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Model of a Pilot Constructed Treatment Wetland in Uganda

René Eschen

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IHE DELFT
Rijksuniversiteit Groningen

Supervisors: Dr Johan van de Koppel
Mr. Sonko Kiwanuka M.Sc.
Ab Grootjans

The conclusions in this report are based on a preliminary study into the functioning of Constructed Treatment Wetland. They require further investigation before they can be used in the management of these systems.

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Contents

Abstract

In this paper a model of a pilot constructed treatment wetland in Uganda is described. Fishes (Nile tilapias) are being cultured in order to recover the cost of the construction and maintenance. The purpose of the model is to assist in the management of constructed wetlands.

The pilot constructed wetland is modeled as two modules, the first describing wastewater treatment ponds and the second module describing the ponds for fish culture. The model has been validated with data from literature and an experiment. The predictions of the modules are analyzed under several conditions that can be influenced by the designer of treatment wetlands. The factors determined as major influences on the treatment efficiency and fish growth are the nutrient load applied to the constructed wetland, the availability of dissolved oxygen and photosynthesis.

The design of future CTW should be based on the amount of nutrients in the wastewater and the volume of wastewater that is available on a regular basis. For the design and maintenance of fish culture ponds the open surface area and measures to prevent excessive algal growth should be considered.

Preface

Everywhere in the world changes in the environment resulting from pollution and eutrophication by man can be seen. This is a serious threat to the wellbeing of man and nature. Treatment wetlands can remove a large part of the nutrients from wastewater, being an efficient solution to eutrophication of natural water bodies. It is widely recognized that the design and management can have much influence on the performance of constructed wetlands.

In this paper, I describe a model predicting the performance of wetlands to assist in the management. It is a simplification of a number biological and physical processes, many of which interact. In order to make the model, I needed knowledge about all processes in the system. Much of this knowledge can be found in literature, but an article often is not entirely on the demanded subject or it does not answer all questions. I therefore thank Dr J.S. Balirwa, Dr T.O. Okia, Dr F. Kansiime, Mr. Nicholas Azza M. Sc. and Mr. Kalibbala for their valuable contributions, which led to improved insight in the system I have tried to model.

This project was financially supported by Dr Ab Grootjans, Stichting Groninger Universiteitsfonds and the Marco Polofonds. I am very grateful to them for giving me the opportunity to do this research as part of my study.

Introduction

Wastewater collection and treatment has been practiced for many years in Europe. The development of sewage collection and treatment systems led to increases in health and life expectations. Because many communities in developing countries lack wastewater treatment, outbreaks of waterborne diseases such as diarrhea and cholera still occur. These diseases spread easily when untreated water is disposed of in water bodies, e.g. wetlands, that also function as a source of water for sanitation or food preparation. An other effect of lack of water treatment can be eutrophication of natural waters. This can cause anoxic conditions and loss of species that serve as source of food. There is a strong and increasing need for solutions. For developing countries, possible solutions have to be cheap (with respect to development as well as maintenance), easily applicable to small, decentralized communities and adapted to the local environment.

A possible system for wastewater treatment is a Constructed Treatment Wetland (CTW). Those can be engineered at virtually any scale and place. CTW incorporate many of the characteristics of natural wetlands; the main difference is their origin. Some of the properties can be replicated relatively simple, but others need time and maintenance (Kadlec and Knight, 1996). Although some treatment takes place in natural wetlands, CTW are a better solution for wastewater treatment than dumping of wastewater on natural water bodies. CTW are less subject to fluctuations in performance than natural wetlands and the high nutrient concentrations do damage to no organism other than those in the CTW itself.

Wastewater treatment by means of CTW has been researched since the 1950s (see Kadlec & Knight (1996) for an overview). CTW have been applied in a number of countries, but most of the applications were in temperate regions. Some examples of the tropical CTW come from Kenya (Nyakango, 1997) and some Asian countries (Koottatep and Polprasert, 1997). Until now, there are very few studies on application of CTW in tropical regions.

In Kirinya, Jinja municipality (Uganda), a pilot treatment wetland has been constructed in order to investigate the application of CTW in small communities in tropical regions. This is one of the first experiments where the functioning of this wastewater treatment method is being investigated in a tropical environment (Okurut, 2000). As far as I could retrieve, the experiment is the first where the use of indigenous plant species is being investigated in a tropical CTW. Before this CTW was built, the treatment performance of these plant species was investigated under laboratory conditions (Kansiime, 1993; Okurut, 1993; Kiwanuka, 1996; Sekiranda, 1996).

To make it more attractive for communities to invest in building and maintenance of a CTW, research is done on the possibility of culturing fishes in the treated wastewater (Kiwanuka, 1999; Matovu, 2001). The effluent water from a CTW can be re-used in order to limit eutrophication further by recycling of the nutrients and fish culture (Liang et al., 1999). Nutrient recycling occurs by means of conversion into biomass by primary producers. In aquatic environments, these are phytoplankton, which can be converted into fish biomass by predation. Fishes grown in this way are the cheapest source of animal protein (Matovu, 2001). They can therefore be a good addition to the people's regular diet. By selling the fishes on the market the cost of building the CTW can be recovered.

The aim of the present study is to analyze the Kirinya CTW system and to develop a model to assist in the management of the system. The resulting model can be used in the design of future CTW for small communities. The working of the CTW will be analyzed in order to determine the important variables and processes. In analogy with the Kirinya CTW the model will consist of modules. The model will be validated with existing data from literature and with data obtained from an experiment.

Methods

Description of the Kirinya CTW

The Kirinya CTW consists of a series of ponds (as described by Okurut, 2000) connected in series. The first part is meant for wastewater treatment. The second part is meant for fish culture and the last part removes any waste products originating from fish culture. In the first and third part macrophytes, either *Phragmites maritimus* or *Cyperus papyrus*, grow in laterite gravel. Key features of these macrophyte species are the dense virtual monocultures they form in their natural habitats and the high growth rates they achieve with the related high rate of nutrient uptake (Gaudet, 1977; Kansiime and Nalubega, 1999; Okurut, 2000). The laterite gravel is substratum for the macrophytes, and the gravel has some phosphorus-binding potential (Okurut, 2000). In this part of the CTW system an area is unplanted for re-aeration of the water. This has been shown to have a strong positive effect on treatment efficiency (Okurut, 2000). Many of the processes taking place in the treatment process consume oxygen and therefore the system performance relies heavily on the availability of dissolved oxygen (O).

