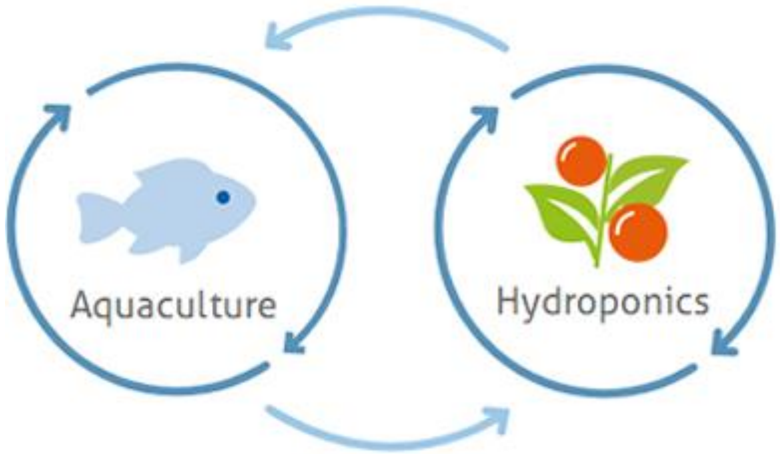
Biobased Chemistry and Technology

BSc Thesis Biotechnology or Biosystems Engineering

Modelling excretion of Nile tilapia (Oreochromis niloticus) in a recirculating aquaculture system; dynamic system approach



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Innovative Aquaponics for Professional Application

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Abstract

This study is related to aquaponics, which is a technique that combines aquaculture with hydroponics. In this study, aquaponics is based on a commercial scale recirculating aquaculture system (RAS) for Nile Tilapia (Oreochromis niloticus) and hydroponics is based on a nutrient film technique (NFT) production system. The focus of this study was to determine the appropriate strategy for recycling water to the hydroponic system. The appropriate strategy is based on minimizing total suspended solids (TSS) and to maximize total ammonia nitrogen (TAN), resulting in the objective to minimize TSS:TAN ratios when recycling water to the NFT system.

A model describing TAN and TSS concentrations within different compartments of the RAS has been made. The model consists of five modules that have been calibrated against literature data. The model investigates the influence of hourly excretion on TAN and TSS concentrations by tilapia within different compartments of the RAS. The effect of different design parameters on TAN and TSS concentrations for multiple feeding strategies, based on feeding frequency and fish tank systems fed at complementary times has been evaluated. Subsequently, recommendations have been made for an appropriate strategy for recycling water to the hydroponic system.

The results of the simulations show that the TSS:TAN ratios changed significantly over time for each feeding strategy. Furthermore, it could be concluded that fish tank systems fed at complementary times had a negative effect on TSS:TAN ratios. Also, feeding more frequently had an adverse effect on the TSS:TAN ratio. However, this negative effect could be decreased significantly by decreasing the RAS flowrate. Additionally, increasing the backwash flowrate and decreasing the RAS flowrate (with the accompanying system volumes to maintain hydraulic retention time (HRT)) improves the TSS:TAN ratio in the backwash significantly. However, to reach the TSS:TAN ratios presented in this research an extra settling tank should be implemented. Moreover, recycling water from the permeate instead of the backwash to the hydroponic system has been concluded to be a better strategy. Lastly, it is advised to temporarily decrease the RAS flowrate to increase TAN concentrations drastically when recycling water to the hydroponic system.

It is advised to hourly monitor excretion rates and not to work with fish tank systems fed at complementary times. Furthermore, it is advised to maximize the backwash flowrate and minimize the RAS flowrate as the appropriate strategy to recycle water from the backwash to the NFT production system. Lastly, it is advised to perform more research on the possibilities 1)to recycle the permeate instead of the backwash to the NFT production system and 2)to temporarily decrease the RAS flowrate in order to decrease TSS:TAN ratios when recycling water from the permeate or backwash.

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1 Introduction

Aquaponics is a technique that combines production of aquatic species (aquaculture) with soilless plants (hydroponic). Nowadays, aquaponics is mainly implemented on small scale systems. the objective of the European Union project INAPRO is the development of aquaponics towards commercial scale. INAPRO stands for "*Innovative Aquaponics for Professional Application*". INAPRO aims for improving current approaches to rural and urban aquaponics through the development of a model and the integration of innovative technologies to save water, energy and nutrients [1]. Models will be made by INAPRO to predict outcomes of aquaponic systems, while data will be gathered from experimental work to validate these outcomes. If successful, these models can then be used to simulate aquaponic systems on commercial scale, making aquaponics commercially more attractive.

For optimal use of nutrients and water in aquaculture systems combined with hydroponic systems, RAS are often used. A RAS is a system in which fish are cultured and waste water is recycled. In order to recycle water, waste products such as TAN and TSS should be filtered. This must be done to prevent accumulation of waste products, leading to toxic concentrations [2]. In most RAS, a trickling filter (biological filter) is used for the removal of TAN and a drum filter (mechanical filter) combined with a settling tank (mechanical filter) is used for the removal of TSS. By using mechanical and biological filters TSS can be retained and TAN can be converted to less toxic nitrite (NO_3) [3-5]. To prevent toxic NO_3 concentrations, water has to be discarded occasionally and fresh water has to be replenished to the RAS. This system will contribute to optimal usage of nutrients and water in RAS. In an aquaponic system, the water discarded from the RAS can be recycled by the hydroponic system. For the appropriate recycling conditions for the hydroponic system, TSS should be minimized to prevent damage to the roots of soilless plants and TAN should be maximized to promote plant growth [6].

Nowadays, few models describe the system level behaviour of a RAS for Nile tilapia (Oreochromis niloticus) on commercial scale. The models that do describe system level behaviour in aquaculture mostly do not incorporate hourly excretion of wastes by tilapia [7, 8], while literature showed that postprandial excretion fluctuate significantly [9]. Furthermore, the models that do describe system level behaviour do not incorporate multiple feedings per day or multiple fish tank systems fed at complementary time [8, 10, 11]. However, literature indicated that multiple feedings per day for tilapia is highly recommended due to higher yields [12]. For fish tank systems fed in complementary time no models have been found, although it is applied in certain systems [13]. Also, most models focus on module dynamics rather than system dynamics [3, 4, 14]. Finally, to our knowledge no research describes the effects of design parameters, such as flowrates through and volumes of the mechanical- and biological filters and the fish tank system, on the system dynamics of a RAS.

The objective of this study was to reflect and better understand factors influencing TAN and TSS concentrations within different compartments of a commercial scale RAS. Simulating hourly postprandial excretion resulted in a more realistic model on TAN and TSS concentrations. Incorporating the effect of different feed strategies, based on feeding frequency and using fish tank systems fed at complementary times, resulted in better understanding of their influence on TAN and TSS concentrations. Testing the effect of design parameters gave better insight on their influence on TAN and TSS concentrations. The final goal was to find the appropriate strategy for recycling water from the RAS to the hydroponic system.

For this purpose, the following research questions have been set up:

1. How does the waste excretion of tilapia influence waste concentrations within the RAS
2. How do different feeding strategies influence waste concentrations within the RAS
3. How do design parameters influence waste concentrations within the RAS
4. What is the appropriate strategy for recycling water to plants (hydroponic system)

A model in Python was built to simulate the effect of hourly waste excretion by tilapia on TAN, TSS and NO_3 concentrations [15]. Multiple feeding strategies and design parameters of the RAS were simulated. The feeding strategies were based on different feeding frequencies for a single fish tank system and for 2 fish tanks systems fed in complementary time. For the design parameters the flowrates of the RAS and the backwash were tested, with the accompanying drum filter volume and settling tank volume. The effect of hourly excretion on TSS and TAN concentrations were evaluated for different feeding strategies. Also, the effect of the design parameters on TSS and TAN concentrations in relation to different feeding strategies was evaluated. Finally, the results were used to determine the appropriate strategy for recycling water from the RAS to the hydroponic system.

In chapter 2 the model description of the RAS is given, based on 5 modules. Each module is described on its own based on a set of equations. In chapter 3, the modules of each compartment are calibrated against literature data and the results are presented and discussed. Subsequently, the modules are linked to simulate system level dynamics. In chapter 4, the effect of hourly excretion, different feeding strategies and design parameters on TSS and TAN concentrations are evaluated. Also, an attempt has been made to improve the appropriate strategy for recycling water to the hydroponic system. In chapter 5, the conclusions and recommendations are presented.

2 Model description

Self-functioning modules were modelled to represent different compartments within the RAS (Figure 1). In this chapter, each module described separately based on background information obtained from literature. Each module consists of functions described by a set of variables, design parameters and parameters. The value of these (design) parameters were based on values from literature. The model of each module was tested independently against data obtained from literature and calibrated accordingly. The modules were subsequently connected to study the system-level behaviour. Each self-functioning module works independently and generates outputs. These outputs are required for the inputs of the next modules, thereby interconnecting the modules to an overall model. The main advantage of modular construction is that each module is interchangeable

Figure 1 shows the 5 compartments that were modelled in this study, 1) the fish, 2) the fish tank system, 3) the drum filter, 4) the settling tank and 5) the trickling filter. The system has two loops that are linked by the drum filter. The objective was to make an overall model describing the RAS system to find the appropriate water recycling strategy to the hydroponic system. This was found by testing the effect of design parameters and different feeding strategies on TAN, NO_3 and TSS concentrations

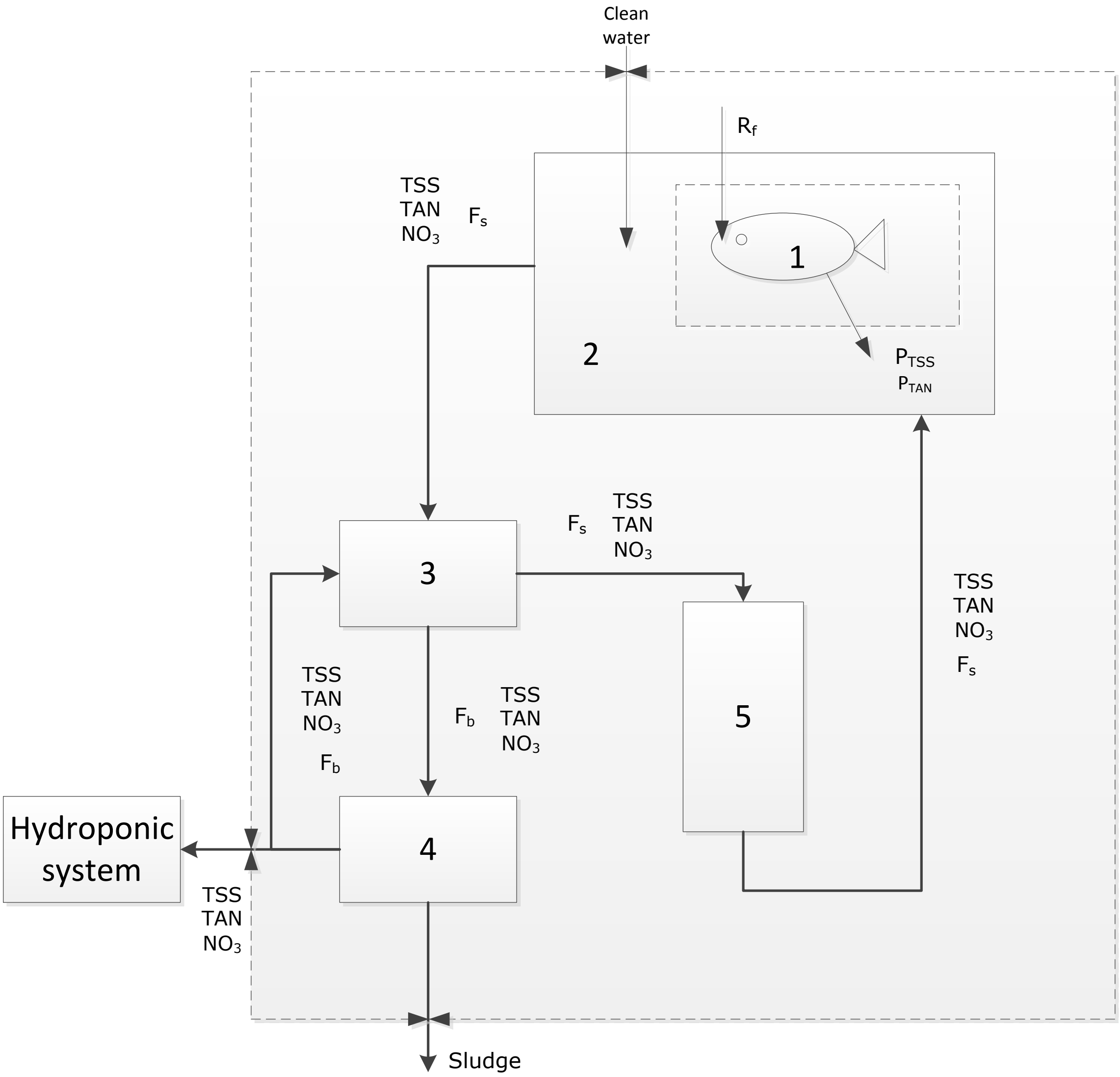

Figure 1 The overall model of all the linked compartments (fish, fish tank system, drum filter, settling tank and trickling filter), their variables (TSS, TAN and NO_3) and the design parameters backwash and RAS flowrate.

