fed to the fish (F) over an entire production period (t) and amount of feed fed per day (F<sub>day</sub>) was calculated as presented in (12) and (13) respectively.

$$F = 0.04 \times Q_f \tag{12}$$

$$F_{day} = \frac{F}{t} \tag{13}$$

Where:

- Q<sub>f</sub> = Quantity of fish (kg)
- F<sub>day</sub> = Feed fed to the fish per day (kg)
- F = Feed fed to the fish from stocking to harvesting (kg)
- t = number of days from stocking to the harvesting (days)

The cost of feed was computed as a product of the feed fed and the unit cost of feed as presented in (14) and (15)

$$C_f = F \times \text{unit price per kg} \tag{14}$$

$$C_{f\ day} = F_{day} \times \text{unit price per kg} \tag{15}$$

Where:

- C<sub>f day</sub> = cost of feed per day (KES)
- C<sub>f</sub> = cost of feed from stocking to harvesting age (KES)

The ammonia generated was computed as 2.5% of the feed fed to the fish from as in (16).

$$AMM_{prd} = 0.025 \times F_{day} \tag{16}$$

The ammonia concentration was then estimated using (17).

$$AMM_{conc} = AMM_{prd} \times \frac{10^6}{V} \tag{17}$$

Ammonia produced > 0

Where:

- AMM<sub>prd</sub> = Ammonia produced by the fish (kg)
- AMM<sub>conc</sub> = Ammonia concentration in water (mg/L)
- 0.05mg/L < AMM<sub>conc</sub>

Purification Efficiency Ratio (PER) was expressed as presented in (18). This was based on the postulation that PER varies with flow rate, stocking density and dissolved oxygen.

$$P.E = y \frac{DO}{10,000 \times Q \times SD} \tag{18}$$

And, 0 < P.E ≤ 100

Where:

- y = a proportionality constant (m<sup>3</sup>.min/L<sup>2</sup>)
- PE = purification efficiency
- DO = the dissolved oxygen (mg/L)
- Q = the system flow rate (L/min)
- SD = the system stocking density (kg/m<sup>3</sup>)

Since the main contaminant to be removed is Ammonia, the amount of ammonia removed was expressed as in (19);

$$AMM_{Re} = \frac{PE}{100} \times AMM_{prd} \tag{19}$$

Where:

- AMM<sub>Re</sub> = Removed ammonia (mg/L)
- E = Purification efficiency (%)
- AMM<sub>prd</sub> = Ammonia Produced (mg/L)

The residual ammonia was computed as in (20):

$$AMMLL = AMM_{prd} - AMM_{Re} \tag{20}$$

Where:

- AMMLL = Residual ammonia
- AMMLL ≤ 0.05mg/L

pH of the production water was presented as in (21)

$$pH = S \times (-\log [H^+]) \tag{21}$$

and 6 < pH < 9.5

Where:

- [H<sup>+</sup>] = Concentration of hydrogen ions (mol/L)
- [OH<sup>-</sup>] = Concentration of hydroxyl ions (mol/L)
- K<sub>b</sub> = ionization constant of ammonia (1.8 x 10<sup>-5</sup>)
- c = concentration of ammonia (mol/L)
- =  $\frac{AMM_{conc}(mg/L)}{1000 \times MM}$
- MM = molar mass of ammonia (17.031g/mol) and,
- [OH<sup>-</sup>] =  $\sqrt{(K_b \times c)}$
- [H<sup>+</sup>] =  $\frac{10^{-14}}{[OH^-]}$

NB: In this study, the water pH was not modified. However, the basaltic pumice used was expected to keep the treated water pH slightly above the neutral point.

The Electrical conductivity (EC) of the system was expressed as presented in (22)

$$EC = N \times AMM \tag{22}$$

Where:





The model development involved the coding of the equations presented in Section 2.1 using MATLAB's App-designer. The RAS Computer simulation model has currently three tabs: the input, the output, and the data tab.

3.1.1. *Input tab*

The input tab appears as presented in Fig. 2. The Input tab is divided into three minor panels: fish, energy consumption and a panel that consists of the most important parameters of the model – stocking density &

flow rate. The user enters the input and according to these values, the output can be determined through formulas that are defined in the code view.