The second part of the system is unplanted. Fishes are cultured in this part of the system. The cultured fishes are Nile tilapias (*Oreochromis niloticus* Linné). The choice for this species was made because of its high growth rate and economical value (Matovu, 2001). The fishes feed on the algae in the pond. The algal density is the most influencing variable in this pond: the algae consume nitrogen at a high rate and photosynthesis accounts for the high O and ammonia concentrations during daytime.

The first and third part of the CTW system are meant for wastewater treatment. They are referred to as Type I ponds in this paper. The second part is used for fish culture aiming at the highest production of fishes. This part is referred to as Type II ponds in this paper. The water is pumped from one pond into the next once per seven days.

Type I ponds

The module for type I ponds is meant to investigate treatment efficiency of these ponds. The module describes the dynamics of two state variables: O and total dissolved nitrogen (N) in the water. The removal of nitrogen is modeled here as measure for the treatment efficiency of the CTW. Nitrogen is influenced by uptake by the macrophytes and coupled (de-) nitrification. O is an important variable in the pond, influencing the rates of many biological and chemical degradation processes. O is influenced by reaeration, radial oxygen leaking (ROL), coupled (de-) nitrification, biochemical and chemical oxygen demand (BOD and COD). ROL is a mechanism in which the macrophytes transport oxygen to the rhizosphere. BOD is a measure of the oxygen consumption of microorganisms in the oxidation of organic matter, COD is the amount of a chemical oxidant required to oxidize the organic matter (Kadlec and Knight, 1996).

The period of exponential growth of the macrophytes is very short, after which the rooting and standing biomass tend to be stable (Gaudet, 1977; Okurut, 2000). Therefore macrophytes are assumed to be constant in this type. I assume that the nitrification rate and thus the nitrate concentration limits the rate of denitrification and that nitrification is followed immediately by denitrification of the nitrate produced in the pond (Kansiime and Nalubega, 1999; Okurut, 2000). Following that assumption I model the nitrification process only.

A simple representation of the dynamics of nitrogen and oxygen in the module for type I ponds is

$$\frac{dN}{dt} = -\text{uptake} - \text{nitrification}(N) \quad (g\ d^{-1}) \qquad (1)$$

$$\frac{dO}{dt} = \text{reaeration} + \text{ROL} - \text{nitrification}(O) - \text{BOD} - \text{COD} \quad (g\ d^{-1}) \qquad (2)$$

Where N represents total dissolved nitrogen in the water of the pond (g), O the dissolved oxygen (g), ROL stands for Radial Oxygen Leaking (g d^{-1}), BOD is the Biochemical Oxygen Demand (g d^{-1}) and COD the Chemical Oxygen Demand (g d^{-1}). The used parameter values are listed in appendix 1: Units and parameter values.

Total dissolved nitrogen

Uptake of nitrogen by macrophytes is a relation depending mainly on the nitrogen concentration and the standing biomass:

$$Uptake = M^* u_M^* S_p^* \frac{N}{k_N + N} \ (g\ d^{-1}) \tag{3}$$

Where M is the total biomass (g N m^{-2}), u_M is the uptake rate (g g^{-1} d^{-1}), S_p the surface area of the pond (m^2) and k_N the half saturation constant limiting the uptake at low concentrations of nitrogen (g).

Nitrification is governed by a rate constant and the nitrogen concentration. The process is double limited by the O and N levels. Because nitrification is an aerobic process, it will be limited by the O concentration below a critical concentration. The limitation below a N level is the result of the affinity of the nitrifying bacteria for ammonia. The nitrification kinetics are described by equation

$$Nitrification(N) = N^* c_N^* \frac{O}{K_O + O} * \frac{N}{K_N + N} \ (g\ d^{-1}) \tag{4}$$

Where c_N is a rate constant (g g^{-1} d^{-1}), O is the concentration O (g), K_O is the half-saturation constant for O concentration (g) and k_N the half saturation constant limiting nitrification at low concentrations of nitrogen (g) (Stenstrom and Paduska, 1980).

Dissolved oxygen

O in the water originates from the air. Without consumption, O develops towards the concentration at saturation. If O is below saturation, there will be an inflow over the air-water interface. In case of oversaturation the surplus of O will diffuse out of the water. The rate at which reaeration occurs depends on the diffusity of oxygen in water (Chapra, 1997). This relation is described by equation

$$Reaeration = c_D * S_p * (O_s - O) \ (g\ d^{-1}) \tag{5}$$

Where c_D is the diffusity of oxygen in the water (m d^{-1}) and O_s is the O level at saturation (g). ROL depends on a rate constant and the area covered with macrophytes. This is denoted as equation

$$\text{Radial oxygen leaking} = \frac{O_s - O}{O_s} * c_{ROL} * M * S_p \ (g\ d^{-1}) \qquad (6)$$

Where c_{ROL} is the rate constant ($g\ g^{-1}\ d^{-1}$). The changes in O caused by nitrification are described by equation (4), multiplied by the amount of O used per ammonium for nitrification:

$$\text{Nitrification(O)} = \text{Nitrification(N)} * r_{ON} \ (g\ d^{-1}) \qquad (7)$$

Where r_{ON} is the amount of O consumed per nitrified ammonium ($g\ g^{-1}$). The amount of O used in degradation of organic compounds (Biochemical and Chemical Oxygen Demand, BOD and COD) is described by exponential relations that depend on the initial oxygen demand, a first order constant and the time from the reloading of the pond:

$$BOD = k_{BOD} * BOD_i * e^{(k_{BOD} * t)} \ (g\ d^{-1}) \qquad (8)$$

$$COD = k_{COD} * COD_i * e^{(k_{COD} * t)} \ (g\ d^{-1}) \qquad (9)$$

Where COD_i and BOD_i are the initial oxygen demands (g) and K_{COD} and K_{BOD} are first order decomposition rate constants ($g\ g^{-1}\ d^{-1}$).

Type II ponds

The module of type II ponds describes the changes of fish density, algal density (both expressed as nitrogen), N and O. The algal density is influenced by growth(A) and predation by fishes. The fish density is determined by growth(F) and their basal metabolism. Nitrogen is influenced by growth(A) and nitrification. O is determined by reaeration, photosynthesis, COD, BOD, nitrification and respiration by fishes and algae.

