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Water Quality Management in Aquacultural Production using Aquasmat

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Abstract

This paper introduces a newly developed model, *AQUASMAT,* and its potential applications, especially in the tropical environment. *AQUASMAT* can help identify and quantify the cause, effect and relationships between water quality parameters, the physical environment and aquatic ecosystem. It is well suited for production ponds and other water bodies, as well as for predicting general pond dynamics. *AQUASMAT* is a valuable tool for water quality modeling and aquacultural management. In this overview, the model is shown to have the following capabilities: (1) a graphical user interphase and management data capability; (2) identification and quantification of cause and effect relationships of feed with respect to chemical water quality parameters, the physical environment, and aquatic ecosystem; (3) analysis of complex relationships in impaired production ecosystems and suggestion of cause and management of the various causes of impairment; (4) prediction of feed wastage and economic viability of the production system; (5) presentation of the effect of different management operations on fish yield; (6) tracking of more than 40 parameters which are not easily obtainable from conventional measurement procedures. The model can thus help to fill the knowledge gap and also explore cost-effective and appropriate management measures for ailing aquacultural production systems.

Key words: Fish, Feed, Water quality, *AQUASMAT*, Applications

Introduction

The complexity of aquatic ecosystem due to seasonal and annual variations; and multiple interactions has made it difficult to predict how the aquatic community will respond to changes in pollutants or environmental conditions with simple methods of analysis, especially if the methods address a single stressor at a time. This has necessitated the development of numerous water quality models which have been used for years as tools to interpret, predict and better understand the water quality changes, eutrophication and hydrodynamics in rivers, lakes, estuaries, reservoirs or a combination of them.

Simulation models of production systems facilitate the study and evaluation of the complex-interactions and provide a working tool to conduct numerous "what if" experiments quickly, evaluating the consequences of various hypotheses or management-strategies (Cuenco, 1989). They can also be used to make intelligent predictions about the consequences of various management strategies, thereby facilitating the day –to- day management of aquacultural operations (determining stocking and feeding rates, predicting dissolved oxygen levels and examining the effects of different management strategies). Simulation models therefore, offer great potentials for the study and design of agricultural/aquacultural production systems and for education and training. They are also useful where experimentation results are lacking, incomplete, too expensive, or impossible to get.

Aquacultural systems as aquatic production ecosystems are highly complex. This is because of the biological variability added to the physical and chemical processes that operate in these systems. The biotic (living organisms) and abiotic (water quality factors such as pH, temperature, dissolved oxygen, organic matter, ammonia-ammonium, phosphorous etc., and climatic factors such as solar radiation, wind, evaporation and precipitation) and management components make the understanding of the aquatic ecosystem difficult. The study of interactions between components is seldom feasible to experiment on in their natural environment. This has led to incomplete and expensive experiments, lack of useful result and understanding of the system.

The development of a simulation model that can predict the success or failure of a culture system under various management conditions, will not only fill in the research knowledge gap, it will also remove the trial and error of available management methods involved in fish production, minimize cost and resource wastage, enhance production and boost commercial fish farming in Nigeria.

The need for AQUASMAT

Aquaculture, the farming of aquatic organisms under controlled or semi controlled conditions, remains a growing, vibrant and important production sector for high protein food. Its potentials have been clearly demonstrated by the rapid expansion of this sector; with an annual growth rate of about 10% between 1984 and 1995 in Nigeria, compared with 3% for livestock meat and 1.65% for captured fisheries production (Diana, 1993; FAO, 2005). However, the expansion of this sector has been fraught with some problems. Welcomme (1996) reported that the rapid expansion in aquacultural production in the 1980's was slowed, due to deteriorating water quality and increased occurrence of diseases, especially in semi intensive and intensive culture systems which involve dense populations of fish and enormous wastes comprising largely uneaten feed and excreted matter. Reducing the waste loads from fish farming and optimizing pond water quality have been achieved in some developed countries, however, there is an increasing need to understand the dynamics of aquaculture system. This necessitated the development of Aquacultural Simulation and Management Tool (*AQUASMAT*); a model for predicting the fate and effects of feed, with the view of monitoring, managing and enhancing aquacultural production at minimum resource wastage.