Feed conversion ratio in aquaculture is the ratio of feed taken by the fish to the fish weight gain. A high value of feed conversion ratio is an indication of feed waste while a lower feed conversion ratio is an indicator of efficient feed intake. The lower the feed conversion ratio the higher the profits since less feed is used to generate more fish flesh

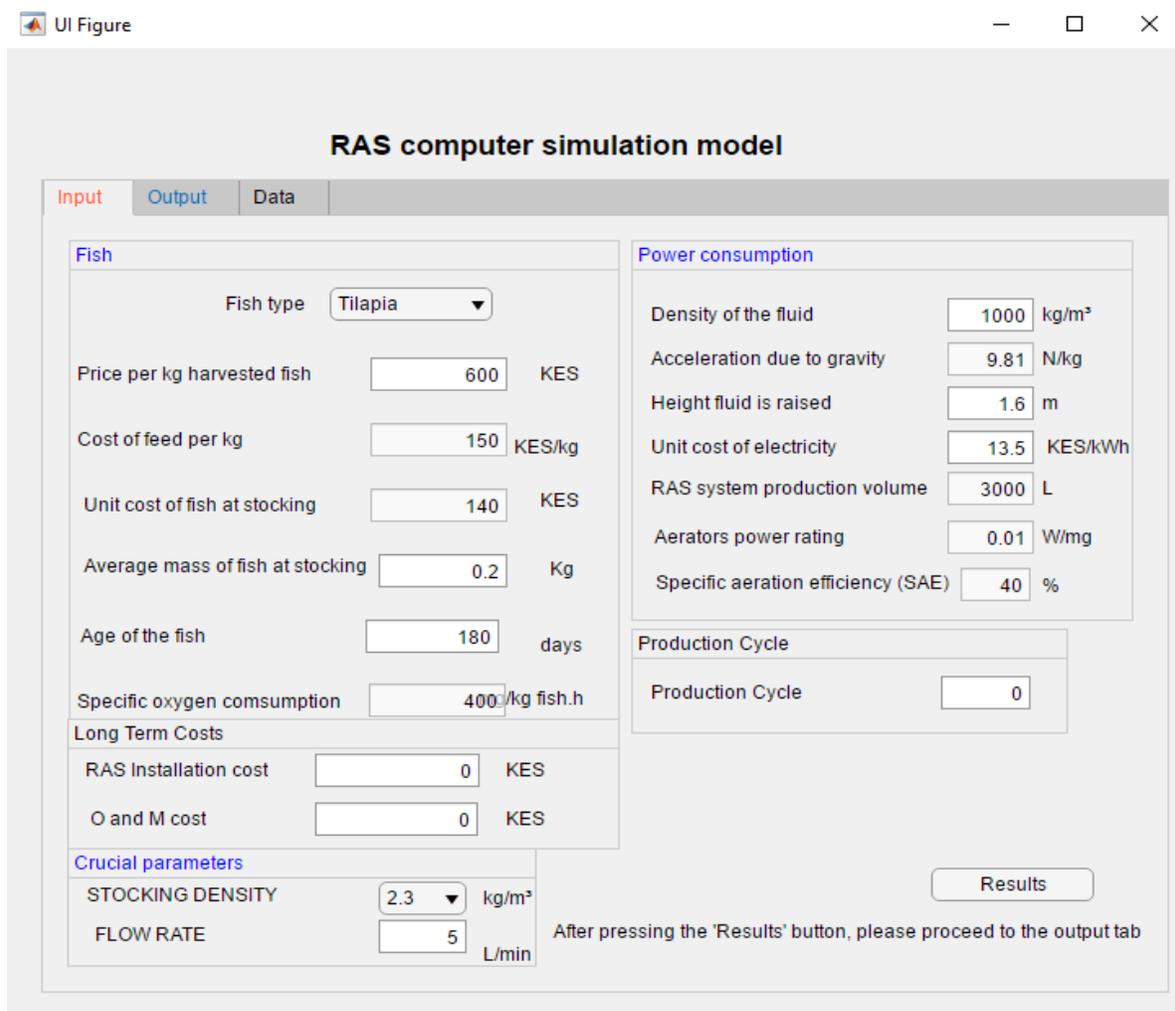


Fig. 2: The input panel of the RAS computer model

3.1.2. *Output tab*

The output tab is as presented in Fig. 3. In the output tab, the user finds results through the input values.