A simple representation of the dynamics of type II ponds is given below:

$$\frac{dA}{dt} = \text{growth} - \text{basal metabolism} \ (g\ d^{-1}) \qquad (10)$$

$$\frac{dF}{dt} = \text{feeding} - \text{death} \ (g\ d^{-1}) \qquad (11)$$

$$\frac{dN}{dt} = \text{excretion} - \text{uptake} - \text{nitrification} \ (g\ d^{-1}) \qquad (12)$$

$$\frac{dO}{dt} = \text{reaeration} + \text{photosynthesis} - \text{nitrification} - COD - BOD - \text{respiration} \ (g\ d^{-1}) \qquad (13)$$

Where A is the algal density (g N), F the fish density (g N), N the total dissolved nitrogen (g) and O represents the dissolved oxygen (g). The used parameter values come from literature and an experiment. The values from literature are listed in appendix 1: Units and parameter values. The experiment is described after the description of the module.

Algal density

The net growth of the algal population is modeled as logistic growth. When net growth is negative, the nitrogen released by mineralisation flows back into the nitrogen pool. Growth depends on the algal density, the intrinsic growth rate as a function of the available nutrients and the carrying capacity, also as a function of the available nutrients. The functions for intrinsic growth rate and carrying capacity were deducted from the results of the algal growth experiment.

$$\text{Growth}(A) = r(N) * A * \left(1 - \frac{A}{K(N)}\right) \quad (g\ d^{-1}) \tag{14}$$

Where r(N) is the intrinsic growth rate (r(N)=0.0825118 + 1.30987*ln(N), $g\ g^{-1}\ d^{-1}$) and K(N) is the carrying capacity (K(N)=121.52 + 164.76*ln(N), g). Fishes can reduce the algal density by predation:

$$\text{Predation} = c_F * F * \frac{A}{A_{min} + A} * \frac{O}{O_{min} + O} * \frac{O_{max} - O}{O_{max}} \quad (g\ d^{-1}) \tag{15}$$

Where c_F is rate of feeding ($g\ g^{-1}\ d^{-1}$) and A_{min} is a constant limiting uptake at low algae concentrations (g N) and O_{min} and O_{max} are the half saturation constants for the limiting O values on the upper and lower side respectively (both g).

Fish density

The fish density increases by conversion of food into biomass. This is expressed as predation (15) multiplied by a conversion factor and one for oxygen stress:

$$\text{Growth}(F) = \text{Predation} * c_C \quad (g\ d^{-1}) \tag{16}$$

Where c_C the part of the algae taken up that is converted into biomass (g g^{-1}). Apart from death caused by oxygen stress, the fish density decreases as a result of the basal metabolism of the fishes:

$$\text{Basal metabolism} = d_F * F \ (\text{g d}^{-1}) \tag{17}$$

Where d_F is the rate of the basal metabolism (g g^{-1} d^{-1}).

Total dissolved nitrogen

The nitrogen concentration increases by excretion of the not converted food by fishes. The amount of excreted nitrogen depends on predation (15) and the part that is converted into biomass:

$$\text{Excretion} = \text{Predation}*(1-c_C) \ (\text{g d}^{-1}) \tag{18}$$

The nitrogen concentration decreases by the net growth of algae, governed by equation (14), and nitrification. Nitrification in ponds of type II is also governed by equation (4).

Dissolved oxygen

Reaeration, nitrification, COD and BOD take place in ponds of this type following the same kinetics as in ponds of type I. These processes are governed by equations (5), (7), (8) and (9) respectively. Photosynthesis seems to be the process with the largest influence on the O in this type of ponds during daytime. It is represented in the model by an equation which describes a linear relation between photosynthesis and the algal density

$$\text{Photosynthesis} = c_P * A * \text{Light} \ (\text{g d}^{-1}) \tag{19}$$

Where c_P is the rate of photosynthesis (g g^{-1} d^{-1}) and Light, an expression for the day-night cycle:

$$\text{Light} = 0.5 * (\sin(\Pi * d * 2) + 1) \tag{20}$$

Respiration is divided in a part for respiration by fishes and a part for respiration by algae (both linear):

$$\text{Respiration} = F * r_F + A * r_A \ (\text{g d}^{-1}) \tag{21}$$

Where rF and rA are the respiration rates of the fishes and algae (g g^{-1} d^{-1}).

Algae growth experiment

Algae from the Kirinya Pilot Treatment Wetland (100mls of water sample with algae from pond) were grown in duplo in 2 liters of "nutrient solution", consisting of wastewater (from anaerobic pond), diluted with distilled water (wastewater 0.5, 0.25, 0.125 and 0.0625 of total volume). The algae concentration was determined indirectly by colorimetric measurement of the Chlorophyll-*a* concentration (APHA, 1992) with $V_1=10$ and p=10. At the beginning of the experiment the Chlorophyll-*a* concentration in the wastewater and the water sample containing algae were determined ($V_1=0.2$) and during the experiment each day for one week. Before taking the sample, the water in the buckets was mixed and after taking the sample, the volume in the buckets was topped up with nutrient solution. The buckets were outside the central laboratory of the National Water and Sewerage Corporation in Kampala, Uganda. The experiment was done from 28-03 to 12-04-2001. The size of the samples has been changed during the course of the experiment due to the low initial concentrations and the high concentrations of algae later in the experiment that clogged the filters that were used to examine the samples. From the data the intrinsic growth rate of the algae and the carrying capacity were calculated for the different sewage dilutions. Regression analysis was done in order to find a relation between the sewage strength and intrinsic growth rate and the carrying capacity.

Parameterization

The parameters used for the analysis of the model are listed in appendix 1: Units and parameter values. References for values from literature are given where applicable. The values that lack a reference are the rate of photosynthesis, the respiration rates, the half saturation constant for predation, the conversion factor for conversion of fed algae into biomass and the basal metabolism of fishes.

The photosynthetic and respiration rates cause the daily fluctuations in O in the type II pond. Different values for those alter the amplitude of the fluctuations. The fluctuations are severe in the real system, causing oxygen stress during the night.