1) The fish were modelled based on their hourly postprandial excretion rate, which determine the amount of TSS and TAN that end up in the 2) fish tank system. The fish tank system was modelled as a continuous stirred tank reactor (CSTR) in which the wastes excreted by the fish are ideally mixed to be sent to the mechanical and biological filters. 3) The drum filter separates most of the solids from the waste stream of the fish tank. The retentate of the drum filter contains most of the solids and flows to 4) the settling tank. The settling tank removes solids from the retentate by gravity. These solids are retained in the basin of the settling tank and discarded periodically. The water flow from the settling tank to the drum filter forms the backwash, which prevents the drum filter from clogging. Few solids from the drum filter stay dissolved in the permeate that flows to the 5) trickling filter. The trickling filter oxidizes TAN to NO_3. The water coming out of the trickling filter recirculates back to the fish tank. NO_3 accumulates within the system since it is not removed; therefore water has to be recycled occasionally from the settling tank to the hydroponic system while new water has to be replenished to the fish tank.. The waste water can then be used in the hydroponic system to grow plants..

2.1 Fish

The concentrations in the system and temperature of the system are dependent on the fish that are grown (Table 1). In this model tilapia is used. The accumulation of these products in the fish tank are dependent on the amount of waste excreted by the fish and the flow rate through the fish tank.

Table 1 Water quality parameters for tilapia [2]

Parameter	Tilapia
Temperature (°C)	24-30
Oxygen (mg L^{-1})	4-6
CO_2 (mg L^{-1})	30-50
SS (mg L^{-1})	<20
TAN (mg L^{-1})	<3
NH_3-N (mg L^{-1})	<0.06
Nitrite-N (mg L^{-1})	<1
Chloride (mg L^{-1})	>200

The amount of TAN and TSS excreted by the fish is dependent on amount of feed added to the fish, contents of the feed, time interval between feedings and rate of gastric emptying. Previous research shows a linear correlation between the amount of feed added to the fish tank and the amount of TAN and TSS excreted by the fish [16-18]. To the best of our knowledge no research suggest that tilapia excrete NO_3. It is therefore assumed not to be excreted by the fish. Research has also shown a linear correlation between the protein content in the feed and TAN that has been excreted [19]. The feeding frequency does not have a direct influence on the total amount of TAN excreted [20]. However, lower feeding frequencies does result in greater amounts of feed added per feed to the fish tank. This could in turn results in stronger fluctuations in the waste water concentrations [9, 21].

Not the feeding frequency but the feeding interval determines the gastric evacuation rate which in turn is related to the return of appetite of the fish. When the feeding frequency is high the feeding interval becomes too short, resulting in incomplete hydrolysis of feed in the digestive system, which causes gastric evacuation of poorly digested feed [9]. When the feeding frequency is low, the yield of fish decreases [20, 22]. The proper feeding frequency is concluded to be 3 times per day with a minimum feeding interval of 4 hours. The 4 hour interval is needed for optimal weight gain of tilapia in relation to sufficient usage of feed and return of appetite [20, 23].

For higher yields of fish also a proper photoperiod cycle is applied. Unfortunately, the energy usage by fish is not only linked to growth but also maintenance. Applying short photoperiods can result in energy loss by the fish. Also the oxygen consumption rate by the fish increases. Long photoperiod cycles result in lower energy loss and less oxygen consumption [24]. Energy loss is lowest for tilapia when grown under 24L:24D (hours of light followed by hours of dark cycle) cycles (45.4 kJ kg^{-1} d^{-1}) and highest when grown under 3L:3D cycles (56.2 kJ kg^{-1} d^{-1}). To maximize the biomass yield the photoperiod with the highest growth rate of fish is applied. Several studies support different feeding frequencies with different photoperiods [23, 25, 26]. In this model long photoperiod cycles are applied to minimize energy losses by the fish: 18L:6D, which is recommended by the majority of the studies. For the 2 fish tank system fed at complementary times, artificial light is assumed. Using artificial light is not uncommon and is already done in commercial systems [13].

One research tracked the postprandial digestion of feed by tilapia over time. This resulted in a excretion relation defined in percentages of feed over time for tilapia fed 3 times per day at 28 °C [9]. Based on this relation a simplified model has been made which reflects the excretion *vs* postprandial feeding hours of the fish. In this model it is assumed that the excretion of TAN reflects the same behaviour as the gastric evacuation of TSS.

Figure 2 shows the simplified model of the fish. This model reflects the flows of excretion in relation to feed fed to the fish. The excretion of nitrogenous compounds takes place in dissolved form via the gills or in particulates through faeces. The TAN excretion rate only accounts for the gills of the fish. The remaining 10 % of TAN is excreted as particulates in the faeces of the fish [2]. It is assumed that the ammonia in the particulates is retained by the drum filter and is not converted by bacteria in the RAS.

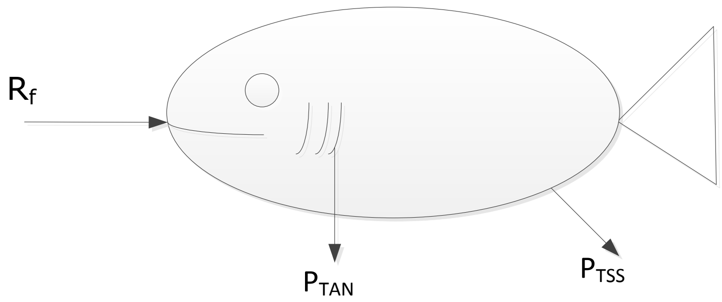

Figure 2: A simplified excretion model for the fish. Feed is being consumed, TAN is excreted through the gills and the TSS through gastric evacuation [27]

Equations:
The list of symbols and their definitions for different variables, parameters and estimated parameters are given in Appendix A. The value assigned to the parameters are obtained from literature.

The percentage of feed remaining in the fish (V_T) is calculated based on the volume of feed at time 0 ($V_0(t_0)$), the instantaneous evacuation rate (b) and the time elapsed after feeding (t), this is reflected by the equation 1. V_0 is constant and is related to the stomach volume of the fish, which in turn is related to the fish size. Shorter feeding interval than 4 hours result in an increase of V_0, but causes incomplete hydrolysis of feed. In the model it is assumed that V_0 remains constant. The instantaneous evacuation rate is set to be relatively constant, independent from feeding frequency. Suggesting that the evacuation rate is independent of feeding frequency or feeding interval [9].

The integral of equation 1 formed the basis for the excretion module. Data points from literature that represent V_T were gathered and curve-fitted to equation 2, where a(=95.7) and c(=0.318) are the estimated parameters and P_T the fraction (therefore, divided by 100) undigested feed at t. The fraction of postprandial wastes that have been excreted between to time points ($P_{T,T+1}$) is calculated by subtracting the P_T from two subsequent time points, this is reflected by equation 4, in which the next time point (τ) is defined as 1 hour later.

It is assumed that the excretion rate through the gills resembles the excretion rate via gastric evacuation. This assumption resulted in the excretion rates of TAN (P_{TAN}) and TSS (P_{TSS}) as a function of $P_{T,T+1}$, an approximation for TAN that is excreted 0.092 (X_{TAN}), an approximation for TSS that is excreted 0.25 (X_{TSS}), protein content of the feed 0.35 (PC), amount of feed given to the fish (R_f), as described in equation 4 and 5. The excretion of TAN by tilapia takes immediately place after feeding the fish [28]. This means, that there is no retention time to be modelled before gastric evacuation takes place.

$$\int_{V_0}^{V_T} dV/V = -\mathrm{b} * \int_{t_0}^{t} \mathrm{d}t \qquad (1)$$

$$P_T = (\mathrm{a} * e^{-\mathrm{c}*t})/100 \qquad (2)$$

$$P_{T,T+\tau} = (\mathrm{a} * e^{-\mathrm{c}*t} - \mathrm{a} * e^{-\mathrm{c}*t+\tau})/100 \qquad (3)$$

$$P_{TAN} = X_{TAN} * PC * R_f * P_{T,T+\tau} \qquad (4)$$

$$P_{TSS} = X_{TSS} * R_f * P_{T,T+\tau} \qquad (5)$$

2.2 Fish tank system

In RAS production, several tanks are used for different stages of fish growth. These tanks are modelled as multiple CSTRs in parallel, assuming constant feed in each tank. To manage the waste concentrations in the fish tank a proper flowrate should be assigned to the overall system. The fastest accumulating waste product determines the RAS flowrate. Although, sometimes additional design constraints can determine the minimal flowrate required for the system design, such as HRT for the fish tank or the biofilter [29, 30]. Since waste produced by fish is dependent on feeding time and gastric evacuation rate the waste streams can fluctuate significantly over time. This is due to the fact that most of the gastric evacuation takes place at the first post-prandial hours [9].

By assuming constant feed, it is assumed that the fish maintain constant size. The stage of development of the fish grown in a fish tank determines the fish density (Table 2) [31]. By increasing the amount of intermediate stages the fish density stay relatively the same. Therefore, the fish tank volume is also maintained the same. The following assumptions are made based on literature: the fish are fed daily 27.5 kg of feed, the total fish tank system volume is 50 m^3 [30] with an average HRT of 0.5 h [32].

Table 2 Stage of fish development in relation to density and required fish tank volume

	Fish density (kg m^{-3})	Tank volume (m^3)
Juvenile	30	6.4
Fingerling	40	11.3
Growout	50	17.5

Figure 3 represents the model of the fish tank. Where multiple fish tanks are operated in parallel, each with different fish sizes. Feed is added every fed to the fish in the proper amount in relation to fish size and amount of fish. Fresh water can be added to compensate for water recycled (to the hydroponic system).

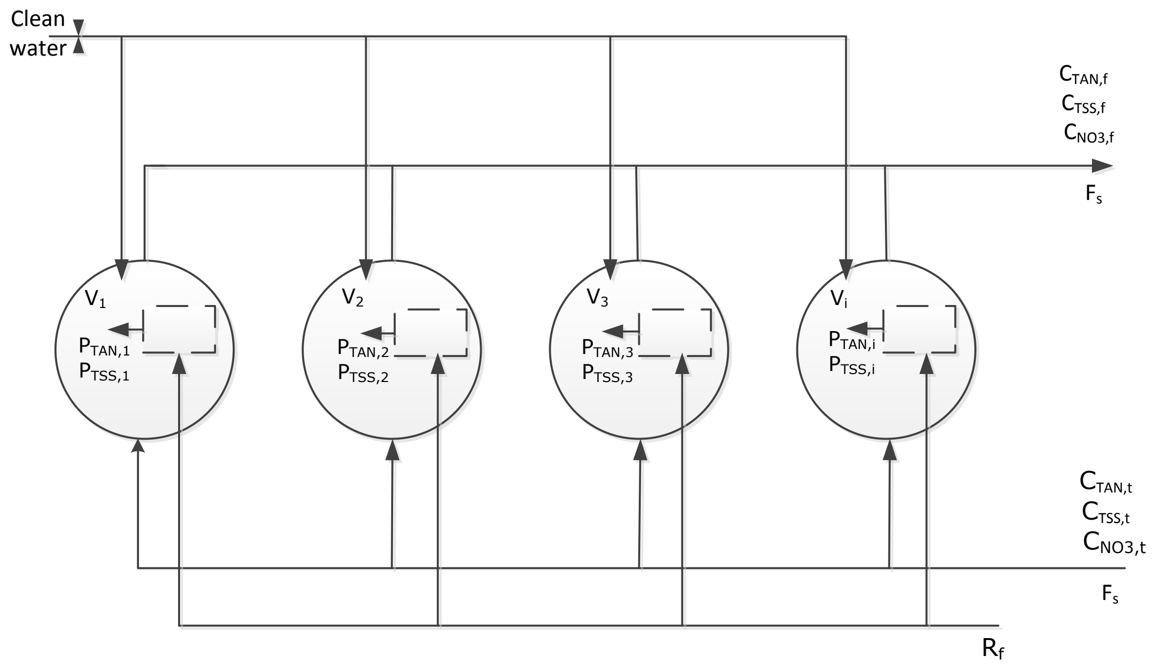

Figure 3: Fish tanks in parallel reflecting the fish tank system in detail of the overall model. Filtered water with low waste concentrations enters the fish tanks. The water inflow takes up the waste products produced by the fish after feeding. The outflow with higher waste concentrations is directed to the mechanical and biological filters. Now and then fresh water is added to prevent high NO_3 concentrations.

Equations:
The fish tank illustrated in Figure 3 is modelled as a single unit. This resulted in an overall volume for the fish tank system (V_f) and a constant HRT (HRT_f) for each fish tank, defined by equation 6 and 7. The volume is dependent on the amount of fish produced and therefore to the amount of feed added to the fish tanks. Prerequisite for minimal HRT_f was the determining factor for the minimal flowrate required for the RAS (F_s), as described by equation 8. From literature the values for V_f, HRT_f and R_f has been taken. The F_s was determined by V_f and the HRT_f, as described by equation 8. It is assumed that the waste

streams of all the fish tanks mix adequate. This resulted in the equations 9 and 10, describing the fish tank system as a single CSTR, in which F_s is assumed to be constant. P_{TAN} and P_{TSS} describe the amount of waste that is being produced by all the fish in all the fish tanks. The TSS and TAN therefore accumulate in the fish tank making the out flow concentration higher than the inflow. Substitution of equation 3 describing $P_{T,T+1}$ into equation 4 and 5 describing P_{TSS} and P_{TAN}, resulted in equations describing the TAN and TSS excreted between two time points after post-prandial time. These equations were substituted in equation 9 and 10, which resulted into equation 11 and 12. These equations were used for the module describing the fish tank system.