These values are a first step in the analysis to optimization.



3.1.3 Data tab

The Data tab is as presented in Fig.4. In the Data tab, the user can seek the optimized value by comparing the

theoretical value with the values obtained by data collection.

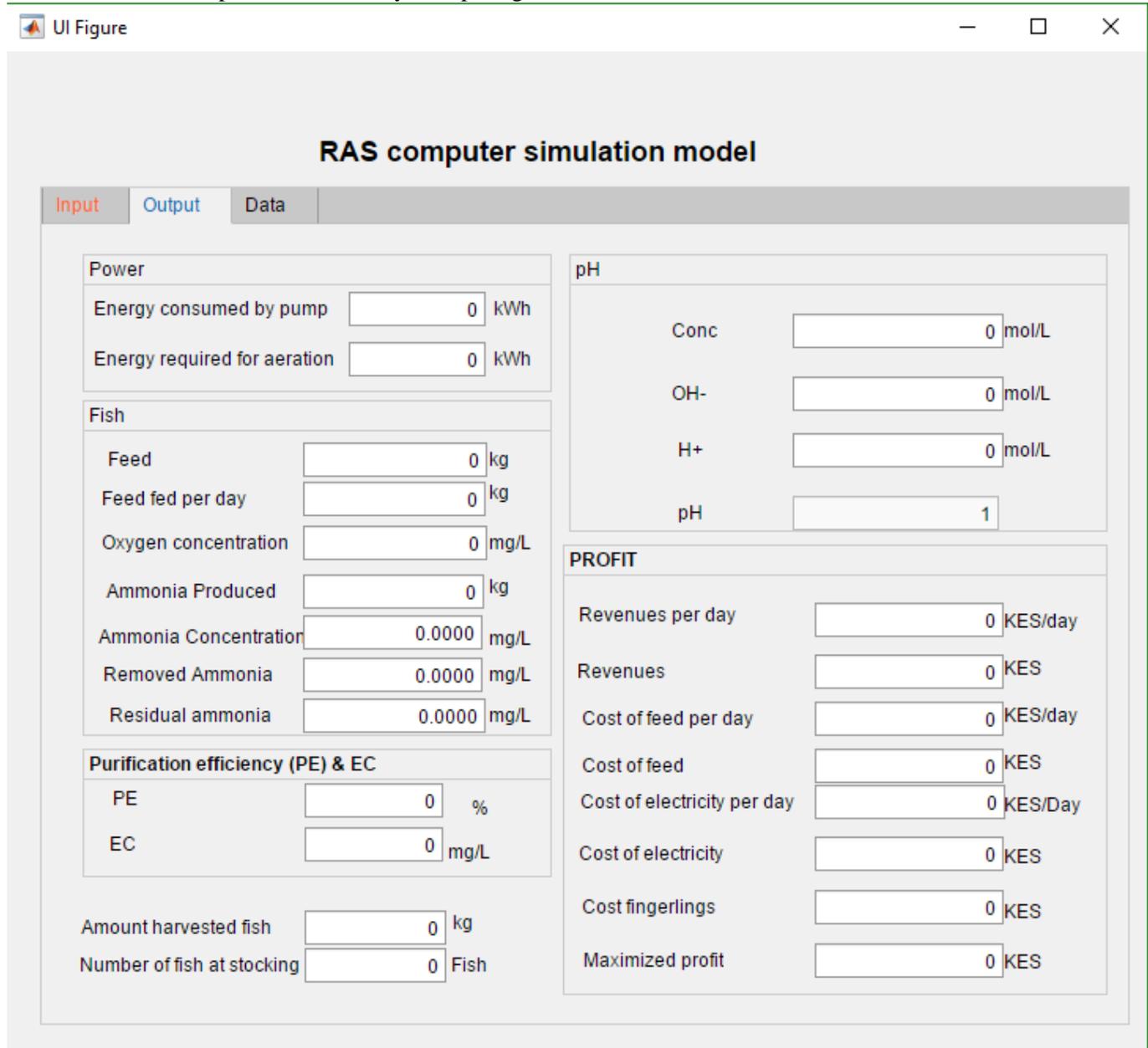


Fig. 3: The Output panel of The RAS computer Model

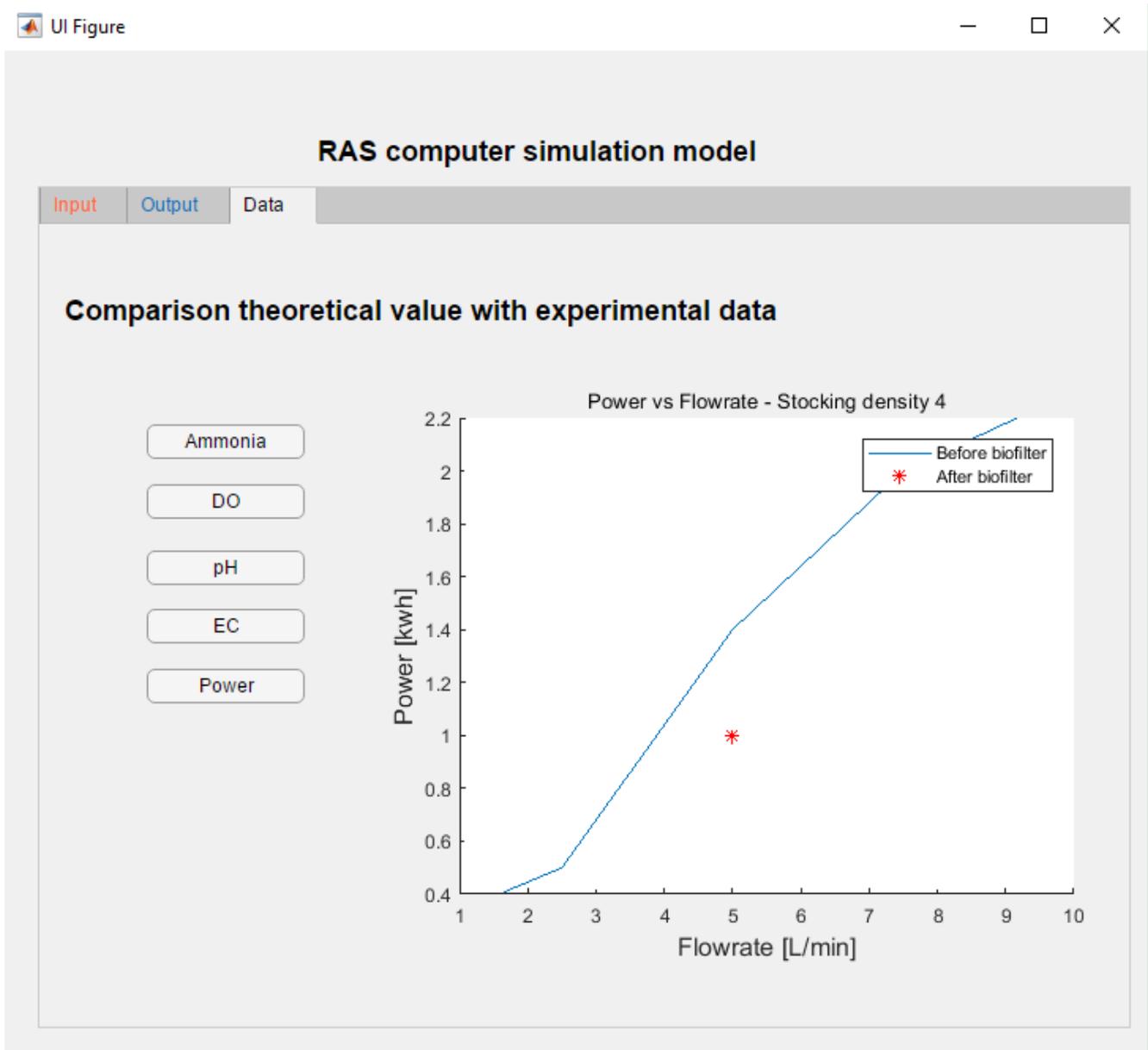


Fig.4: The Data tab of the RAS computer Model

In the Data tab, if ever the Ammonia button is clicked, the graph should plot the data achieved from experiments and the data obtained from a theoretical viewpoint. Through this way the user can determine whether the model needs to be adjusted or if it is closer to optimization. Optimal values were obtained from the evaluation of curves/trends of the different water quality parameters and energy consumption. Water flow and water quality parameter values were deemed optimal if they both led to lower cost of production and hence more revenues while at the same

time maintaining favorable conditions for the fish to thrive.

### 3.2. Optimal flowrate and environmental levels for different production density

From the developed model and with the aid of Excel and MATLAB optimizer, the optimal energy and environmental requirements for the different production densities were found to be as presented in Table I.