The half saturation constant for predation had to be introduced to prevent the predation equation (15) from becoming negative. A realistic function for predation would be linear (Batjakas, 1997), but such function becomes easily negative. A negative value would imply that the algae predate on the fishes, which is not realistic. When entering the model in the computer, the expressions for predation by fishes (15), growth(F) (16) and excretion (18) have been entered as a function that only gives an output if the net growth of the fishes is equal to or greater than 0. For negative growth of fishes the output is 0.

Fish (1952) and Moriarty (1973) investigated the digestion in tilapia species, showing that not all ingested food was digested. Moriarty (1973) found out that the effectiveness of the digesting enzymes is subject to a daily cycle in the feeding pattern. I used a constant value for the effectiveness of the digestion.

Results

Algae growth experiment

Up to day 4 there is a steady increase of the concentration at each of the sewage strengths. After the fourth day the concentration decreases for the highest sewage strengths. This is shown in figure 1. From these data the carrying capacities and intrinsic growth rates were deducted. For the carrying capacities the average of the last three algae concentrations for each sewage strength was taken. The average was assumed to be the carrying capacity for that sewage strength. The relation between sewage strength versus the carrying capacity is plotted I figure 2. The calculated relation between sewage strength (S, as g N m^{-3}) and carrying capacity (K) is K(N)= 121.52 + 164.76*ln(N). For the intrinsic growth rate the algal-density was plotted versus growth (g g^{-1} d^{-1}) for the different sewage strengths. Regression analysis was done on the plotted data and the intercepts of the regression lines were taken as intrinsic growth rates. These are plotted in figure 3. The calculated relation between S and the intrinsic growth rate (r) is r=0.0825118 + 1.30987*ln(N). This relation is plotted in figure 3.

Figure 1. Algae growth experiment: Algae concentrations in different sewage strengths.

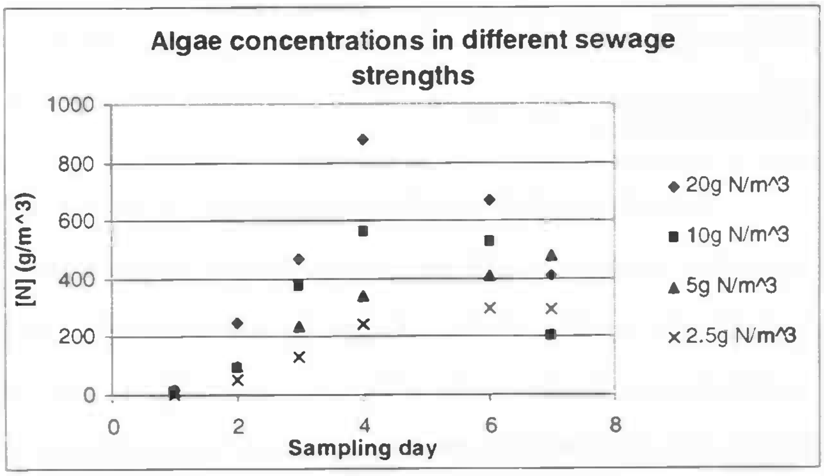


Figure 2. Algae growth experiment: carrying capacity (K) versus sewage strength (S).

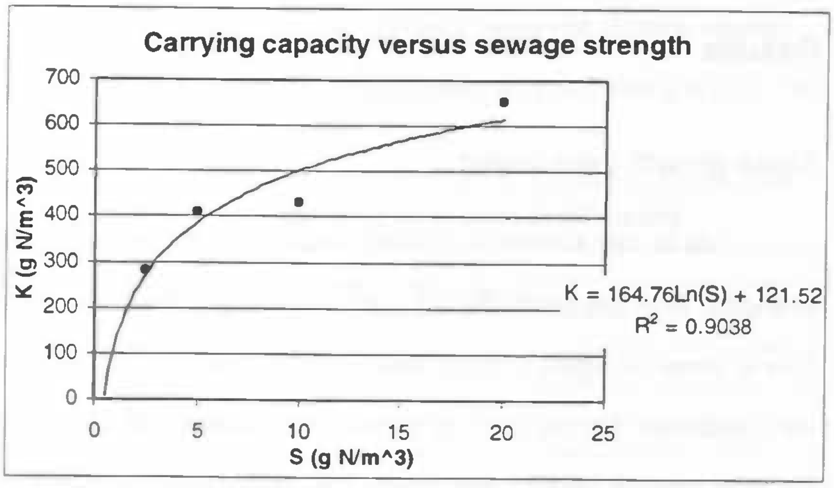
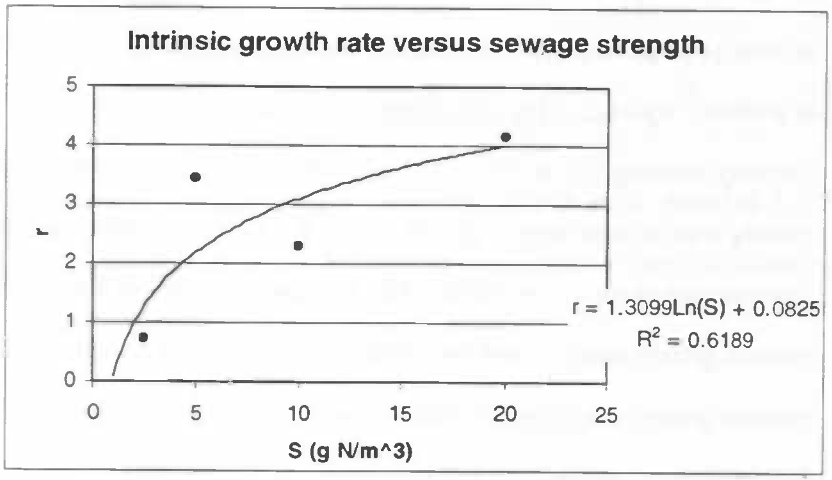