For the double fish tank system working with a complementary feeding schedule a new model was made. For convenience, only the TSS has been explained, since TAN has the same approach. The double fish tank model can be created by modelling two overall models of the fish tank system working with complementary feeding schedules. For working with complementary feeding schedules two models of the fraction of feed excreted between two time points after a certain post-prandial time has been used, described by equation 13 and 14. The subscripts in these equations resemble the fish tank system. The same CSTR model of a single fish tank system was used, resulting in equation 15 and 16. Due to the fact that the fish tank system has been split up in two new systems, the V_f and F_s has also been halved, resulting in $V_{f,d}$ and $F_{s,d}$. The same substitution to obtain the overall model as described for a single fish tank system has been applied, resulting in equation 17 and 18. Adding up the outflow concentrations of these fish tank systems ($C_{TSS,f,1}$, and $C_{TSS,f,2}$) described by equation 17 and 18 and dividing them by 2, resulted in the overall outflow concentration of the double fish tank system($C_{TSS,f,c}$), described by equation 19.

$$V_f = \sum_{i=1}^{n_f} V_{f,i} \tag{6}$$

$$HRT_f = HRT_{f,i} \tag{7}$$

$$F_s = \frac{V_f}{HRT_f} \tag{8}$$

$$\frac{dC_{TAN,f}}{dt} = (F_s * C_{TAN,t} - F_s * C_{TAN,f} + P_{TAN})/V_f \tag{9}$$

$$\frac{dC_{TSS,f}}{dt} = (F_s * C_{TSS,t} - F_s * C_{TSS,f} + P_{TSS})/V_f \tag{10}$$

$$\frac{dC_{TAN,f}}{dt} = ((F_s * C_{TAN,t} - F_s * C_{TAN,f} + X_{TAN} * PC * R_f * (\mathrm{a} * e^{-\mathrm{c}*t} - \mathrm{a} * e^{-\mathrm{c}*t+\tau})/100)/V_f \tag{11}$$

$$\frac{dC_{TSS,f}}{dt} = ((F_s * C_{TSS,t} - F_s * C_{TSS,f} + X_{TSS} * R_f * (\mathrm{a} * e^{-\mathrm{c}*t} - \mathrm{a} * e^{-\mathrm{c}*t+\tau})/100)/V_f \tag{12}$$

$$V_{T,T+\tau,1} = (\mathrm{a} * e^{-\mathrm{c}*t1} - \mathrm{a} * e^{-\mathrm{c}*t1+\tau})/100 \tag{13}$$

$$V_{T,T+\tau,2} = (\mathrm{a} * e^{-\mathrm{c}*t2} - \mathrm{a} * e^{-\mathrm{c}*t2+\tau})/100 \tag{14}$$

$$\frac{dC_{TSS,f,1}}{dt} = (F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,1} + P_{TSS,1})/V_{f,d} \tag{15}$$

$$\frac{dC_{TSS,f,2}}{dt} = (F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,2} + P_{TSS,2})/V_{f,d} \tag{16}$$

$$\frac{dC_{TSS,f,1}}{dt} = (F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,1} + X_{TSS} * R_f * (\mathrm{a} * e^{-\mathrm{c}*t1} - \mathrm{a} * e^{-\mathrm{c}*t1+\tau})/100)/V_{f,d} \tag{17}$$

$$\frac{dC_{TSS,f,2}}{dt} = (F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,2} + X_{TSS} * R_f * (\mathrm{a} * e^{-\mathrm{c}*t2} - \mathrm{a} * e^{-\mathrm{c}*t2+\tau})/100)/V_{f,d} \tag{18}$$

$$\frac{dC_{TSS,f,c}}{dt} = ((F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,1} + X_{TSS} * R_f * (\mathrm{a} * e^{-\mathrm{c}*t1} - \mathrm{a} * e^{-\mathrm{c}*t1+\tau})/100)/V_{f,d} + (F_{s,d} * C_{TSS,t} - F_{s,d} * C_{TSS,f,2} + X_{TSS} * R_f * (\mathrm{a} * e^{-\mathrm{c}*t2} - \mathrm{a} * e^{-\mathrm{c}*t2+\tau})/100)/V_{f,d})/2 \tag{19}$$

2.3 Drum filter

The mechanical filter is required for the removal of TSS within a RAS. TSS within a RAS originate from faeces, uneaten feed and decaying fish and bacteria [33]. When TSS are not removed they can have an adverse effect on the system, leading to damaged fish gills, an increases in biochemical oxygen demand, the reduction of nitrification rate of the biofilter and consequently an increase of ammonia in the system [34]. Thus by maintaining acceptable TSS concentrations by proper mechanical filtration the production rate can be increased.

97% of the particles originating from uneaten feed are greater than 60 microns and are therefore easy to remove [35]. This model assumes that all undigested feed is removed immediately in the fish tank by a drain. Furthermore, by neglecting decaying bacteria and fish, the assumption has been made that all TSS originate from faeces.

The TSS that originate from faeces can be divided into two groups, namely fine and large particles. Research based on particle size distribution in intensive RAS demonstrated that particles smaller than 20 microns account for 95% of the total amount of particles. These particles in turn make up 40 to 70% of the TSS by weight [36]. According to the same study the specific gravity of the solids should be around 1.19. Although, others suggest that the specific gravity is most likely to be around 1.05 for tilapia. The reason why the specific gravity is much lower could be due to the fact that faecal matter is cached making it less dense [35]. The low specific gravity of faecal matter and low TSS concentration in the outlet of the fish tanks makes settling tanks inconvenient as a first treatment step.

Due to the low settling velocity, drum filters are suggested as a solution for removing the large particles as a primary treatment step. The large particles can be removed by using screen filters with pore size diameters in the range of 40 to 100 microns. These drum filters have efficiencies ranging from 30 to 80% [37]. It is assumed that smaller pore sizes of the drum filter increases removal efficiency. Although, several studies showed that smaller pore size than 60 microns did not increase or barely increased removal efficiency [38, 39]. Smaller pore sizes require excessive backwashing and are impractical due to pressure losses [37]. Therefore, it is best to use a drum filter with a pore size of 60 microns. Drum filters mainly retain particles equal or larger to the pore size of the sieve. But, smaller particles can be retained due to bridging of bigger particles, trapping smaller particles. In addition the TSS concentration determines the filter efficiency [37].

The shear caused by pumping water through the RAS can affect particle size distribution. Research concluded that larger particles do break up into smaller particles. However, particles smaller than 60 microns were poorly affected by shear (their concentrations did not change greatly due to shear) [40]. Therefore, the assumption has been made that small particles that were not retained by the drum filter do not break up into smaller particles. Furthermore, it can be assumed that the drum filters do not cause particulates to break up in smaller particles do to shear [41]. It is assumed that there are no pumps used between the fish tank system and the drum filter.

The primary treatment step of TSS is mainly done by a drum filter. The permeate of the drum filter (F_s) stays within the RAS and the retentate of the drum filter (F_b) is further concentrated in the settling tank. The water flow out of the settling tank is used for the backwash of the drum filter. Backwash flows range from 0.2-1.5% of the treatment flow by the drum filter [37].

Figure 4 represents the model of the drum filter and the flows going in and out of the drum filter with respect to their waste concentrations. It is assumed that only TSS concentration is affected by the drum filter and not the TAN and NO_3 concentrations. It is assumed that the TSS in the backwash are completely retained.

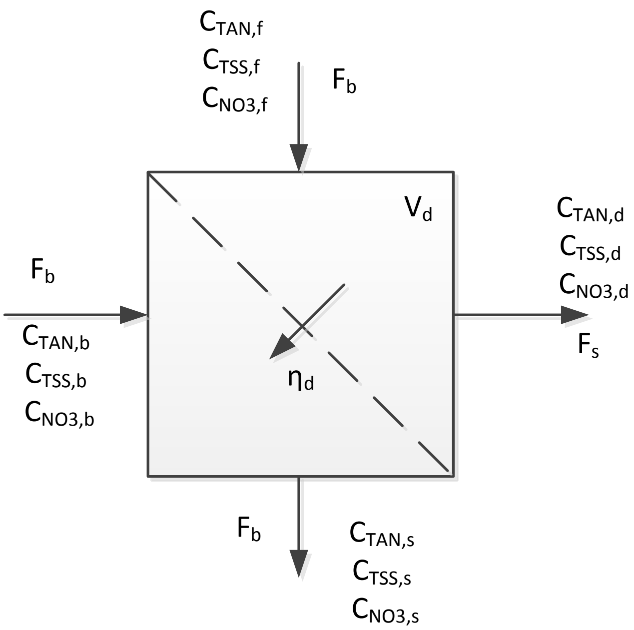

Figure 4: The drum filter model with the inlet flows and concentrations from the fish tank and backwash. TSS from the backwash is completely retained by the drum filter and from the fish tank partially. The retained TSS are directed to the settling tank and the unretained TSS to the trickling filter.

Equations:

Data points from literature that represent TSS concentrations in the inlet of a drum filter ($C_{TSS,f}$) in relation to removal efficiency of a drum filter (η_d) have been gathered and curve-fitted to equation 20, where p_1(=0.86) and p_2(=1.47) are the estimated parameters and ε is the machine epsilon [3]. The machine epsilon is needed to prevent computational division by zero. The η_d determines the fraction of solids that is retained in the retentate or from the permeate. The flowrate of the retentate (flow to the settling tank), which also forms the backwash (F_b 1 m^3 h^{-1}), described by equation 21 is a fraction of the RAS flowrate (d). The concentration balance for TSS in the retentate ($C_{TSS,s}$), defined by η_d, the drum filter volume (V_d 1.6 m^3), F_s and F_b and their concentrations $C_{TSS,f}$, $C_{TSS,b}$ (concentration TSS in the backwash) and $C_{TSS,s}$, is described by equation 22. The concentration TSS in the permeate (flow to the biofilter) ($C_{TSS,d}$) defined by the part of solids that is not retained by the drum filter (1- η_d), V_d and F_s and their concentrations $C_{TSS,d}$ and $C_{TSS,f}$, is described by equation 23. It is assumed that the TSS in the backwash stay within the retentate and do not go into the permeate. Substituting equation 20 into equation 22 and 23 resulted in equation 24 and 25. These equations form the basis of the drum filter module.

$$\eta_d = p_1 * e^{\left(\frac{-p_2}{\varepsilon + C_{TSS,f}}\right)} \tag{20}$$

$$F_b = F_s * d \tag{21}$$

$$\frac{dC_{TSS,s}}{dt} = (\eta_d * F_s * C_{TSS,f} + F_b * C_{TSS,b} - F_b * C_{TSS,s})/V_d \tag{22}$$

$$\frac{dC_{TSS,d}}{dt} = ((1-\eta_d) * F_s * C_{TSS,f} - F_s * C_{TSS,d})/V_d \tag{23}$$

$$\frac{dC_{TSS,s}}{dt} = (p_1 * e^{\left(\frac{-p_2}{s + C_{TSS,f}}\right)} * F_s * C_{TSS,f} + F_b * C_{TSS,b} - F_b * C_{TSS,s})/V_d \tag{24}$$

$$\frac{dC_{TSS,d}}{dt} = ((1 - p_1 * e^{\left(\frac{-p_2}{s + C_{TSS,f}}\right)}) * F_s * C_{TSS,f} - F_s * C_{TSS,d})/V_d \tag{25}$$

2.4 Settling tank

Since the size of TSS in intensive RAS are mainly smaller than 30 microns, it is assumed that settling velocity lies close to the lowest value [36]. Settling tanks function poorly when separating particles smaller than 100 microns [37]. However, settling tanks are still widely applied as a second filtration step.

Research has been done on the settling velocity of TSS due to fish wastes. Reported settling velocities for tilapia wastes range from 0.01-11.54 cm s^{-1}. It is important to take into account the factors that influence settling efficiency, such as feed ingredients and hydraulic surface load (HSL). Currently little is known about the effect of feed ingredients in relation to settling velocity of wastes. Even if research has shown that there is no relation further research should still be conducted since others contradict these results. HSL shows a positive effect on separation efficiency when decreased. This effect does not increase significantly when HSL reaches 1 cm s^{-1} [42].

Current models for the settling tank efficiency describe a linear relation between TSS and settling velocity [43]. This is most likely caused by flocculation of solids [4]. The effect of flocculation has been described by Brownian motion or by orthokinetic flocculation. Brownian motion is the random motion of particles in a solution causing collisions and thus flocculation. Flocculation caused by this effect decreases when particle size increases. Orthokinetic flocculation is caused by induced velocity gradients in the liquid. These velocity gradients can be induced by bringing the liquid into motion with different settling velocities of particles with different sizes and densities. The variation of settling velocities between particles arises the opportunity of interaction and can therefore cause flocculation [44]. Hence, the increased concentration of the retentate by the drum filter causes an increase in flocculation dynamics. This results in an increase in settling efficiency dynamics. This has also been reported by Cripps and Kelly, whom recommend settling tanks only to be used as a second separation step [45].

One of the biggest smolt farms cultivating salmon and trout in Fjon in Norway also makes use of a settling tank as a second separation step. The efficiency of the settling tank in Fjon has been modelled and showed an efficiency greater than 90%. Results proved an exponential relation between TSS in the inlet of the settling tank and the efficiency of the settling tank. The hydraulic retention time of this settling tank was approximately 9 hours, with an area to volume ratio of 0.6 m^{-1} and a HSL of 1 m h^{-1} [4]. Previous research indicated that the HSL of the smolt farm (0.0278 cm s^{-1}) lies close to the settling velocity of the smallest particulates of tilapia [42]. This implies that the model of the settling tank from the smolt farm in Fjon can be implemented for a RAS with tilapia, if the same HRT and HSL is applied. Furthermore, one can now also assume that most of the small solids will be separated by the settling tank.

In this study, a settling tank is modelled as a second separation step. Figure 5 reflects the retentate from the drum filter going into the settling tank and the backwash going out of the settling tank back to the drum filter. According to INAPRO the end of the settling tank is the appropriate place to recycle water to the hydroponic system. The dynamics of the end of the settling tank are represented by the backwash and therefore used to simulate the stream to the hydroponic system. This flow is managed by a valve and is opened whenever toxic waste concentrations for tilapia are nearly reached. The solids stay behind in the settling tank and should be disposed occasionally to prevent anaerobic conditions leading to denitrification and nitrogen losses now and then. It is assumed that TAN and NO_3 do not settle. Also it is assumed that no further reactions take place within the settling tank, resulting in changes of TAN and NO_3 concentrations.