Table I  
Optimal energy, flow rate, and water quality parameters for different stocking density

Stocking density (kg/m <sup>3</sup> )	Flow rate (l/min)	Optimal ammonia (mg/L)	Optimal pH	Optimal DO (mg/L)	Optimal EC (mg/L)	Optimal power (kWh)
2.3	1.500	0.002	6.20	1.72	55.20	0.35
3.5	1.5-2	0.004	6.90	2.24	84.00	0.53
4.0	3-3.5	0.004	7.20	2.56	96.00	0.68
5.0	4- 4.5	0.005	7.75	3.20	120.00	0.85
7.0	5-6.5	0.007	8.85	4.48	168.00	1.21
9.0	8-9.0	0.009	9.95	5.76	216.00	1.50
10.0	11-12	0.010	10.50	6.40	240.00	1.87

Optimal values in the conclusion were obtained from the evaluation of curves/trends of the different water quality parameters and energy consumption. Water flow and water quality parameter values were deemed optimal if they both led to lower cost of production and hence more revenues while at the same time maintaining favorable conditions for the fish to thrive.

At this flow rates and energy consumption levels, the water quality parameter is at the optimal levels for the aquatic organisms to thrive. The optimal environmental requirements for Nile tilapia are to be 3mg/l dissolved oxygen, 6.9 - 9.0 pH, and 27°C - 30°C of temperature and less than 0.05mg/l of ammonia [25] At this parameter

levels, the fish fed and behaved normally and showed no signs of stress.