Development of AQUASMAT

Fish depend on their environment (water) for the supply of resources (food, oxygen), removal of metabolic wastes (ammonia, carbon dioxide, feces, urine) and for maintenance of conditions suitable for growth, survival and reproduction (temperature, pH, salinity, etc.). A good knowledge and understanding of the fish environment is a prerequisite for an articulated management program and increased production. Research efforts have been made with species such as eel, trout, channel catfish, *etc*. (Hargreaves & Tomasso, 2004; Wang *et. al*., 2008), that are not peculiar to our environment, hence, the possibilities of variation in waste loads and treatments cannot be overruled, considering the differences in environmental factors, feeding and operational methods. The knowledge of our locally farmed species and their environmental interactions and processes are therefore, important in developing a management tool that will enhance fish farming in Nigeria. In view of this, the model was developed for warm water fish production.

The model is written in C#; a flexible object-oriented programming language that has features, such as "polymorphism" and "inheritance" that makes large complex programming easy. *AQUASMAT* is made up of numerous sub-routines, classes and methods that reduce complexity of the model as shown in figure 1. *AQUASMAT* simulates the fate and effects of feed and other management operations in intensive production systems. It does this by simultaneously computing each of the major physical, chemical and biological processes for each day of the simulation period; therefore it is a process-based or mechanistic model. This means that it explicitly simulates the numerous processes and interactions in an aquatic production ecosystem.

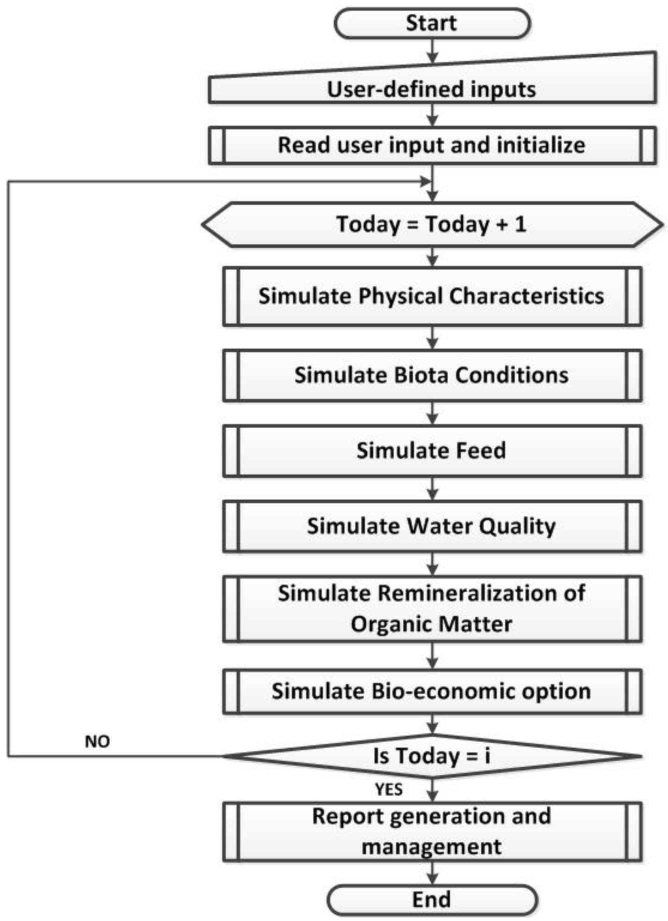

Figure 1: Flowchart of process of simulation for *AQUASMAT*

Theory of Water Quality Parameters in AQUASMAT

In *AQUASMAT*, the major water quality processes are divided into dissolved oxygen sub models, ammonia sub model, CO_2 model, pH model and temperature model.