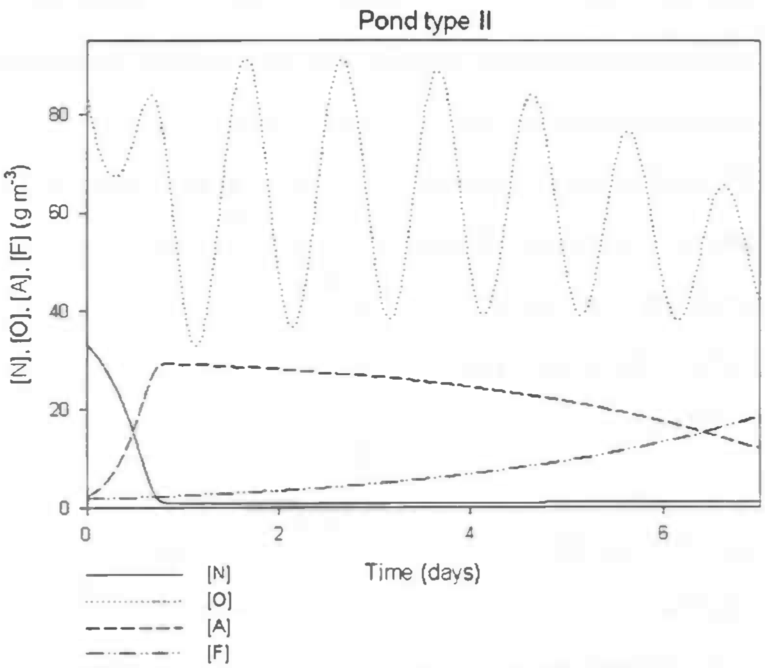
Figure 3. Algae growth experiment: Intrinsic growth rate (r) versus sewage strength (S).



Model analysis

Simulations with the model result in plots of the state of the variables during a seven-day period. A typical plot is shown in figure 4. From the figure can be told that with increasing algal density, the nitrogen concentration decreases. Algae photosynthesize during the day, causing a strong increase of O, which is consumed by respiration during the night. When the fish biomass increases, the predation increases also, resulting in a stronger decrease of the algal density and a slight increase of N. When the algal density decreases, the model predicts that the amplitude of the fluctuations of the O level becomes less large.

Figure 4. Typical output of the model: type II pond. N_0=40 g m^{-3}, A_0= 1.8 g, F_0=1.8 g, S_p:V_p=1.667, V_p=12 m^3, O_i=7.5 g m^{-3}.



The model has been analyzed by varying the values of those parameters that can be influenced when designing a new CTW (setup). For type I ponds these are N_0 (weekly nitrogen load), c_{ROL} (oxygen leaking rate of the macrophytes) and S_p (surface area, volume of water). c_{ROL} can not be influenced (it can, by the choosing different plant species), but because there is a large variety of values in literature, the choice of the used value can influence the output of the model. For type II ponds the analyzed parameters are nutrient load, A_0 (initial algal biomass), F_0 (initial fish biomass) and the relation between S_p (open surface area) and the volume of the pond (V_p).

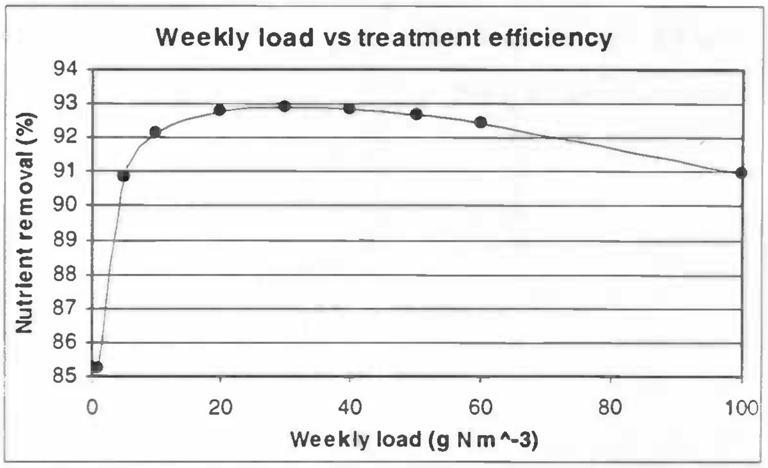
Type I ponds

The different parameter values of type I ponds were compared with the predicted treatment efficiency (% nitrogen removal) of the pond. The results are presented in figures 5 and 6.

Weekly load

The model predicts optimum performance (approx. 92.9% nitrogen removal) of the module at a weekly load of around 30 g N m^{-3}. The performance declines faster when lower load are applied than with increasing loads. The performance does not decline strongly in either situation though (range from 85.2 to 92.9% for loads between 1 and 100 g N m^{-3}). This is shown in figure 5.

Figure 5. Relation between weekly load (g N m^{-3}) and treatment efficiency (% nutrient removal). c_{ROL} = 0.4241 d^{-1}.

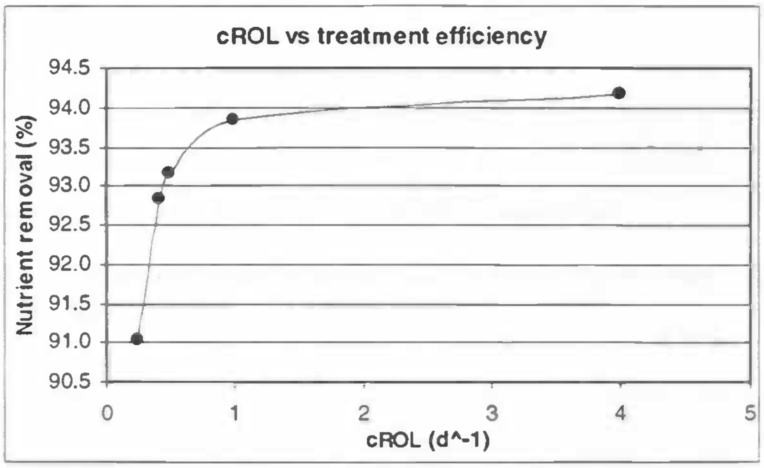


Uptake by plants removes about 0.05 g N m^{-2} each day. This is about equal to 1.5% weekly nitrogen removal. The main process in nitrogen removal is coupled (de-) nitrification, which removes the rest of the nitrogen.

Oxygen leaking rate

The performance of the system is predicted to be inhibited by low oxygen leaking rates. When c_{ROL} is increased the system performance approaches an optimum (approx. 94.5%). The effect of different values for c_{ROL} is presented in figure 6.

Figure 6. Relation between c_{ROL} (d^{-1}) and treatment efficiency (% nutrient removal). Nutrient load = 40 g N m^{-3}.