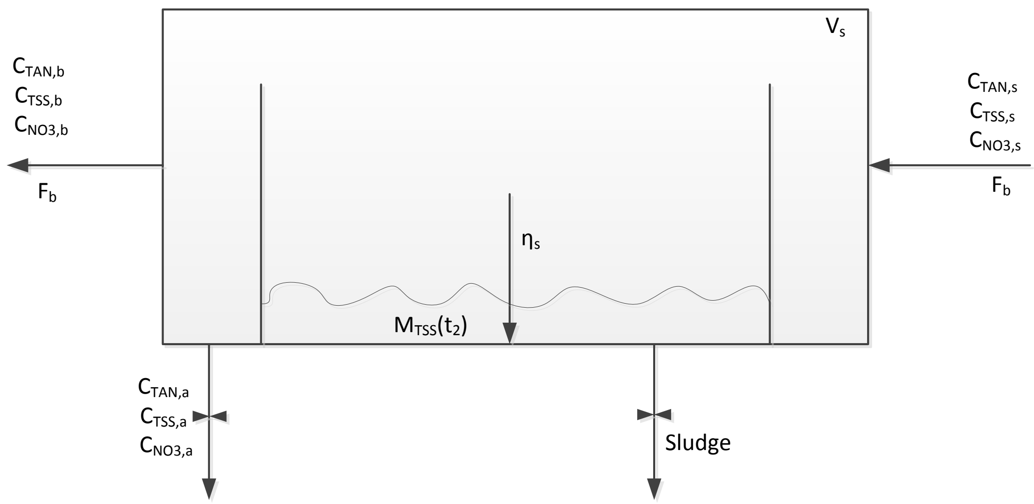

Figure 5 The settling tank model only retains TSS and therefore does not affect NO_3 and TAN concentrations. The inlet from the drum filter contains high TSS concentrations and settle in the basin. The out flow of the settling tank is used as a backwash for the drum filter. Intermittently water is recycled to the hydroponic to manage NO_3 levels in the RAS.

Equations:
Data points from literature that represent TSS concentrations in the inlet of a settling tank ($C_{TSS,s}$) in relation to removal efficiency of a settling tank (η_s) have been gathered and curve-fitted to equation 26, where p_3(=0.889) and p_4(=0.046) are the estimated parameters and ε is the machine epsilon [4]. The machine epsilon is needed to prevent computational division by zero. The η_s determines the fraction of solids that is retained in the settling tank. Since the settling tank is dependent on low settling velocities of solids, the HSL should also be kept low. Due to this low HSL the retention time of the settling tank can be relatively high. This high retention time used from literature can be used to determine the settling tank volume (V_s 9 m^3) (27) [4].

The concentration balance for $C_{TSS,b}$, defined by η_s, V_s, F_b and their concentrations $C_{TSS,b}$, $C_{TSS,s}$, is described by equation 28.Substitution of equation 26 in 28 results in equation 29. Here one can clearly see that the efficiency of the settling tank increases when inlet concentrations are higher. Although, higher concentrations does not per se mean lower outlet concentrations in the backwash. Equation 29 has been used to simulate the settling tank module.

Equation 30 has been set up to describe the TSS that have been retained by the settling tank. The total amount of solids retained at a certain moment was calculated by summing up the total amount of change in concentrations in the backwash. Multiplying this summation by the backwash flow results in the total mass of TSS that have been retained.

$$\eta_s = p_3 * e^{\left(\frac{-p_4}{\varepsilon + C_{TSS,s}}\right)} \tag{26}$$

$$V_s = HRT_s * F_b \tag{27}$$

$$\frac{dC_{TSS,b}}{dt} = ((1-\eta_s) * F_b * C_{TSS,s} - C_{TSS,b} * F_b)/V_s \tag{28}$$

$$\frac{dC_{TSS,b}}{dt} = ((1 - p_3 * e^{\left(\frac{-p_4}{\varepsilon + C_{TSS,s}}\right)}) * F_b * C_{TSS,s} - C_{TSS,b} * F_b)/V_s \tag{29}$$

$$\mathrm{M}_{TSS}(t_2) = \sum_{t_1}^{t_2} C_{TSS,i}(t_{i+\tau} - t_i) * F_b \tag{30}$$

2.5 Trickling filter

There are many different systems used for the removal of TAN out of a RAS. In this case a trickling filter was applied. The dynamics of the trickling filter were described as a cascade of CSTRs (continuous stirred tank reactor). This gives a simplified representation of the dynamics of a plug flow system.

The trickling filter consists of a plastic media on which nitrifying bacteria grow and form a biofilm. These nitrifying bacteria consist of two major groups, namely *Nitrosomonas* and *Nitrobacter*. The *Nitrosomonas* are autotrophic bacteria, which convert ammonia tot nitrite {1}. Subsequently *Nitrobacter* also autotrophs convert the toxic nitrite to less toxic nitrate {2}. For the bacteria to drive their lifecycle they produce energy due to the reactions given below. To maintain their cell biomass they also take up bicarbonate, resulting in an overall balance {3}. These balances represent the stoichiometry of the nitrifying biofilm.

$$NH_4^+ + 1.5\,O_2 \longrightarrow 2\,H^+ + H_2O + NO_2^- \qquad \{1\}$$

$$NO_2^- + 1.5\,O_2 \longrightarrow NO_3^- \qquad \{2\}$$

$$NH_4^+ + 1.83\,O_2 + 1.98\,HCO_3^- \longrightarrow 0.021\,C_5H_7O_2N + 0.98\,NO_3^- + 1.041 H_2O + 1.88\,H_2CO_3^- \qquad \{3\}$$

The stoichiometric balance shows that every g of TAN that is oxidized approximately 3.25 g of oxygen is consumed and 3.38 g of NO_3 and 0.132 g of biomass is produced [5]. It is assumed that the growth rate equals decay of the nitrifying bacteria, resulting in a steady state of the biofilm.

The trickling filter consists of a media on which the nitrifying bacteria form a biofilm. This biofilm of nitrifying bacteria has a certain thickness and stagnant layer around it through which TAN and oxygen needs to diffuse. TAN concentrations in the bulk of the trickling filter are generally lower than when oxygen becomes rate limiting. Therefore, it is assumed that TAN is the rate limiting substrate in the reaction rate of the nitrifying bacteria [46]. The reaction rate of the biofilm has been described as a function of Monod dynamics. However, the reaction kinetic is also influenced by the diffusion coefficients and thickness of the biofilm and the stagnant layer. A model describing Monod dynamics of a biofloc has been used in this research [47]. Since this research uses a biofilm the thickness of the biofloc had to be corrected. The diffusion coefficients determine the rate at which substrate penetrates the stagnant layer and biofilm. The value of these diffusion coefficients of TAN and oxygen through a biofilm and stagnant layer at 25 °C have been researched [48]. Another research has described the biofilm thickness and the concentration changes in the stagnant layer for trickling filters at 20-28 °C. By taking the point at which concentrations in the water start to differ from bulk concentrations one can determine the stagnant layer thickness [49]. The thickness of the stagnant layer is an assumption, since it is normally dependent on the turbulence of the water flow which is correlated to the Reynolds number. A higher flow rate through the trickling filter means a higher Reynolds number, which in turn causes a thinner stagnant layer and consequently has a positive effect on the reaction kinetics of the nitrifying bacteria. The Monod dynamics which describe the reaction rate of the nitrifying biofilm is not only dependent on the diffusion coefficients and layer thicknesses, but is also a function of the apparent kinetic constant and the maximum reaction rate. The apparent kinetic constant has been studied for biofilms. This study indicated a relation between biofilm thickness and the apparent kinetic constant for biofilms with a stagnant layer. The apparent kinetic constant, that is applicable for biofilms with the same thickness as a biofilm of a nitrifying trickling filter taking the stagnant layer into account has been described [47]. The maximum reaction rate of nitrifying bacteria in a biofilm without a stagnant layer has also been studied for an intensive recirculating tilapia facility [50].

Literature reports many more factors influencing the performance of a trickling filter. One research has summarized these parameters and their influence on the nitrification kinetics of a biofilm. Most of these parameters were left out since modelling of these parameters is time consuming and do not contribute to the system dynamics that will be modelled. In this model it is assumed that mixing is adequate, oxygen is not rate limiting, alkalinity is kept at proper concentrations and the pH is maintained between certain levels [5].

The overall change in TAN concentration over the trickling filter has been used to determine the NO_3 accumulation within the system, by using the stoichiometric balance. By assuming ideal mixing of NO_3 in the whole system the concentration has been calculated. This was done due to the slow accumulation rate of NO_3 and high flow rates of the RAS.

The trickling filter volume is based on the total production rate of TAN by the fish and the average consumption rate of TAN by the trickling filter. These values have been taken from literature and correspond with the amount of feed given to the fish, which is related with the total TAN production of the fish [30].

Figure 6 reflects the module of the trickling filter that has been made. It is made up of a cascade of five CSTRs describing a simplification of plug flow dynamics. The model that has been made incorporates diffusion limitations through the biofilm and the stagnant layer and the accompanying apparent kinetic constant for the rate limiting substrate. The inflow is from the drum filter. The trickling filter does not affect the TSS. It reduces the toxic TAN to less toxic NO_3, which forms the outflow of the trickling filter.

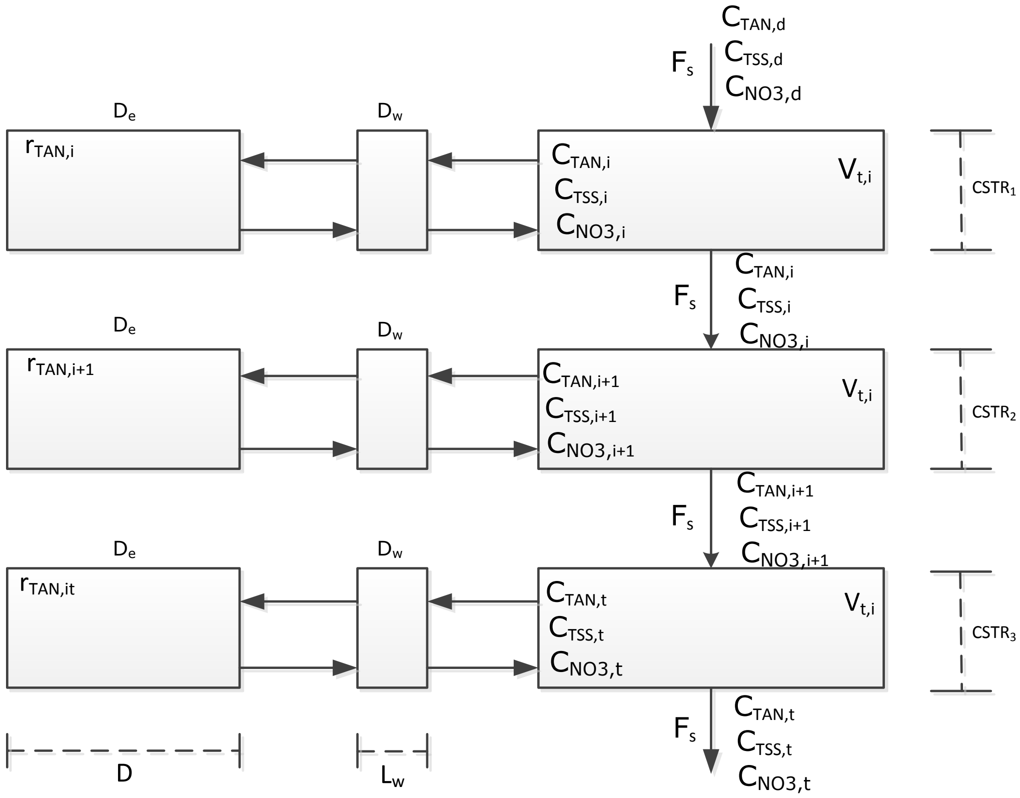

Figure 6 The trickling filter model is described by a cascade of CSTRs. Each block forms a CSTR and has its own reaction kinetics, due to different bulk concentrations. D and L_w form respectively the biofilm thickness and stagnant layer thickness, resulting in the diffusion limitation described by D_e and D_w. The inflow is from the drum filter. TSS are not affected by the trickling filter. The out flow of the trickling filter is directed back to the fish tank.

Equations:
The volume of each block of the trickling filter ($V_{t,i}$) has been calculated by dividing the overall volume of the trickling filter (V_t 9.81 m^3) by the number of blocks used (n_t 5), resulting in equation 31. The number of blocks used to model the trickling filter as a cascade has been validated in chapter 3.5. Each block of the trickling filter is assumed to behave as a CSTR to simplify the modelling strategy, which is described by F_s, $V_{t,i}$, inflow concentration TAN ($C_{TAN,i}$), outflow concentration of TAN ($C_{TAN,i+1}$) and the consumption rate of TAN ($r_{TAN,i+1}$), leading to a cascade of CSTR based equations described by equation 32. The $C_{TAN,i}$ from one black is the $C_{TAN,i+1}$ of the previous black. $r_{TAN,i+1}$ which has been described by Monod dynamics is dependent on the rate limiting substrate $C_{TAN,i+1}$, biomass concentration (X), apparent kinetic constant (k_s), maximum growth rate (μ_{max} 0.0521 h^{-1}) and the stoichiometric ratio (Y_s) resulting in equation 33 Previous research has described Monod dynamics by taking diffusion limitation into account. This resulted in equation 35, in which D_w and D_e are the diffusion coefficients of the stagnant layer and the biofilm and L_w and D are the thickness of the stagnant layer and the biofilm. The maximum consumption rate (r_{TAN}^{max} 31.66 g m^{-3} h^{-1}), which is dependent on μ_{max}, X and Y_s, has been described by equation 35. Substitution of equation 35 in 34 resulted in equation 36. Substitution of equation 36 in equation 32 resulted in

equation 37, which describes the overall equation of the dynamics of an individual block of a cascade of CSTRs in a trickling filter. In which the initial inflow of the cascade is dependent on the outflow concentrations of the drum filter and the outflow forms the inflow concentration of the fish tank.