Dissolved Oxygen Sub-model

Dissolved oxygen is a function of re-aeration, photosynthesis, respiration, decomposition and nitrification. Re-aeration and photosynthesis are the sources while respiration, decomposition and nitrification are the sinks. Equation 1 presented below is a modification of Park and Clough (2009) and Mwegoha *et. al.* (2010) equation for change in concentration of DO.

$$\frac{dDO}{dt} = DO_{loading} + DO_{air} + DO_{photo} - BOD - \left(R_{organism}\right) - DO_{Nitri} \qquad [1]$$

where:

dDO/dt = change in concentration of dissolved oxygen ($g/m^3 \cdot d$);
$DO_{loading}$ = dissolved oxygen loading from manual aeration ($g/m^3 \cdot d$);
DO_{air} = atmospheric exchange of oxygen ($g/m^3 \cdot d$),
DO_{photo} = oxygen produced by photosynthesis ($g/m^3 \cdot d$),
BOD = instantaneous biochemical oxygen demand ($g/m^3 \cdot d$),
$R_{organisms}$ = sum of respiration for all organisms ($g/m^3 \cdot d$),
DO_{Nitri} = oxygen taken up by nitrification ($g/m^3 \cdot d$)

CO_2 Sub-model

Similar to other nutrients, it is produced by decomposition and is assimilated by plants; it also is respired by organisms. *AQUASMAT* modeled CO_2 based on Park and Clough (2009) and Mwegoha *et. al.* (2010).

$$\frac{dCO_2}{dt} = R_{CO2} + D_{CO2} - CO_{2plant} \qquad [2]$$

where:

dCO_2/dt = change in concentration of carbon dioxide ($g/m^3 \cdot d$);
R_{CO2} =carbon dioxide produced by respiration ($g/m^3 \cdot d$); i.e
D_{CO2} = carbon dioxide derived from decompositions ($g/m^3 \cdot d$);
CO_{2plant} = assimilation of carbon dioxide by plants ($g/m^3 \cdot d$).

pH Model

According to Park and Clough (2009), dynamic pH is important in simulations for several reasons:

i. pH affects the ionization of ammonia and potential resulting toxicity;
ii. pH also affects the decay of organic matter and denitrification of nitrate which could eventually feed back to the animals;

AQUASMAT modeled pH based on Park and Clough (2009)

$$pH_{avg} = A + B + \sinh^{-1}\left(\frac{Alk - 5.1 \cdot DOC}{C}\right) \qquad [3]$$

where:

$$A = -\log\sqrt{\lambda} \qquad [4]$$
$$B = 1/\ln(10) \qquad [5]$$
$$C = 2 \cdot \sqrt{\lambda} \qquad [6]$$
$$\lambda = H2CO3^{*} \cdot CCO2 + pkw \qquad [7]$$

$$H2CO3^{*} = 10^{-(6.57-0.0118 \cdot T_{avg}+0.00012 \cdot T_{avg} \cdot T_{avg}) \cdot 0.92} \quad [8]$$

where:

pH_{avg}	=	predicted pH ;
Alk	=	mean Gran alkalinity (200µeq $CaCO_3$/L);
DOC	=	dissolved organic carbon (mg/L);
5.1	=	average µeq of organic ions per mg of *DOC*;
$H2CO3^{*}$	=	first acidity constant;
CCO2	=	CO_2 expressed as µeq/L multiplied by conversion factor of 22.73(µeq/mg);
pkw	=	ionization constant for water (1e-14);
0.92.1	=	correction factor for dissolved CO_2.