Surface area

The effect of applying different areas of wetland to treat the wastewater has no effect on treatment efficiency (not shown). The processes removing nutrients from the pond depend either on the nutrient load (g N m^{-3}), which is dependent of the surface area (volume) of the pond, or on the amount of O transported into the pond by radial oxygen leaking (g m^{-2}), which is linearly related to the area of the pond.

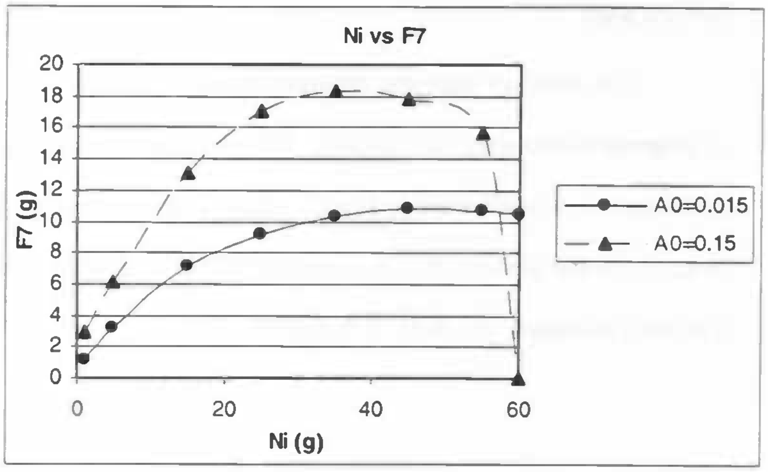
Type II ponds

The nutrients that are not removed in type I ponds can be converted into biomass in type II ponds. The primary producers in this module are algae which in turn are the food for the fishes. The nutrient load from type I ponds is called initial nutrient concentration (N_I, g).

Nutrient load

For situations with different initial algal densities (A_0) there is an optimal N_i value (with highest predicted fish biomass yield) with lower values below and above it. The fish biomass yield at different N_i is shown in figure 7 for two situations. In the optimal situation there are many algae to feed on and therefore the fish growth is best. At below-optimal values there are few algae and this causes reduced fish growth because the fishes eat the algae faster than the algae grow. In above-optimal values of N_i the growth of algae can not be kept in control by the fishes, which leads to high densities of algal that photosynthesize so much that the fishes suffer from oxygen stress, which reduces their growth (Matovu, 2001). The optima are different for the two A_0 values. The optimum for the higher A_0 density coincides with a higher algal density after seven days, because the initial algae population is larger, resulting in more growth of the algal population, more predation and thus more fish growth. The optimum occurs at lower N_i values because the algae grow faster at higher nitrogen concentrations. The algal density at which oxygen stress occurs is reached sooner.

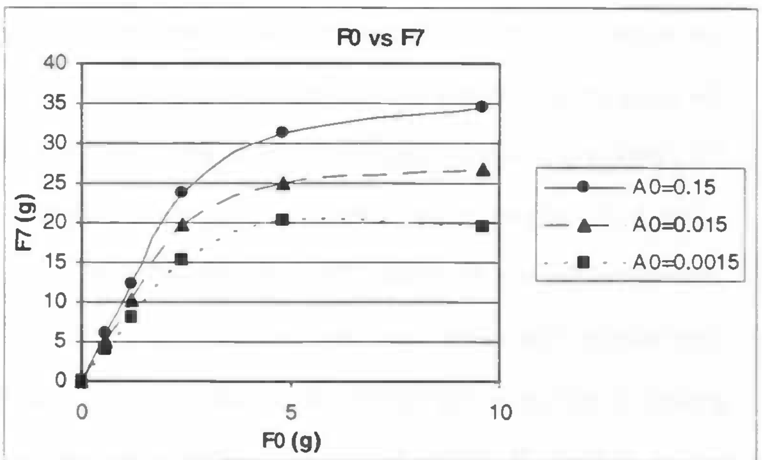
Figure 7. Relation between initial nutrient concentration (N_i, g) and the fish biomass after seven days (F_7, g) for two different initial algal densities (A0, g m-3). F_0=1.8 g, S_p:V_p=1.667, V_p=12 m^3, O_i=6 g m^{-3}.



Initial fish and algal biomass

The effect of the initial fish biomass (F_0) on the fish biomass on the seventh day (F_7) has been analyzed for three situations with different initial algal biomass (A_0). The result is plotted in figure 8. In all situations the increase in initial F_0 coincides with an increase of fish biomass for F_0 values up to 4.8. The increase of the fish density over the seven-day period is related to the increase of the food (algae). When the algae are extinct as a result of predation, the fishes starve. If A_0 is low, the algae get extinct at lower values of F_0, which can be concluded from figure 8 at F_0=9.6, where the fish growth for the situation with the value for A_0 is decreasing when compared to F_0=4.8. In the other situations the fish growth relative to smaller F_0 values is increasing still.

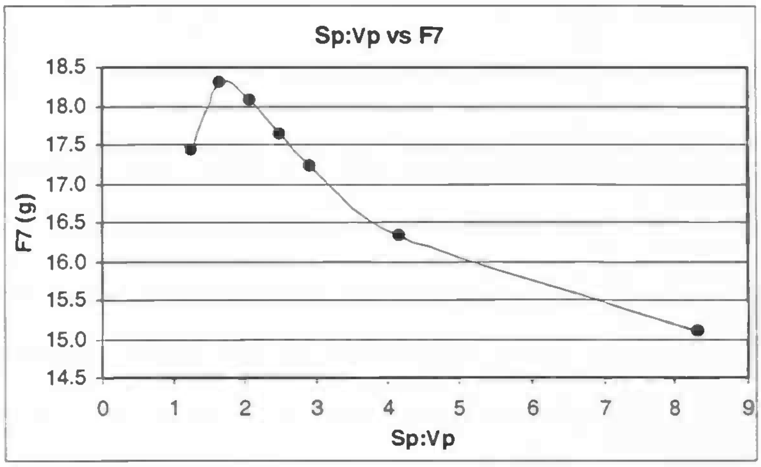
Figure 8. Initial fish biomass (F_0, g) versus fish biomass after 7 days (F_7, g) for three different initial algal biomass situations (A_0, g m^{-3}). N_0=40 g m^{-3}, S_p:V_p=1.667, V_p=12 m^3, O_i=6 g m^{-3}.