The total accumulation of NO_3 at moment t_2 $M_{NO3}(t_2)$ described by equation 38 is dependent on all the concentration changes of TAN within the before moment t_2, the molar weight of TAN (MW_{TAN}), F_s and the stoichiometric ratio of TAN to NO_3 ($Y_{N/T}$). NO_3 concentration at time t_2 ($C_{NO3}(t_2)$) described by equation 39 is dependent on $M_{NO3}(t_2)$ and V_f, assuming that the whole system is ideally mixed and that the system is twice the volume of V_f.

$$V_{t,i} = \frac{V_t}{n_t} \tag{31}$$

$$\frac{dC_{TAN,i+1}}{dt} = (F_s * C_{TAN,i} - F_s * C_{TAN,i+1})/V_{t,i} - r_{TAN,i+1} \tag{32}$$

$$r_{TAN,i+1} = \mu_{max} * \frac{X}{Y_s} * \frac{C_{TAN,i+1}}{k_s + C_{TAN,i+1}} \tag{33}$$

$$\mu_i = \frac{C_{TAN,i+1} * \mu_{max}}{k_s + C_{TAN,i+1} + \mu_{max}(L_w/D_w + D/D_e)} \tag{34}$$

$$r_{TAN}^{max} = \mu_{max} * \frac{X}{Y_s} \tag{35}$$

$$r_{TAN,i} = \frac{C_{TAN,i+1} * r_{TAN}^{max}}{k_s + C_{TAN,i+1} + \mu_{max}(L_w/D_w + D/D_e)} \tag{36}$$

$$\frac{dC_{TAN,i+1}}{dt} = (F_s * C_{TAN,i} - F_s * C_{TAN,i+1})/V_{t,i} - \frac{C_{TAN,i+1} * r_{TAN}^{max}}{k_s + C_{TAN,i+1} + \mu_{max}(L_w/D_w + D/D_e)} \tag{37}$$

$$M_{NO3}(t_2) = \frac{\sum_{t_1}^{t_2} C_{TAN,i}(t_{i+1} - t_i) * F_s * Y_{N/T}}{MW_{TAN}} \tag{38}$$

$$C_{NO3}(t_2) = \frac{M_{NO3}(t_2)}{V_f * 2} \tag{39}$$

3 Module and model dynamics and calibration

Each module of the RAS is calibrated individually. After calibration, the modules are interlinked forming the overall model. Finally, the overall model is checked for proper functioning.

3.1 Fish

The excretion model is based on data from literature, that has been curve-fitted (r^2 = -0.645), which describes the retained feed by tilapia fed 3 times per day with a feeding interval of 4-5 hours(Figure 7) [9]. The excretion model for tilapia that has been made describes the percentage of feed that has been excreted over time (Figure 8 and Figure 9). The excretion model depends on feeding frequency, feeding interval, initial feed, night time(no feed) and time difference between the two fish tank systems, based on a single fish tank system or 2 fish tank systems fed at complementary time. This model has been used for testing the effect of 5 feeding strategies on TSS and TAN concentrations within the system (Table 3).

Table 3 Different feeding strategies that have been used in relation to feeding interval (Δ)

Feeding strategy	feeding interval (h)	Feeding strategy #
fed 2x, single fish tank	6	1
fed 3x, single fish tank	6	2
fed 2x, double fish tank	6	3
fed 3x, double fish tank (Δ=4h)	4	4
fed 3x, double fish tank (Δ=6h)	6	5

Feeding hours and feed quantity given to the fish depends on the feeding strategy applied, complete description can be found in Appendix B. Below one can find the results for feeding strategies 1 (Figure 8) and 5 (Figure 9).

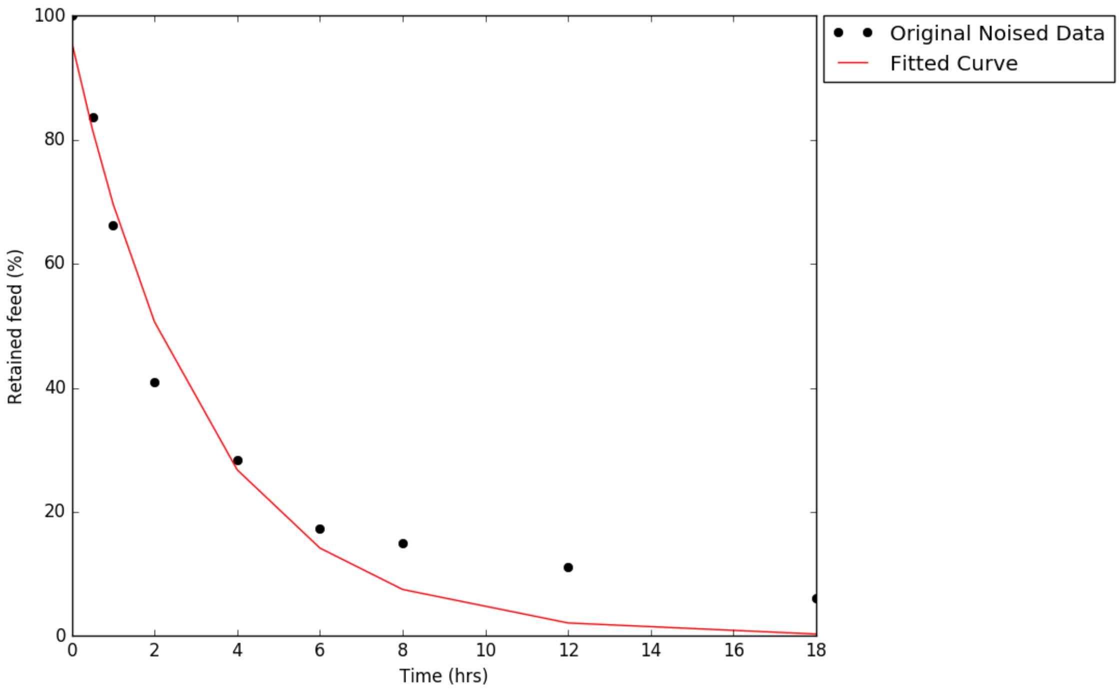

Figure 7 Curve-fitted data points from literature that describe the % retained feed over time.

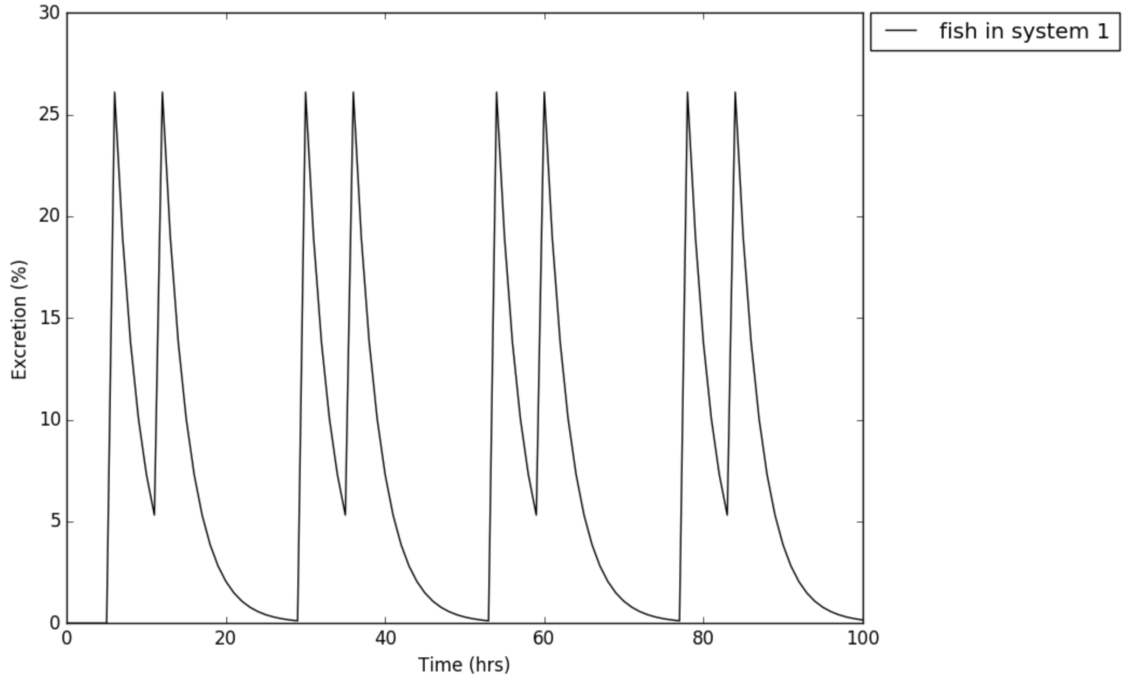

Figure 8 Percentage feed excreted over time by tilapia. This is a non-complementary system operated with a feeding frequency of 2 times per day and a feeding interval of 6 hours. During night time the excretion rate keeps on dropping until fed again.

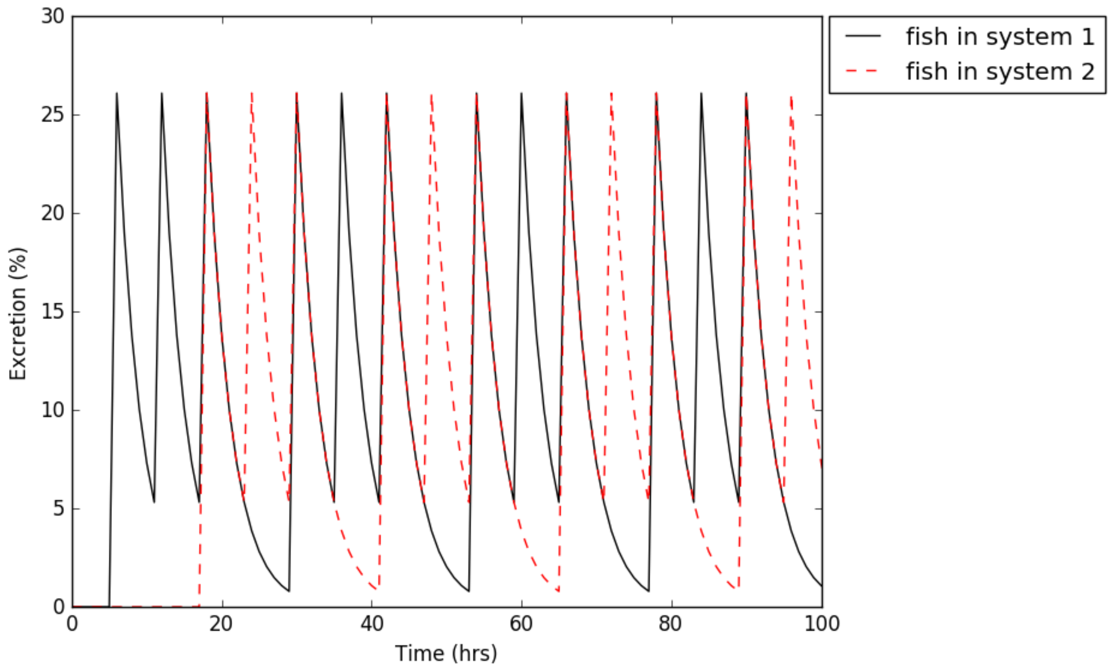

Figure 9 Percentage feed excreted over time by tilapia. System 1 and 2 are operated with a feeding frequency of 3 times per day and a feeding interval of 6 hours. During night time the excretion rate keeps on dropping until fed again. Due to a complementary feed system 2 is fed 12 hours later, therefore excretion also starts 12 hours later.

Figure 8 shows the model results, based on a single fish tank system. The initial feed is at t=6 hours, with a feeding frequency of 2 times per day and a feeding interval of 6 hours. The total excretion between two feed is the cumulative sum of all percentages through one feeding interval. The percentage that is not excreted forms the partially digested or uneaten feed. Figure 9 shows the model results, based on an initial feed at t=6 hours with a feeding frequency of 3 times per day. The first two time intervals between feed are 6 hours after this there is a feeding interval of 12 hours (night time). Figure 9 also shows the results of a second system of fish tanks that working with a complementary feed. The complementary time is exactly 12 hours later (initial feed at t=18 hours).

Unfortunately the complementary feed strategy modelled in Figure 9 has periodic overlaps. An additional feeding strategy is tested, with a feeding interval of 4 hours. In total 5 feeding strategies are tested in this study (Table 3).

3.2 Fish tank system

The fish tank system, which describes multiple fish tanks operated in parallel was modelled as a single CSTR. In this CSTR, fish excrete waste products as described in chapter 3.1. These waste products dissolve in the water of the fish tank and end up in the outflow of the fish tank system. The model for the fish tank system has been made and simulated. Figure 10 shows the model for TAN concentrations in the outlet of a fish tank system over time.