### 3.3. Model Validation

Once the optimal flow rates were obtained from the RAS simulation model, the RAS experiments were repeated for the different stocking densities. The experiments involved setting the optimal flowrate obtained for each stocking density and measuring the water quality parameters and energy consumed. The validation results were as presented in Tables II and III

Table II  
Validation results in the production tank

Flow rate (L/min)	Stocking Density (kg/m <sup>3</sup> )	Ammonia in the production tank	Dissolved Oxygen in production tank	pH in the production tank	Ec in production tank	Energy (kWh)
1.5	2.3	0.023	6.01	7.55	358.67	0.40
1.5-2	3.5	0.022	5.46	7.58	362.67	0.50
3-3.5	4.0	0.025	5.29	7.66	371.67	0.57
4- 4.5	5.0	0.030	4.23	7.93	377.00	0.70
5-6.5	7.0	0.039	4.26	8.01	380.00	0.93
8-9	9.0	0.050	4.96	8.05	382.00	1.25
11-12	10.0	0.060	4.97	8.13	387.67	2.50



Table III  
Validation results after the biofilter

Flow rate (L/min)	Stocking Density (kg/m3)	Ammonia After Biofilter	Dissolved Oxygen after biofilter	pH after biofilter	Ec after biofilter
1.5	2.3	0.019	2.80	7.25	358.00
1.5-2	3.5	0.020	2.88	7.53	365.00
3-3.5	4.0	0.028	1.91	7.76	371.00
4- 4.5	5.0	0.029	1.87	7.83	376.00
5-6.5	7.0	0.035	2.73	7.85	381.00
8-9	9.0	0.039	4.73	7.94	382.00
11-12	10.0	0.050	2.98	7.98	383.00