Pond area:volume ratio

The effect of different pond area:volume ratios (S_p:V_p) on the fish density after seven days has been investigated with the volume of the pond kept constant (V_p=12m^3). The surface area is important because the size of it determines the amount of oxygen that can be transferred between the water and the air. A small water surface area leads to arising of the O concentrations because the algal concentration and thus the oxygen produced by photosynthesis does not change very much. The high O levels inhibit the growth of the fishes. A large surface area also reduces the fish growth due to high levels of O. The cause for these high levels is also a combination of the rate of photosynthesis and the diffusion rate. The relation between pond area and volume is shown in figure 9.

Figure 9. Pond area:volume ratio (S_p:V_p) versus fish biomass after 7 days (F_7, g). A_0=0.15 g m^{-3}, F_0=1.8 g, V_p=12 m^3, N_0=40 g m^{-3}, O_i=6 g m^{-3}.



Discussion

The results of the model analysis are discussed below. First, the effect of the application of different nutrient loads on the type I pond is discussed, then the value for c_{ROL} and the performance of the type I pond as a whole is discussed. After that, the influence of nutrient load, initial fish and algal biomass and the open surface area on the performance of the type II pond is discussed.

Type I pond

From the analysis of module for type I ponds, it is clear that the weekly nitrogen load is the most determining factor for the treatment performance (% nutrient removal) of the system. For optimal nutrient removal the weekly nitrogen load must be around 20 g N m^{-3}. The main process determining nitrogen removal from the wastewater is clearly coupled (de-) nitrification. Uptake of nitrogen by macrophytes is of minor importance. The potential of nutrient uptake is limited by its net productivity (growth rate) (Gaudet, 1977; Vymazal et al., 1998). Because the exponential growth phases of *Cyperus papyrus* and *Phragmites mauritianus* are relatively short (Okurut, 2000), it is assumed that the macrophytes in the model are in the stationary growth phase, in which the uptake rates are generally low. The plants could be kept growing exponentially by periodically harvesting standing biomass to induce high nutrient uptake rates, but harvesting removes only a small part of the nitrogen from the system (Vymazal et al., 1998; Kansiime and Nalubega, 1999), making it a cost-inefficient method of wastewater treatment. Apart from that aspect, the re-growth capacity of the plants is reduced after several harvests (Okurut, pers. comm.).

The second determining factor is the oxygen leaking rate of the macrophytes. Although this is a property of the planted species, the accuracy of the measurement (or guess) can strongly influence the output of the module. The range of values found in literature has been tested on the model, but the limits were 0.26 and 4 d^{-1}. Beyond these limits the model would process unreliable output (jumpy behavior). The rate used in the model has been calculated from data presented by Brix (1990). He observed that almost all oxygen introduced by aeration was consumed in the rhizosphere, with very little oxygen entering the surrounding soil. The rate stated by Kansiime and Nalubega (0.017 d^{-1}, 1999) is too low, because at that rate the oxygen entering the soil is not sufficient to remove the nutrients. Possibly they did not measure in the rhizosphere. From his results, Brix (1990) concluded that nitrification contributed for only 30% of total nitrogen removal. One reason he gives is that most of the wastewater flows over the substratum, not entering the rhizosphere. Bowmer (1987) also observed the presence of preferential flow paths in an experiment with dye tracers to investigate the rates of nutrient removal. This indicates that much of the wastewater did not flow through the aerated rhizosphere, limiting system performance. This may not be of major importance in the Kirinya Pilot Treatment Wetland however, because the macrophytes are planted in gravel (10-52 mm in diameter, Okurut, 2000) which possibly leaves enough space for the water to percolate through the rooting zone of the wetland.

The overall performance of the type I pond module is very good (over 90% nutrient removal). This can be attributed to the high O concentrations throughout the simulated time, because the nitrification process is hardly limited ever. This is not realistic however, as many researchers have found that O levels in both constructed and natural wetlands are generally too low for nitrification to take place at optimal rates (e.g. Brix, 1990, Kadlec and Knight, 1996; Kansiime and Nalubega, 1999). The origin for this deviation from reality lies possibly in the absence of organic matter and its degradation in the module. Addition of this process may lead to a higher oxygen consumption, because of the degradation process itself, which occurs by bacteria that have a higher affinity for oxygen than the nitrifiers (Kansiime and Nalubega, 1999). The oxygen consumption is also increased because the degradation process introduces nitrogen into the system. This nitrogen is subject to nitrification, for which oxygen is needed. As a result, low O concentrations could prevail, lowering the treatment efficiency of the pond and introducing the need for unplanted areas where less organic matter accumulates in the pond. In these areas the available O would be mainly available for nitrification and nitrogen removal would be more efficient. The effect of non-vegetated areas in constructed wetlands has been shown to improve the ammonium removal from wastewater, increasing nitrogen removal from 25 to over 90% (Okurut, 2000).

Type II pond

The nutrient concentration in the water is the most determining factor for the performance of type II ponds. Low concentrations hold back the growth of the algae and make the population vulnerable to predation. High concentrations have a strong positive effect on the growth of the algae, but the high rate of photosynthesis that is related to the high algal density has a negative effect on the fish growth. The concentration can be altered by diluting the water from type I ponds (i.e. varying the volume ratio between type I pond and type II pond) and by applying different nutrient loads to the type I pond.

The initial fish biomass and initial algal density are very important for the maximum algal density that is achieved. The relative reduction of a large algae population is less than the reduction of a small population with the same fish biomass, leaving a more vital population. Higher fish densities initially reduce the algal population more, making the algal more vulnerable, which eventually results in the extinction of the algae in the pond. In nature, predation will not lead to total extinction of algae. The feeding efficiency of Nile tilapia, a filter feeding phytoplanktivore, has its lower limit around 60 cells per ml. At higher densities, the loss of cells due to predation is linearly related to the algal density (Batjakas et al., 1997). Batjakas et al. mention that a maximum density exists after which a sharp decrease of predation occurs, but they do not mention a concentration nor a reason for this decline.

The relation between open surface area of the pond and total volume has been analyzed because designing a deeper pond can be beneficial for saving on the land area used by the CTW and it can level out very low or high O concentrations because of the increased area open for oxygen diffusion. The outcome of the analysis was that an increase of the ratio surface area versus volume of the pond reduces the fish biomass yield over a seven-day period. This seems to be an artifact caused by the fact that growth of fishes is limited by high O concentrations in this model. The growth inhibition occurs at too low O levels. The expected outcome was that fish biomass increase over a seven-day period is reduced below some ratio only.