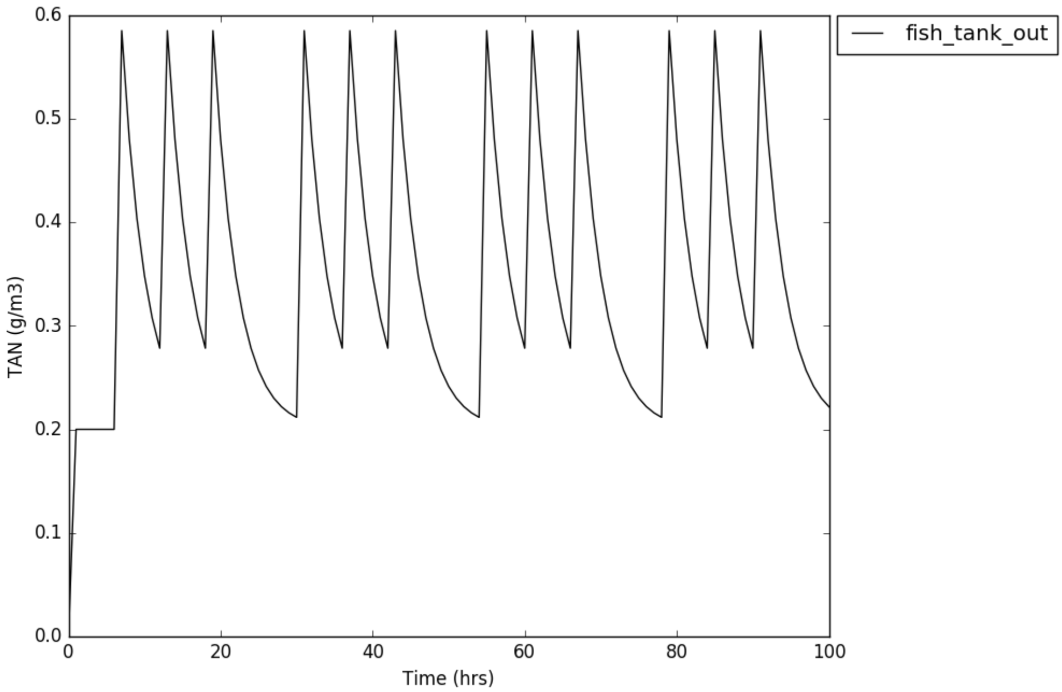

Figure 10 CTAN in the outflow of the fish tank over time

This model reflects the concentration TAN in the outflow of the fish tank over time. TSS is not discussed, since this model reflects the same dynamics. During the first 6 hours, the outflow concentration of TAN is equal to inflow concentration, because the fish are not fed yet. The fish excretion as described in chapter 3.1 increases when fed and decreases postprandial till next feed. These dynamics are reflected in the outflow concentration of the fish tank. After the third feed the fish are not fed again until the next day. This results in almost complete depletion of excretion during night time, resulting in an outflow concentration that lies close to the inflow concentration.

3.3 Drum filter

The model describing the drum filter is based on data from literature, that has been curve-fitted (r^2 = 0.325), which describes the percentage retained solids in relation to the inlet concentration (Figure 11) [3]. The drum filter has two different inflows, two different outflows (retentate and permeate) and an efficiency factor which is determined by the inlet TSS from the fish tank. Figure 12 describes the TSS in the permeate. Figure 13 describes the TSS in the retentate.

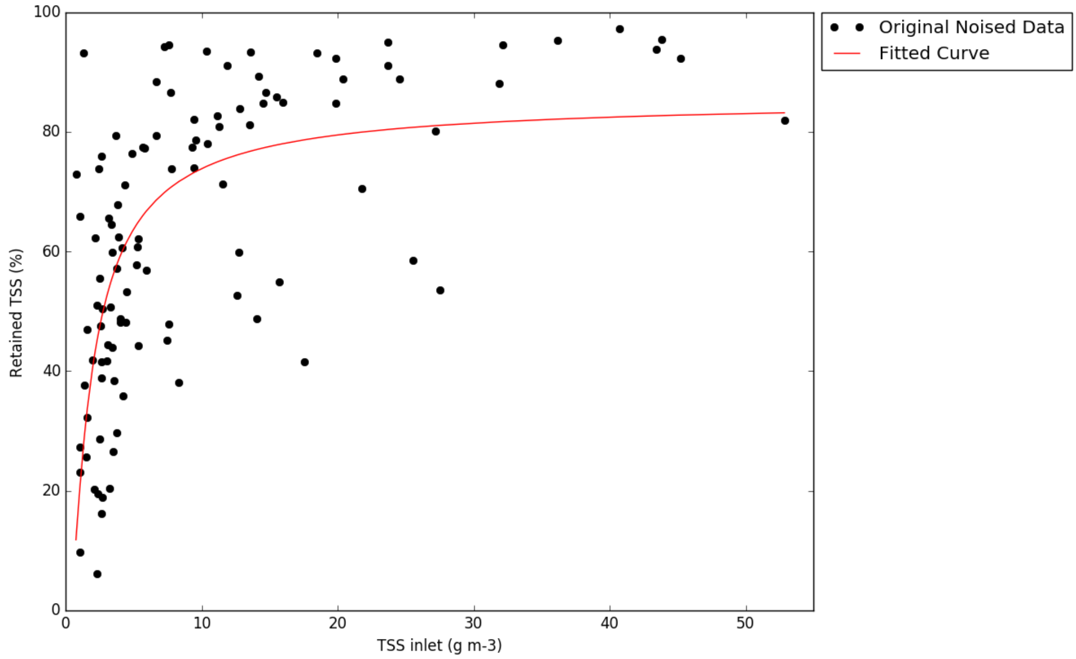

Figure 11 Curve-fitted data points from literature that describe the % TSS retained by the drum filter in relation to the inlet TSS

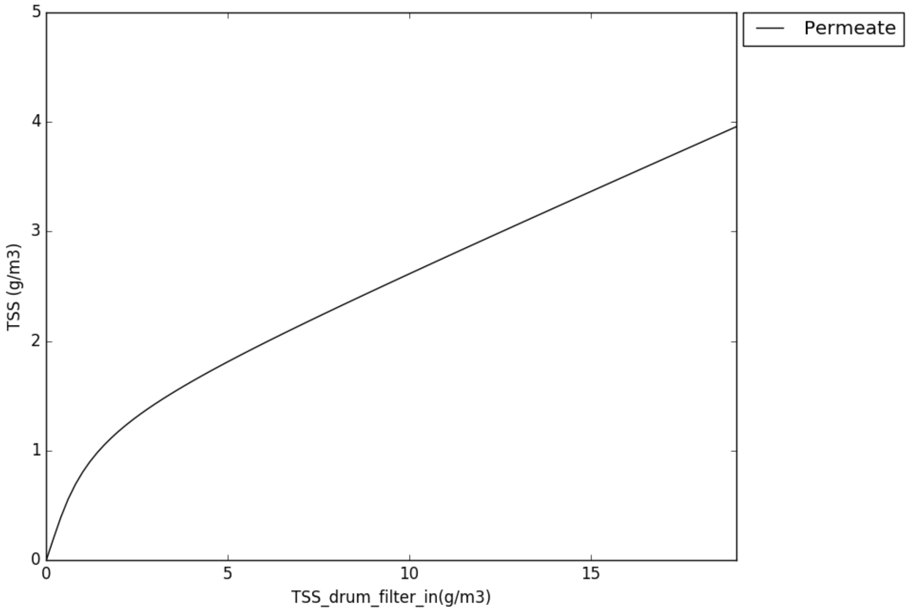

Figure 12 TSS in the permeate in relation to the TSS in the inlet of the drum filter

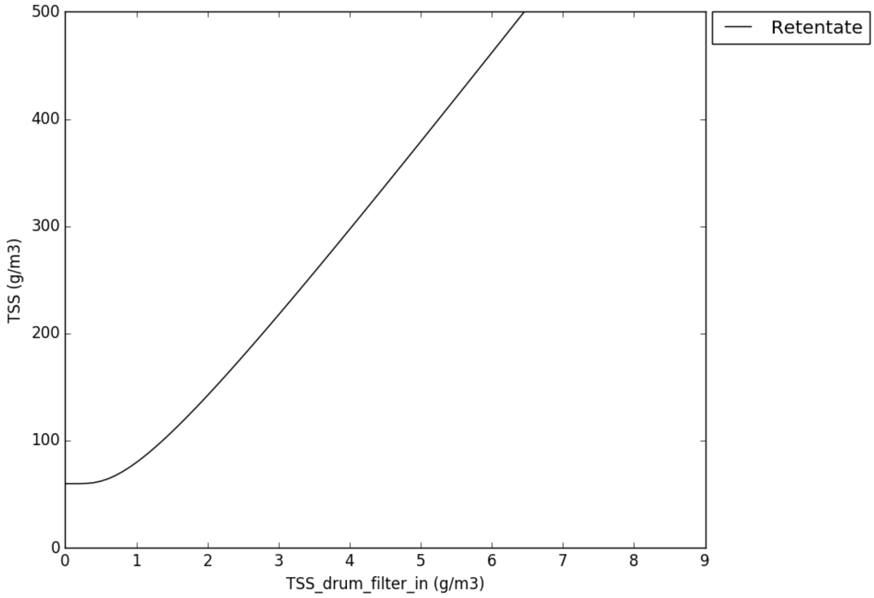

Figure 13 TSS in the retentate in relation to the inlet TSS of the drum filter

Figure 12 shows that the TSS in the permeate is solely dependent on the inlet TSS from the fish tank. It can be seen that the drum filter reaches its maximum efficiency rapidly. The maximum efficiency is reached when the graph follows linear dynamics, it can therefore be said that the drum filter reaches its maximum efficiency rapidly. The maximum efficiency is approximately 86% (chapter 2.3).

Figure 13 describes the TSS in the retentate, which is dependent on the TSS in the backwash and fish tank outflow and consequently the resulting efficiency of the drum filter. Due to the fact that F_b is 100 times smaller than F_s the retained TSS get concentrated 100 times. As can be seen in Figure 13 the model reacts to the inlet concentration from the backwash, which is 60 g m^{-3}. The outlet concentration is the same as the inlet concentration of the backwash when the inlet concentration of the fish tank is equal to 0. The inlet concentration from the backwash does not influence the efficiency of the drum filter. When the inlet concentration of TSS of the fish tank increases the TSS concentration in the retentate also increases dramatically. The higher the inlet concentration of the drum filter from the fish tank system the higher the drum filter efficiency, resulting in higher TSS in the retentate.

3.4 Settling tank

The model describing the settling tank is based on data from literature, that has been curve-fitted (r^2 = 0.214), which describes the percentage settled solids in relation to the inlet concentration (Figure 14) [4]. The outlet concentration of the settling tank could therefore be determined by the inlet concentration and its impact on settling efficiency (Figure 15).

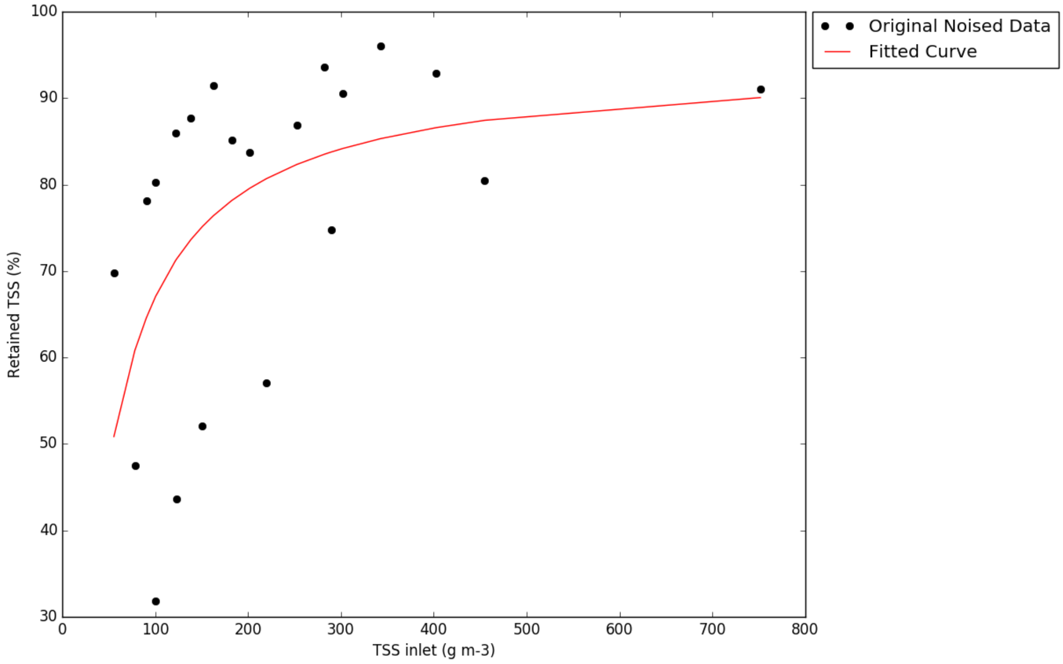

Figure 14 Curve-fitted data points from literature that describe the % TSS settled in the settling tank in relation to the inlet TSS

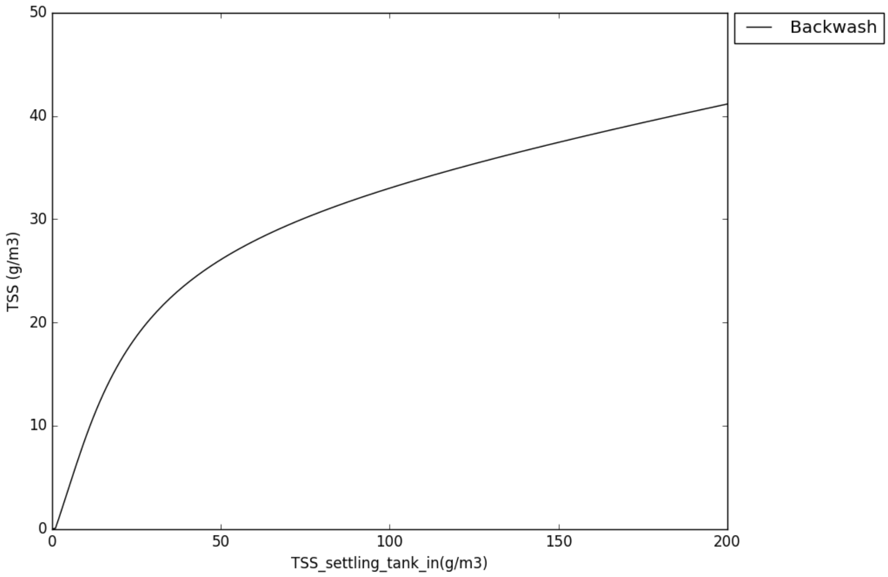

Figure 15 TSS concentration in the backwash to the drum filter in relation to the inlet concentration of the settling tank

Figure 15 describes the dynamics of the settling tank, which responds to TSS in the retentate. High inlet TSS result in high efficiency. The low efficiencies due to low inlet TSS can be explained by loss of Brownian motion or orthokinetic flocculation as discussed in chapter 2.4.