Table III shows the projected costs, revenues take long before break-even as compared to high stocking profits/losses for the different production densities at densities [5]. optimal levels for two production cycles. From the costs/revenues, it is evident that low stocking densities

Table III:  
Projected costs for the RAS system over two production cycles (12 months) for each stocking density

Stocking density(kg/m3)	2.30	3.50	4.00	5.00	7.00	9.00	10.00
<b>Stocking Cost (KES)</b>	1,820.00	2,520.00	2,940.00	3,640.00	5,040.00	6,440.00	7,140.00
<b>Feeds Cost (KES)</b>	3,312.00	5,040.00	5,760.00	7,200.00	10,080.00	12,960.00	14,400.00
<b>Energy Cost (KES)</b>	5.20	6.50	7.41	9.10	12.09	16.25	32.50
<b>Construction Cost (KES)</b>	36,500.00	36,500.00	36,500.00	36,500.00	36,500.00	36,500.00	36,500.00
<b>O &amp; M Cost (KES)</b>	5,475.00	5,475.00	5,475.00	5,475.00	5,475.00	5,475.00	5,475.00
<b>TOTAL cost per Stocking density (KES)</b>	47,112.20	49,541.50	50,682.41	52,824.10	57,107.09	61,391.25	63,547.50
<b>Expected Revenues (KES)</b>	16,974.00	25,830.00	29,520.00	36,900.00	51,660.00	66,420.00	73,800.00
<b>Profit/Loss (KES)</b>	(30,138.20)	(23,711.50)	(21,162.41)	(15,924.10)	(5,447.09)	5,028.75	10,252.50

Most appropriate profit scenarios did not coincide with the best water quality conditions for most of the stocking densities. Conversely, most of the optimal water quality levels did coincide or lead to profitable scenarios [17]. The Nash Sutcliff efficiency (NSE) values and Root Mean Square Error (RMSE) values for the different parameters before and after the biofilter are as presented in Table IV.

From the NSE and RMSE analysis, the model gave a fairly good prediction of pH, DO and energy. The ammonia and EC model predictions did not fairly correspond to the observed values. The ammonia and EC

model values were relatively higher than the observed values. This was attributed to the accumulation of ammonia and EC with time as there were only minimal water exchanges.



Table IV

Nash Sutcliff efficiency values and RMSE values for the different parameters before the Biofilters

Parameter	RMSE (with parameter units)	NSE (Unit-less)	R <sup>2</sup>
Ammonia (mg/L)	0.03	-4.26	0.95
pH	1.33	0.97	0.89
DO (mg/L)	2.39	0.77	0.23
EC (mg/L)	240.86	0.59	0.87
Energy (kWh)	0.29	0.94	0.85

#### 4. Conclusion

The model gave a good prediction for most water quality parameters. From the developed RAS model, the optimal environmental requirements for Nile tilapia were found to be 4mg/L dissolved oxygen, 7.0 pH, 27°C of temperature and 0.03mg/L of ammonia at different flow rates for each stocking density. However, the most appropriate profit scenarios did not coincide with the best water quality conditions for most of the stocking densities.

#### Acknowledgment

The authors wish to thank JICA (Africa-ai-Japan project) which provided financial support to accomplish this research.

#### References

[1] Timmons, M. B., & Ebeling, J. M. (2010). Recirculating aquaculture (Vol. 126). Ithaca, USA: Cayuga Aqua Ventures.

[2] Ebeling, J. M. (2000). Engineering aspects of recirculating aquaculture systems. *Marine Technology Society Journal*, 34(1), 68-78.

[3] Avnimelech, Y. (2006). Bio-filters: The need for a new comprehensive approach. *Aquacultural Engineering*, 172-178.

[4] Munguti, J. M., Musa, S., Orina, P. S., Kyule, D. N., Opiyo, M. A., Karisa, H. C., & Ogello, E. O. (2014). An overview of the current status of Kenyan fish feed industry and feed management practices, challenges and opportunities. *International Journal of fisheries and Aquatic Studies* 1(6), 128-137.