Temperature

Temperature is an important controlling factor in the model. Virtually all processes are temperature-dependent. On the other hand, temperature rarely fluctuates rapidly in aquatic systems. Default water temperature is represented through a simple sine approximation for seasonal variations based on user-supplied observed means and ranges (Park and Clough, 2009).

$$T_{avg} = T_{mean} + \left(-1.0 \cdot \frac{T_{range}}{2} \cdot \left(\sin\left(0.0174533 \cdot (0.987 \cdot (JD + \varphi) - 30)\right)\right)\right) \quad [9]$$

where:

T_{avg}	=	average daily water temperature (^{0}C);
T_{mean}	=	mean annual temperature (^{0}C);
T_{range}	=	annual temperature range (^{0}C);
JD	=	Julian date (d); and
φ(phase shift)	=	time lag in heating

Ammonia

Change in ammonia concentration with time was modified from Hargreaves (1997) and Park and Clough (2009) and expressed as:

$$\frac{dAmm}{dt} = N_{ammEr} + N_{ammdiffrate} - N_x - Amm_{uptake} - Q_{out} \quad [10]$$

where:

dAmm/dt	=	change in concentration of ammonia with time (g/m^3·d);
N_{ammEr}	=	ammonia excretion rate (g/m^3·d),
$N_{ammdiffrate}$	=	rate of sediment ammonia diffusion (g/m^3·d),
N_x	=	nitrification rate (g/m^3·d),
Amm_{uptake}	=	ammonia assimilation by phytoplankton (g/m^3·d),
Q_{out}	=	concentration of discharge parameter (g/m^3)

Ionization of Ammonia

The un-ionized form of ammonia, NH_3, is toxic to fish. Therefore, it is often singled out as a water quality criterion. Un-ionized ammonia is in equilibrium with the ammonium ion, NH^+_4, and the proportion is determined by pH and temperature. According to Bowie *et al* (1985), unionized ammonia is expressed by equation 16 as:

$$NH_3 = NH_{3frac} \cdot Amm \qquad [11]$$

where:

NH_{3frac}	=	fraction of unionized ammonia (unitless);
NH_3	=	unionized ammonia (mg/L);
Amm	=	total ammonia (mg/L),

Nitrate

According to Park and Clough (2009), nitrite occurs in very low concentrations and is rapidly transformed through nitrification and denitrification; therefore, it is modeled with nitrate from Hargreaves (1997) and Park and Clough (2009). The equation is as expresses in equation 17.

$$\frac{dNO_3}{dt} = N_x - \overline{N_x} - Amm_{uptake} - Q_{out} \qquad [12]$$

where:

dNO_3/dt	=	change in concentration of nitrate with time ($g/m^3 \cdot d$).
N_x	=	nitrification rate ($g/m^3 \cdot d$),
$\overline{N_x}$	=	denitrification rate (g/m3d);

Discharge

In stagnant cultures, water exchange is performed periodically to flush out excess nutrients. *AQUASMAT* simulates the discharge rates at 20% of pond water exchange reduces nutrient concentration by 17%. This is presented in equation 13 as:

$$Q_{out} = \frac{\%exchange \times 0.85}{vol.} \times Conc \qquad [13]$$

where:

Q_{out}	=	loss due to water exchange (g/m^3)
%exchange	=	user input percent water exchange (%)
vol.	=	volume of pond (m^3)
0.85	=	conversion coefficient
Conc	=	Concentration of discharged parameter (g/m^3)

Organic Matter

The term 'detritus;' is used to include all non-living organic material and associated decomposers. As such it includes particulate and dissolved material. Detritus is modeled as sediment and dissolved organic matter. It is assumed that its major source is from effect of daily feeding and is modified from Park and Clough (2009) and presented in equation 14.

$$\frac{dDetr}{dt} = Loading + DetrFm - D_{detr} - Q_{out} \qquad [14]$$

where:

dDetr/dt	=	change in concentration of given detritus with respect to time ($g/m^3 \cdot d$);
Loading	=	loading of given detritus from feed ($g/m^3 \cdot d$);
Q_{out}	=	removal due to water exchange (g/m^3)
DetrFM	=	detrital formation ($g/m^3 \cdot d$)
D_{detr}	=	loss due to microbial decomposition ($g/m^3 \cdot d$)