Matovu (2001) stated that the stress the fishes suffer is not related to high oxygen concentrations in the first place, but rather to accumulation of ammonia formed in the photosynthesis process. Ammonia is very toxic even at low concentrations. The low rate of ammonia removal results in high concentrations at the end of the day. Although ammonia production is not modeled separately in this model, it comes to expression by the fact that growth of the fishes is limited at oxygen concentrations lower than those in real systems.

The carrying capacity for algae and the intrinsic growth rate of algae increases with the availability of nitrogen (sewage strength). The relation between nitrogen availability and intrinsic growth rate is not shown to be significant here. The results are possibly different from expected due to predation by zooplankton during the experiment. The presence of zooplankton was confirmed by microscopic observation of a water sample. Both relations can give negative outputs for low nutrient concentrations. This is a consequence of the exponential relations found. The relations as calculated from the data obtained from the experiment are used here however, because it can be assumed that relations exist and there are no better estimates available. More research has to be done to obtain better relations to use in the model.

Although the model is not perfect, terms for the major processes influencing nutrient removal in type I ponds and fish growth in type II ponds are present. In order to obtain more accurate predictions from the module for type I ponds, the mineralisation of organic matter has to be incorporated. To obtain more reliable predictions from the second module, a longer period should be simulated, because in a CTW the fishes grow to marketable size in about three months. Besides a longer simulation period, more realistic terms for predation and growth(F) would result in more reliable predictions. Addition of the accumulation of ammonia could possibly increase the reality of the predictions, especially with respect to the growth of the fishes.

Conclusions

The present model is not a perfect representation of the pilot constructed wetland. The output of the simulations should be interpreted with caution. The main factor determining the performance of the preliminary model described in this paper is the weekly nutrient load. Although the differences in the predicted removal efficiency following application of different nutrient loads are small, the predicted output concentration determines fish biomass increase in the type II pond module in high degree. The removal of nutrients from type I ponds is also predicted to be strongly influenced by the availability of O. The O consumption in the present model is not enough to give predictions that coincide with the situation in the modeled system.

The main problem in the type II ponds is the stress caused by high algal densities. The possibility of keeping the predation pressure relatively constant by culturing fishes of different sizes in one pond should be investigated. By constant predation the algae could be kept in control, instead of explosively growing of the algae when harvesting fishes. Another option to get a grip on the excessive photosynthesis may be to introduce shadow. Either by covering (part of) the pond with plastic sheets, or by controlled growth of duckweed. Duckweed cover prevents light penetration into the water, reducing photosynthesis and algal growth. The reduction of algal growth for food can be compensated by the fact that Nile tilapias can feed on duckweed (Rackhay, 2001). Some water areas could be kept free of duckweed by introducing floating frames in the pond. Plants growing inside these frames can easily be removed (Kalibbala, pers. comm.), giving way to free diffusion of gases.

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Appendix 1: Units and parameter values

	Description	Unit	Range	Used	Reference
S_p	Surface area of pond	m^2			
Dp	Depth of pond	m			
N	Total Kjeldahl Nitrogen	g			
N_0	Total Kjeldahl Nitrogen in influent water Pond type I	$g\ m^{-3}$		40	Lhizibowa (1995)
N_i	Total Kjeldahl Nitrogen in influent water Pond type II	$g\ m^{-3}$			
c_N	Nitrification rate	$g\ g^{-1}\ d^{-1}$		0.48	Stenstrom and Poduska (1980)
k_N	Half saturation constant nitrification	g		1	Stenstrom and Poduska (1980)
k_O	Half saturation constant nitrification	g		0.5	Stenstrom and Poduska (1980)
O	Dissolved oxygen	g			
O_0	O in influent water Pond type I	$g\ m^{-3}$	0-16	2	Matovu (2001)
O_s	O at saturation	g		8	Chapra (1997)
c_D	Oxygen diffusion constant	$m\ d^{-1}$		2.7	Chapra (1997)
c_{ROL}	Oxygen leaking rate	d^{-1}	0.017-12	0.4241	Brix (1990), Kansiime and Nalubega (1999), Okurut (2000)
r_{ON}	Oxygen required for nitrification	$g\ g^{-1}$		4.2	Okurut (2000)
c_P	Photosynthesis rate	$g\ g^{-1}\ d^{-1}$		15	
r_A	Respiration rate algae	$g\ g^{-1}\ d^{-1}$		10	
R_F	Respiration rate fishes	$g\ g^{-1}\ d^{-1}$		10	
COD_0	Initial Chemical Oxygen Demand	g O	2.2-186	186.0	Matovu (2001)
BOD_0	Initial Biological Oxygen Demand	g O	16.0-750	130	Matovu (2001), Lhizibowa (1995)
k_{COD}	1st order rate constant COD	$g\ g^{-1}\ d^{-1}$		0.634	Matovu (2001)
k_{BOD}	1st order rate constant BOD	$g\ g^{-1}\ d^{-1}$		0.291	Matovu (2001)
M	Total biomass	$g\ N\ m^{-2}$		94.7	Okurut (2000)
u_M	Uptake rate	$g\ N\ g^{-1}\ d^{-1}$		0.00028	Okurut (2000)
A	Algal density	g N			
A_0	Initial algal density	$g\ m^{-3}$		0.15	
r(N)	Intrinsic growth rate algae	$g\ g^{-1}\ d^{-1}$		0.083+1.31*ln(N),	This paper
K(N)	Carrying capacity algae	g		121.52 +164.76*ln(N)	This paper
A_{min}	Half saturation constant predation	g N		0.15	
F	Fish density	g N			
F_0	Initial fish density	$g\ m^{-3}$		0.15	
c_F	Growth rate fishes	$g\ g^{-1}\ d^{-1}$		1.24	Matovu (2001)
O_{min}	Half saturation constant fish growth	g O		3	Matovu (2001)
O_{max}	Half saturation constant fish growth	g O		O_s*2	Matovu (2001)
c_C	Conversion fed algae into biomass	$g\ g^{-1}$		0.75	
d_F	Basal metabolism fishes	$g\ g^{-1}\ d^{-1}$		0.02	