[5] Obwanga, B., Lewo, M. R., & Bolman, B. C. (2017). From aid to responsible trade: Driving competitive aquaculture sector in Kenya (2017-092 3R Kenya). Wageningen: Wageningen University & Research

[6] Wik, T. (2004). Modeling, control, and simulation of recirculating aquaculture systems. *Computer Applications in Biotechnology*, 141-146.

[7] Deb, K. (2014). Multi-objective optimization. In *Search methodologies* (pp. 403-449). Springer, Boston, MA.

[8] Nocedal, J., & Wright, S. (2006). Numerical optimization. Springer Science & Business Media.

[9] Wik, T. E., Linden, B. T., & Wramner, P. I. (2009). Integrated dynamic aquaculture and wastewater treatment modeling for recirculating aquaculture systems. *Aquaculture*, 287 (3), 361-370.

[10] Kazmierczak, R. F., & Caffey, R. (1996). *The bioeconomics of recirculating aquaculture systems*. No. 854. Louisiana Agricultural Experiment Station, LSU Agricultural Center.

[11] Verdegem, M. C., Van Dam, A. A., Cabarcas-Nunez, A. A., & Opera, L. (2000, September). Bio-energetic modeling of growth and waste production of Nile tilapia (*Oreochromis niloticus* L.) in recirculation systems. In *Tilapia Aquaculture in the 21st Century, Proceedings of the Fifth International Symposium on Tilapia Aquaculture*, (pp. 368-381).

[12] Alt, D. (2015). *Computer Simulation of Modern Recirculation Systems and their Production Strategies*. Louisiana: Louisiana State University.

[13] Brinkop, W. S., & Piedtrahita, R. H. (1996). Water Quality Modeling for Aquaculture Water Reuse Systems. *AES Technical session 1: open papers*, 1-11.

[14] Losordo, T. M., & Hobbs, A. O. (2000). Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems. *Aquacultural Engineering*, 23(1-3), 95-102.

[15] Pedersen, L. F., Suhr, K. I., Dalsgaard, J., Pedersen, P. B., & Arvin, E. (2012). Effects of feed loading on nitrogen balances and fish performance in replicated recirculating aquaculture systems. *Aquaculture*, 338, 237-245.

[16] Reichert, P. (1994). AQUASIM-A tool for simulation and data analysis of aquatic systems. *Water Science and Technology*, 30(2), 21.

[17] Pedersen, S. (2018). Simulation and Optimization of Recirculating Aquaculture Systems. *Thesis for the degree of licentiate of engineering*, Department of the Electrical Engineering Chalmers University of Technology, Göteborg, Sweden.

[18] Tomer, B. C., & Wheaton, F. W. (1996). Computer Models: Types, Verification, Validation, and Applications in Commercial. *AES Technical Session 1*, 1-11.

[19] Sokolowski, J.A., & Banks, C.M. (Eds.) (2011). Principles of modeling and simulation: a multidisciplinary approach. John Wiley & Sons.

[20] Engle, C. R. (2010). *Aquaculture economics and financing: management and analysis*. John Wiley & Sons.

[21] Smith, G. E., & Nagle, T. T. (1994). Financial analysis for profit-driven pricing. *MIT Sloan Management Review*, 35(3), 71.

[22] Huang, W. B., & Chiu, T. S. (1997). Effects of stocking density on survival, growth, size variation, and production of Tilapia fry. *Aquaculture research*, 28(3), 165-173.

[23] Santos, V. B. D., Mareco, E. A., & Dal Pai Silva, M. (2013). Growth curves of Nile tilapia (*Oreochromis niloticus*) strain cultivated at different temperatures. *Acta Scientiarum. Animal Sciences*, 35(3), 235-242.

[24] Iwama, G. K., & Tautz, A. F. (1981). A simple growth model for salmonids in hatcheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 38(6), 649-656.

[25] Ngugi, C. C., Bowman, J. R., & Omolo, B. O. (2007). *A new guide to fish farming in Kenya*. Oregon: Snell Hall.