Plant (Algae)

Algae growth was modeled as a direct function of feed, which is the major source of nutrient in the pond. Hence, chlorophyll a was modified from Hargreaves (1997) and presented in equation 15.

$$CHLa = \left(\sum_{i=1}^{n}\left(0.127 + \left(0.734.7N_{inputfeed}\right)\right)\right) - Mort_{algae} - Q_{out} \qquad [15]$$

where:

CHLa	=	chlorophyll a concentration (g/m^3),
$N_{inputfeed}$	=	nitrogen input from feed (g/m^3)

Algal mortality can occur as a response to unfavorable environmental conditions. Phytoplankton under stress may suffer increased mortality. The rapid re-mineralization of nutrients in the water column may result in a succession of blooms (Harris, 1986). Sudden changes in the environment may cause the algal population to crash; stressful changes include nutrient depletion, unfavorable temperature, and damage by light (LeCren and Lowe-McConnell, 1980). These are represented by a mortality term by Park and Clough (2009) and modified as presented in equation 16.

$$Mort_{algae} = (KMort + ExcessT + Stress) \cdot CHLa \qquad [16]$$

where:

$Mort_{algae}$	=	death rate of organism ($g/m^3 \cdot d$),
KMort	=	intrinsic mortality rate ($g/g \cdot d$);
ExcessT	=	factor for high temperatures ($g/g \cdot d$),
Stress	=	factor for suboptimal light and nutrients ($g/g \cdot d$).

AQUASMAT provides a convenient and efficient way of modeling an aquacultural production pond or enclosure for either commercial production (increased productivity with minimal resources as a priority) or experimental research (concerned with pond dynamics and subsequent effects) and management. Table 1 below shows the summary of managed parameters by *AQUASMAT*.

Table 1 Summary of managed parameters

Parameter	Range	Colour code	Effect	Suggested decisions
Stocking density	>2000g/m^2	Orange red	At carrying capacity of greater than 2kg/m^2, fish growth reduces, poor feeding, waste in the pond increases, high FCR.	Reduce fish biomass, reduce feeding, increase water exchange
FCR	< 0.5	Orange	Fish weight gain is poor, cannibalism may result	Feed accurate percentage body weight
	>2.0	Red	Fish is over fed, at least 50% of feed is wasted, increased waste loads, increased cost of production	Reduce feed to maintenance ration, perform water exchange,
DO	1 – 3mg/L	Orange	Fish is stressed, feed intake is reduced, high FCR, fish is prone to diseases	Reduce feed to maintenance ration, aerate the pond, perform water exchange
	≤ 1mg/L	Red	Fish is hypoxic, prone to diseases, death may occur	Reduce fish biomass, stop feeding and aerate pond, perform water exchange
Temperature	> 25^0C	Orange	Fish feed intake is drastically reduced, growth is reduced, high FCR, high waste load.	Feed maintenance ration only
	> 35^0C	Orange-red	Reduced DO, poor fish growth, poor feed intake, , high FCR, high waste load	Feed maintenance ration only
pH	< 4	Red	Acid death point, all life in pond may die, high CO_2	Lime the pond and perform complete water exchange
	9 – 11	Orange	Fish is stressed and prone to diseases, slow growth, high FCR, high CO_2	Reduce feed intake, apply agricultural lime, aerate the pond.
	> 11	Red	Alkaline death point, all life in pond may die, TAN may increase	Complete water exchange
Unionized ammonia	0.007 – 2mg/L	Orange	Fish is prone to disease, fish feed intake is reduced, erratic swimming behaviour	Reduce feed intake, reduce fish biomass and increase water exchange
	> 2mg/L	Red	Lethal concentration, death may occur	Feed maintenance ration, reduce fish biomass and increase water exchange
CO_2	> 20mg/L with DO less than 1mg/L	Orange-red	Fish is stressed	Set aeration/degas
Nitrate (NO_3)	>3mg/L	Orange	Fish is prone to disease, fish feed intake is reduced, erratic swimming behaviour	Reduce feed intake, reduce fish biomass and increase water exchange