3.5 Trickling filter

The dynamics of the trickling filter is normally reflected by plug flow dynamics. However, to make simplified iterations and reduce the runtime of the modelling program an approximation of plug flow dynamics has been made by using a cascade of CSTRs(chapter 2.5). To incorporate diffusion limitation parameters obtained from literature describing Monod dynamics with diffusion limitation has been used.

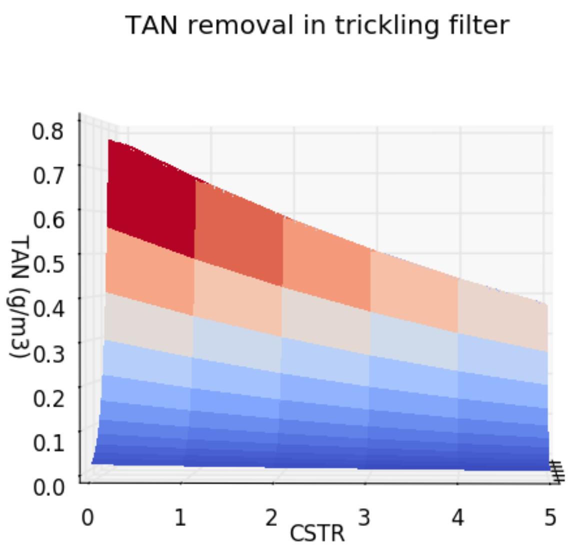

Figure 16 Change of TAN concentration in relation to the depth of a trickling filter described by a cascade of CSTRs

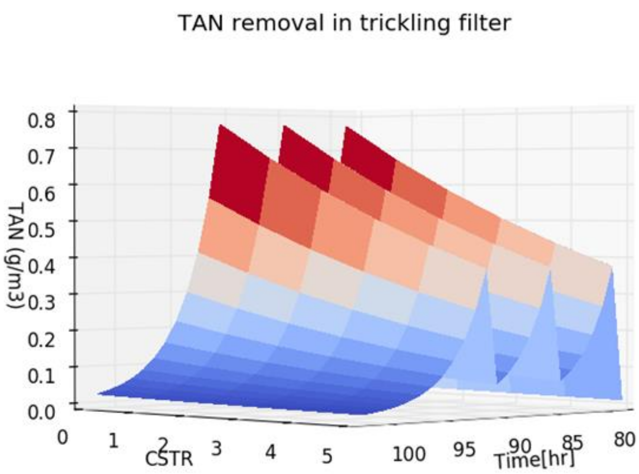

Figure 17 Change of TAN concentration over time in relation to inlet concentration of the trickling

Figure 16 shows the expected dynamics, in which the consumption rate decreases along the depth of the trickling filter due to a decrease in TAN concentrations. The amount of sections used to model the trickling filter (n_t) is therefore justified. When inlet concentrations of TAN are high the overall removal of TAN is also high due to a decrease of the effect caused by diffusion limitation and the apparent kinetic constant (equation 37). When inlet concentrations are low the opposite effect will take place, resulting in low removal rates. The change in TAN concentrations resulted from an average TAN inlet concentration (0.7 g m^{-3}) has been tested against literature. By taking the general value for areal TAN removal rate described by literature (0.45 g TAN m^{-2} d^{-1}) and multiplying it by the specific surface area (200 m^2 m^{-3}) and the retention time (0.0983 h) of the trickling filter of this model, resulted in the overall change of TAN of 0.368 g TAN m^{-3} [30]. This value lies close to the value described by this model of 0.394 g TAN m^{-3}.

3.6 System level model

Coupling the modules resulted in two overall model describing the TSS and TAN concentrations within different compartments of the system . The overall model describing the TSS is based on the modules 1, 2, 3 and 4 (Figure 18). The overall model describing the TAN is based on the modules 1, 2 and 5 (Figure 19).

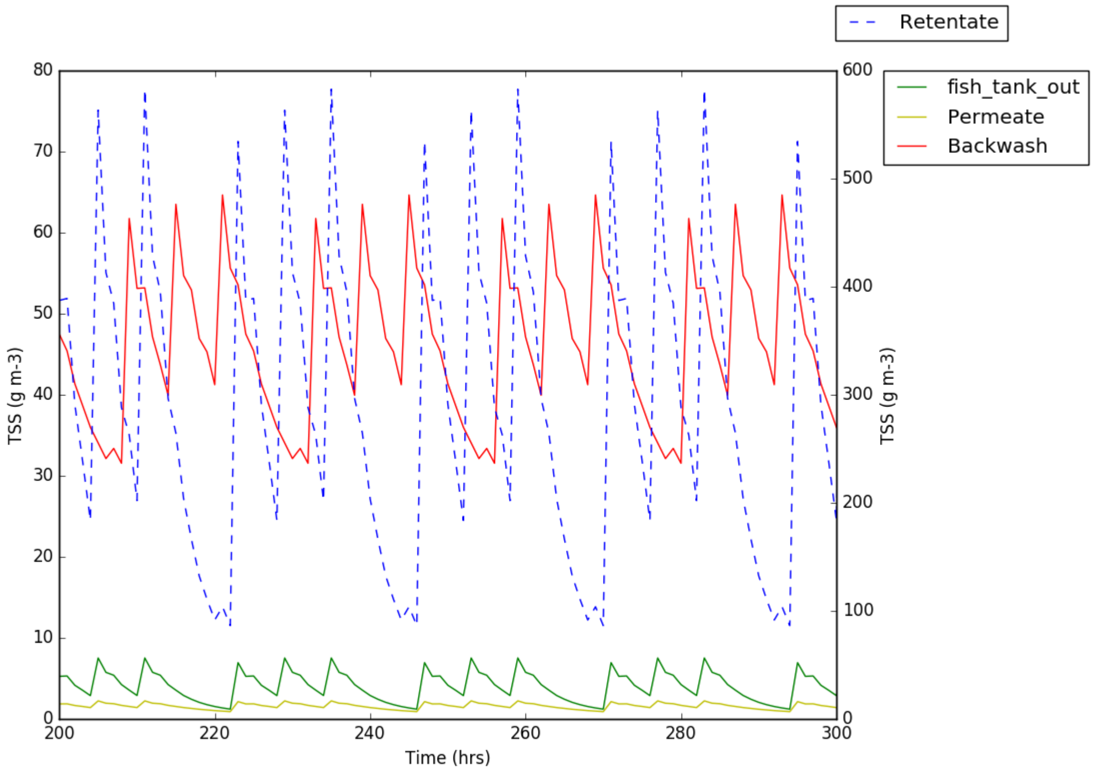

Figure 18 TSS concentrations within different compartments of the RAS when coupling all modules

Figure 18 describes the effect on TSS within different compartments of the system for fish fed 3 times per day with a feeding interval of 6 hours and a night time of 6 hours. Figure 18 shows that every time when fish are fed TSS increase in the waste stream of the fish tank. This stream is filtered by the drum filter resulting in low TSS in the permeate. The retentate of the drum filter has high TSS due to its low flow capacity with respect to the flow capacity from the fish tank (chapter 3.3). These high concentrations that enter the settling tank can than settle easily due to Brownian motion or orthokinetic flocculation (chapter 3.4). Due to the long retention time of the settling tank the TSS in the backwash shift by 9 hours.

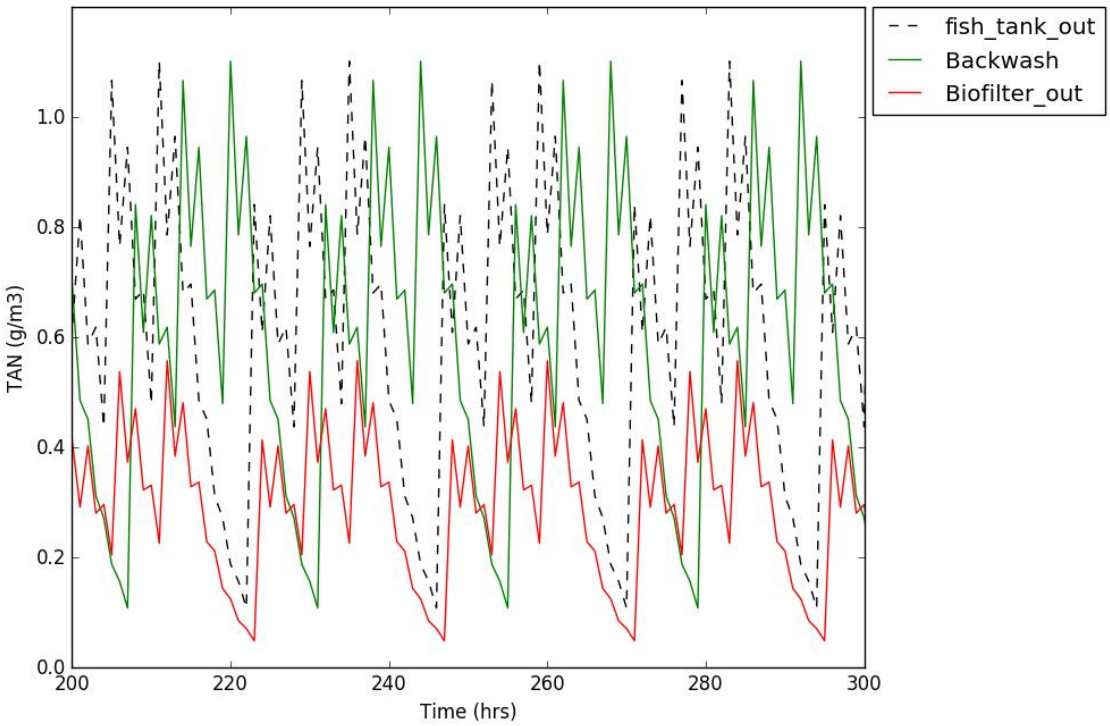

Figure 19 TAN concentrations within different compartments of the RAS when coupling all modules

Figure 19 describes the effect on TAN within different compartments of the system for fish fed 3 times per day with a feeding interval of 6 hours and a night time of 6 hours. This resulted in three major peaks every 24 hours, with maximum TAN every time the fish are fed. The following postprandial hours feed excretion decreases, resulting in lower TAN concentrations. This waste stream with an increased TAN concentration is filtered by the trickling filter and directed back to the fish tank. Not all TAN is removed by the trickling filter. This results in a new peak every 2 hours. After 6 hours the fish are fed again resulting in an even greater peak. This effect of increasing TAN concentrations stops when the fish are fed for the last time. Overnight TAN concentrations drop dramatically due to the fact that most feed has already been excreted. In the backwash the TAN has been retained by the settling tank, resulting in a shift 9 hour shift.

4 Results and discussion

To answer the research questions five feeding strategies have been simulated (Table 3). The feeding hours and the amount of feed given to the fish per fed for different feeding strategies can be found in the Appendix B. After simulation of different feeding strategies TAN concentrations in the fish tank outlet and TSS concentrations in the settling tank outlet have been analysed between day 4 and 20. Measurements started at day 4 to only analyse the system after start-up phase. First the values for maximum and minimum concentrations of TAN and TSS have been collected for different feeding strategies. After this, the values for the average concentrations of TAN and TSS for feeding strategy 1 have been collected. This average formed the baseline for the other feeding strategies. The average deviation from the baseline reflects the shift in the average concentrations. The results are discussed in chapter 4.1.

After reflection on different feeding strategies, the effect of dependent design parameters on the system will be checked. Dependent parameters are parameters that are linked to each other to keep hydraulics constant, listed in Table 6. The trickling filter and fish tank volume have not been changed, since they were based on amount of feed given to the fish per day and the stocking density which are considered to be constant for every system. Certain design parameters are based on a fraction of another design parameter to maintain hydraulics between design requirements (Chapter 2.3). A sensitivity analysis of the dependent design parameters on average values of TAN and TSS was performed. The data points for the maximum and minimum values of TAN and TSS, for a normal run and when a dependent design parameter has been changed, have been collected per feeding strategy. Equation 40 has been set up to calculate the effect of the dependent design parameters on the minimum and maximum concentration. Also, the values for the shift in average TAN and TSS concentrations have been gathered. The results of the effect of changing dependent design parameters are discussed in chapter 4.2.

$$effect = 1 - C_{TSS,new}/C_{TSS,normal} \quad (40)$$

Furthermore, an appropriate strategy for recycling water to the hydroponic system from the backwash is discussed. Different feed strategies will be tested against different dependent design parameters and their influence on the TSS:TAN ratio in the backwash. It is namely important to increase nutrient concentrations, such as TAN for the plants, and reduce TSS to prevent root damage [6]. To create the appropriate conditions for recycling water minimum TSS concentrations and maximum TAN concentrations are used. Lastly, a suggestion is made on recycling water at a different place from the RAS. This is discussed in chapter 4.3.

4.1 Effect of feeding strategies

To analyse the effect of different feeding strategies on TAN and TSS concentrations all parameters need to be kept the same. Therefore, all feeding strategies are given 27.5 kg over 20 days. All TSS concentrations are analysed in the backwash flow and all TAN concentrations are analysed in the (combined)fish tank outflow. The final concentration NO_3 and settled TSS have been modelled for different feeding strategies (Table 4). See Appendix C for normal run of simulations, without changing design parameters (notice that in Appendix C the concentration in the fish tank is not the one of the combined waste stream for complementary systems).