Applications of AQUASMAT

AQUASMAT was applied to production of African catfish (*Clarias gariepinus*) in Agricultural Holding Fish Farm Nig. Ltd., located at Nsukka Enugu State. The concrete tank with dimensions 10m×5m×1m (surface area = 50m^2) was stocked with 1500 juveniles, each weighing 20g and measuring 8cm in length. Site altitude was 405m, wind speed was 1.66 m/s, light intensity was held constant at 3.92Kwhr/m^2day. Feed was modeled as dynamic with minimum and maximum daily feed provided as 1000g and 15000g respectively. Percentage protein content of feed was 43%. Temperature was modeled as constant at 29^0C, pH was dynamic at 6.5, initial concentration of DO was provided as 5mg/L. Initial CO_2, TAN and NO_3 was 0.2 mg/L, 0.5 mg/L and 0.5mg/L respectively. *AQUASMAT* defaults were used for Algae biomass and detritus at 0.1 g/m^3. Aeration was selected and water exchange was carried out once in 90 days.

AQUASMAT addresses a wide variety of water quality issues and monitors parameters that are otherwise difficult to quantify with conventional measurement; it quantifies the processes relating the chemical and physical environment to the biological community. It tracks and quantifies the sources and sinks of major processes such as dissolved oxygen, ammonia, organic matter etc.

The relationship and interaction of dissolved oxygen and carbon-dioxide with fish weight as indicated in Figure 2 shows increase in carbon-dioxide as dissolved oxygen decreases (Mwegoha *et al*., 2010). Furthermore, oxygen consumption of catfish increases as a function of body weight (Figure 2) however, respiration per unit biomass is greatest for small fish (Hargreaves & Tomasso, 2004). Figure 3 shows the relationship between un-ionised ammonia (NH_3) and detritus (organic matter). Despite high rate of organic matter addition to catfish ponds (Figure 4), the accumulation of organic matter is low (Tucker, 1985) as shown in Figure 5, however the absence of dissolved oxygen to fully mineralize the organic matter cause temporarily accumulation which increases the level of un-ionised ammonia in the system (Hargreaves & Tucker, 2003).

The rate of accumulation of detritus dissolved in the water column and sediment in the pond bottom and metabolic waste generated by fish is shown in Figure 5. From the graph, the user can determine appropriate time to perform water exchange and the amount so as to keep waste minimal and increase production. Metabolic waste of fish also increases as fish size increases. Waste water from fish farms is discharged into the environment with little or no knowledge of the quantity released and its effect on the environment. *AQUASMAT* predicts the quantity of waste in the system prior to discharge.

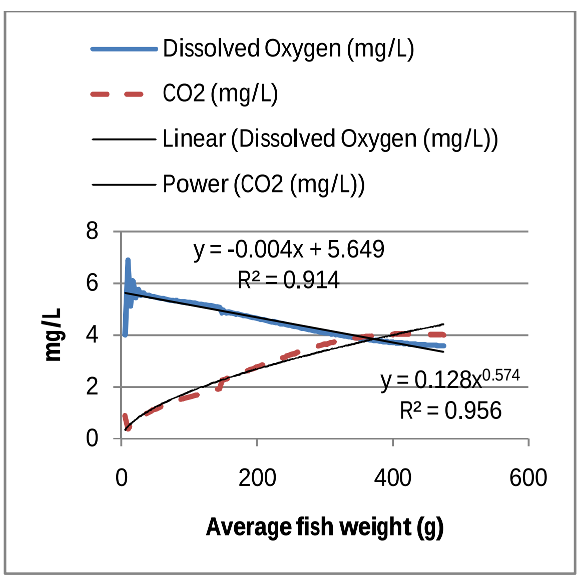

Figure 2: DO and CO_2 against weight of fish

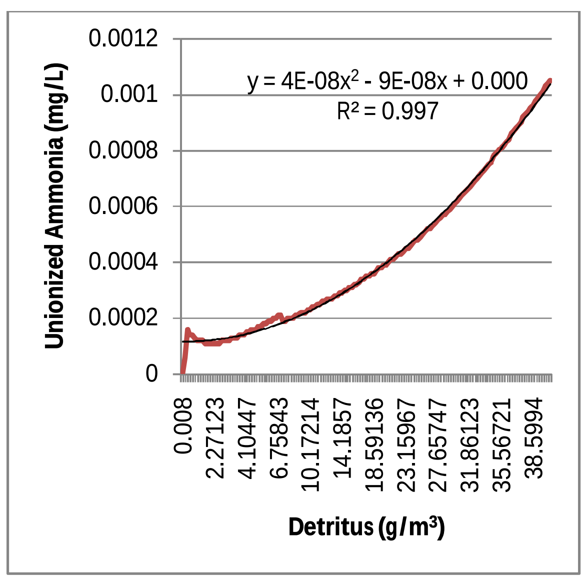

Figure 3: Relationship between unionized

ammonia and detritus

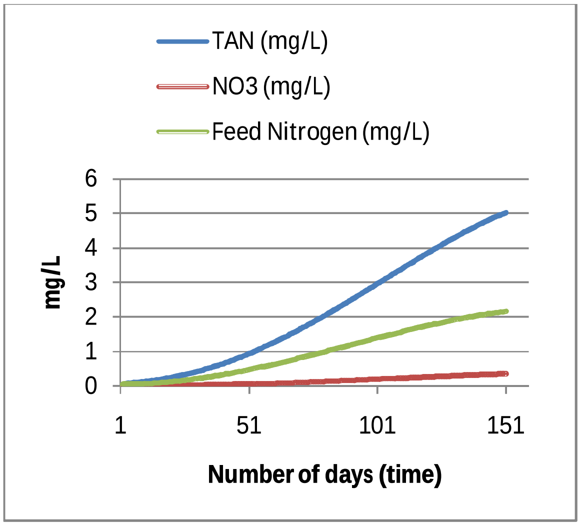

Figure 4: TAN, NO_3 and nitrogen input from feed in the system

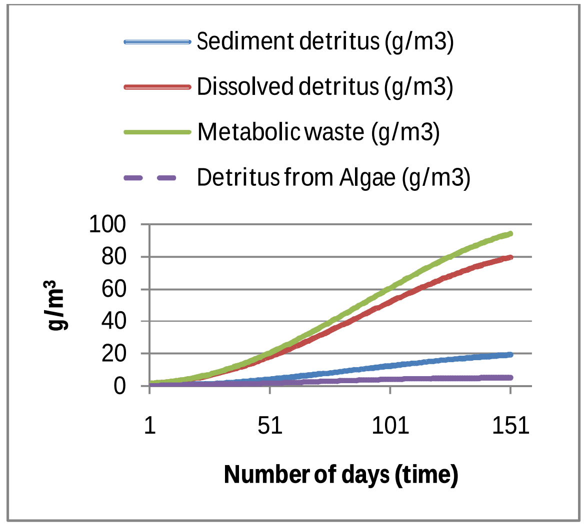

Figure 5: Organic matter accumulation

Conclusion

AQUASMAT, written in Visual C#, was developed based on the mass balance approach. The computer based model was applied to a commercial catfish production and a coherent set of quantifying relationships for fish growth, nitrogen input from feed, water quality processes and interactions was demonstrated with respect to African catfish production. *AQUASMAT* can help researchers in studying the pond ecosystem and experimenting different management operations scenarios without incurring large cost and time involved in carry out field operations. It can also benefit producers in evaluating production potential of a fishpond system, thereby overcoming the hidden costs associated with fish production in ponds.

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