Table 4 Effect of feeding strategies on $C_{NO3}(t_2)$ and $M_{TSS}(t_2)$ at the end of the simulation time

Feeding strategy	$C_{NO3}(t_2)$ (g/m3)	$M_{TSS}(t_2)$ (kg)
1	8.224	116.9
2	7.917	112.5
3	8.160	115.8
4	7.127	101.4
5	7.848	111.4

Applying fewer feeding frequencies resulted in higher final NO_3 concentrations and final settled TSS. This difference is approximately 3 %. Applying shorter feeding intervals resulted in an overall lower final NO_3 concentration. The difference in final concentration for a feeding interval reduced from 6 to 4 hours is approximately 13%. Applying complementary feeding times resulted in later excretion of wastes.

Feeding strategy *vs* waste concentrations

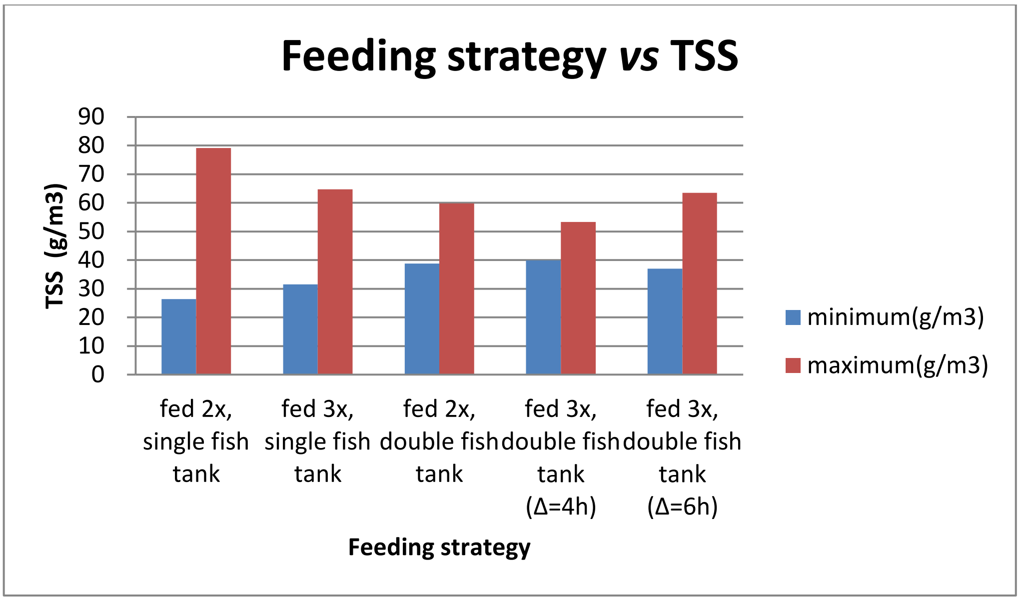

Figure 20 Effect of different feeding strategies on maximum and minimum TSS concentrations in the backwash.

By increasing the feeding frequency maximum TSS concentration are decreased and minimum TSS concentration increased. Complementary fish tank systems fed 2 or 3 times per day show similar effect. Except for a complementary feed of Δ=6h fed 3 times resulted in a slight increase of maximum TSS concentration and decrease in minimum TSS concentration.

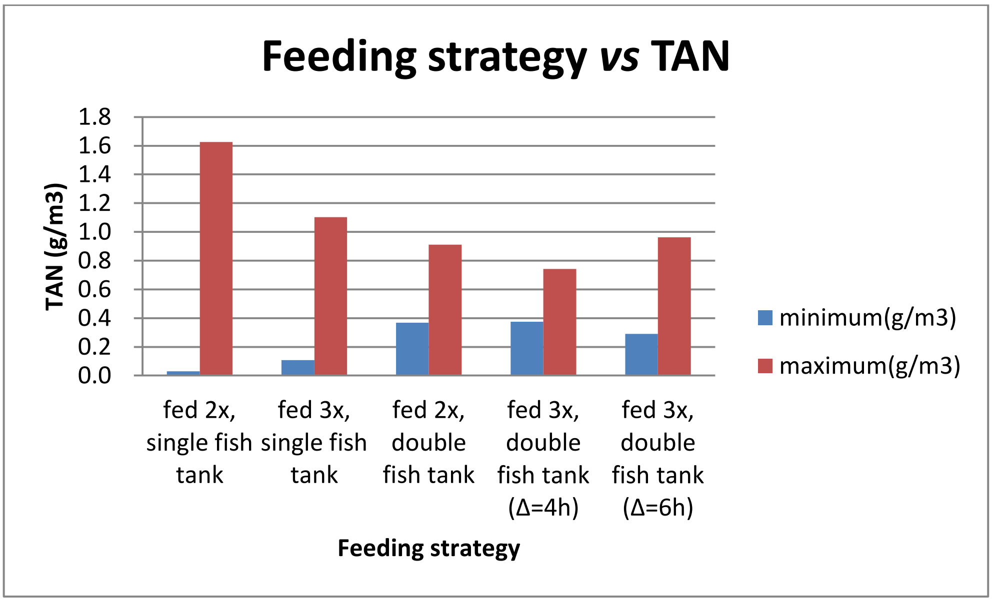

Figure 21 Effect of different feeding strategies on maximum and minimum TAN concentrations in the backwash.

Increasing the feeding frequency resulted in lower maximum TAN concentrations and higher minimum TAN concentrations. Same effect occurred for complementary systems. A complementary feed of Δ=6h fed 3 times per day resulted in a slight higher maximum TAN concentration and lower minimum TAN concentration.

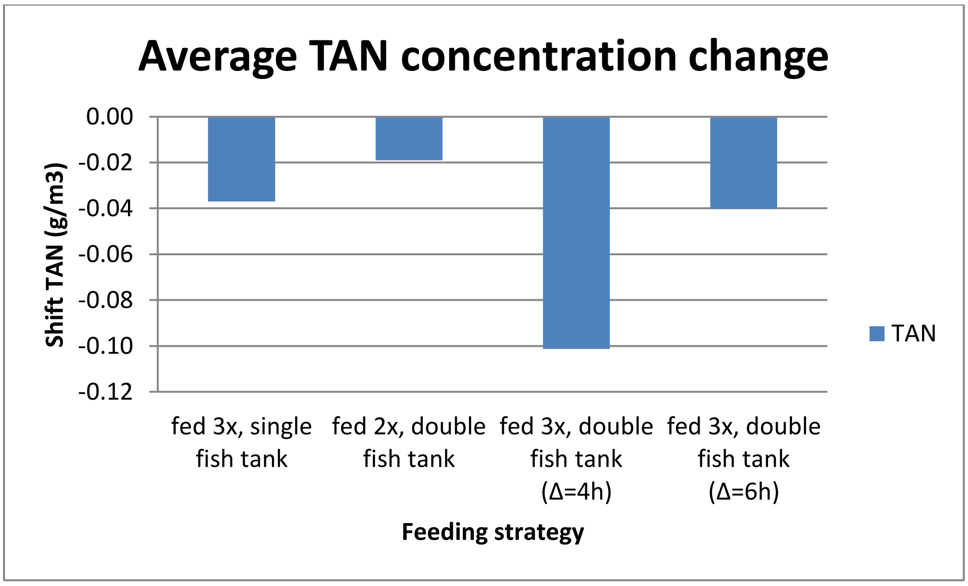

Figure 22 Average change in TAN concentration due to different feeding strategies in the (combined)waste stream out of the fish tank

The average TAN concentration decreased when fish were fed more often. A smaller decrease in average TAN concentration is noticed for fish fed in complementary systems. The biggest shift in average TAN concentration is considered to be for a complementary feed of Δ=4h fed 3 times.

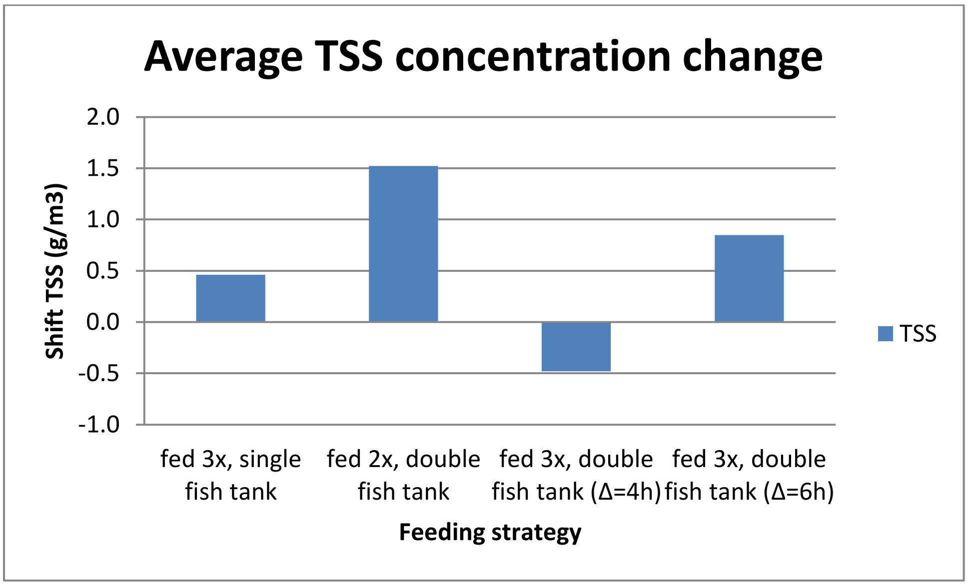

Figure 23 Average change in TSS concentration due to different feeding strategies in the backwash

The average TSS concentration in the backwash for RAS with fish that are fed more often have higher average TSS concentrations. Same effect can be noticed for complementary fish tank systems. A complementary feed of Δ=4h fed 3 times showed a decrease.

4.2 Effect of dependent design parameters

Multiple design parameters are dependent on each other to maintain proper design requirements of the RAS (**Error! Reference source not found.**, describes different design parameters). This dependence is hown in Table 6. The backwash flowrate is linearly correlated to the settling tank volume due to the minimal HRT required for the settling tank, as discussed in chapter 2.4. The RAS flowrate is dependent on the amount of feed added in order to maintain the minimum HRT to prevent waste accumulation. The RAS flowrate determines the fish tank and drum filter volume as described in chapter 2.2 and 2.3. It is assumed that the drum filter volume is linearly correlated to the RAS flowrate. The amount of feed fed in turn determines the trickling filter volume. The backwash flowrate is a factor of the RAS flowrate as described in chapter 2.3. The RAS flowrate can be kept the same when the backwash flowrate is kept between 0.2-1.5% of the RAS flowrate.

Table 5 Nomenclature

symbol	definition
V_t	volume trickling filter (m^3)
V_f	volume fish tank(m^3)
F_s	flow rate RAS (m^3 h^{-1})
V_s	volume settling tank (m^3)
V_d	volume drum filter (m^3)
F_b	flow rate backwash (m^3 h^{-1})

The backwash flowrate has been tested with respect to the settling tank volume. The backwash flowrate has been kept between certain limits, in order to keep the RAS flowrate the same. Subsequently, the RAS flowrate has been changed with respect to the drum filter volume. The fish tank volume is kept the same, resulting in a change in HRT of the fish tank system. The new HRT for the fish tank was kept within the 0.31-1 hour range, which corresponds with the HRT used in literature[32]. This has been done to determine an appropriate waste recycling strategy to minimize TSS concentration in the backwash and to maximize TAN concentration in the system. All dependent design parameters have been changed by 50% to check to the relative effect on minimum and maximum on TSS.

Table 6 Design parameters that are linked to each other

Design parameters	To be considered
F_b, V_s	Yes
F_s, V_d	No
F_s, V_d, V_f, F_b, V_s	Yes, when kept between limits (see chapter 3.2.1)

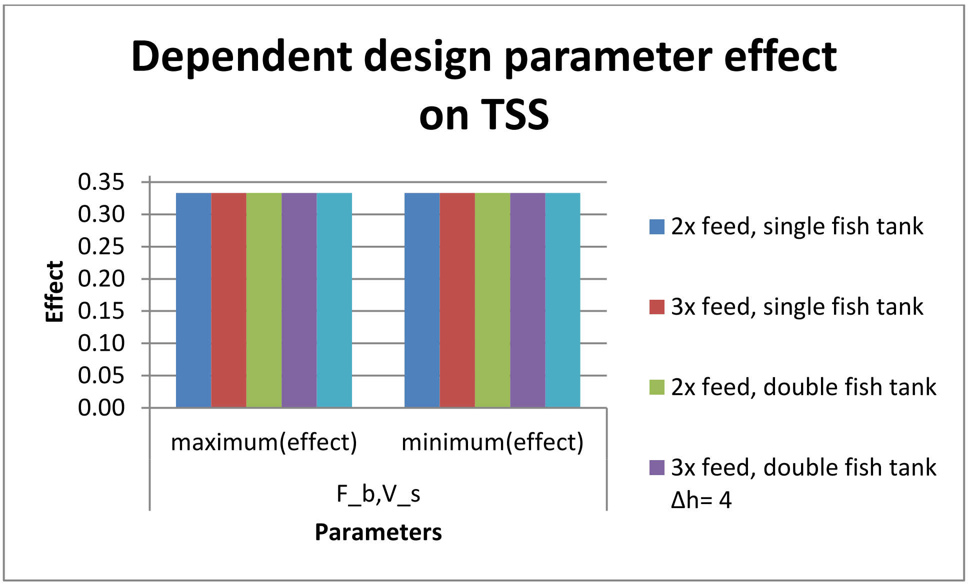

Figure 24 Effect of combined design parameters on TSS concentration in the backwash

The maximum design values for the backwash flowrate has been used for a RAS flowrate of 100 m^3 h^{-1}, maintaining design requirements according to chapter 2.3. The effect of changing these design parameters on the TSS concentration in the backwash is equivalent for all feeding strategies. The maximum and minimum TSS concentration in the backwash are influenced in the same order.

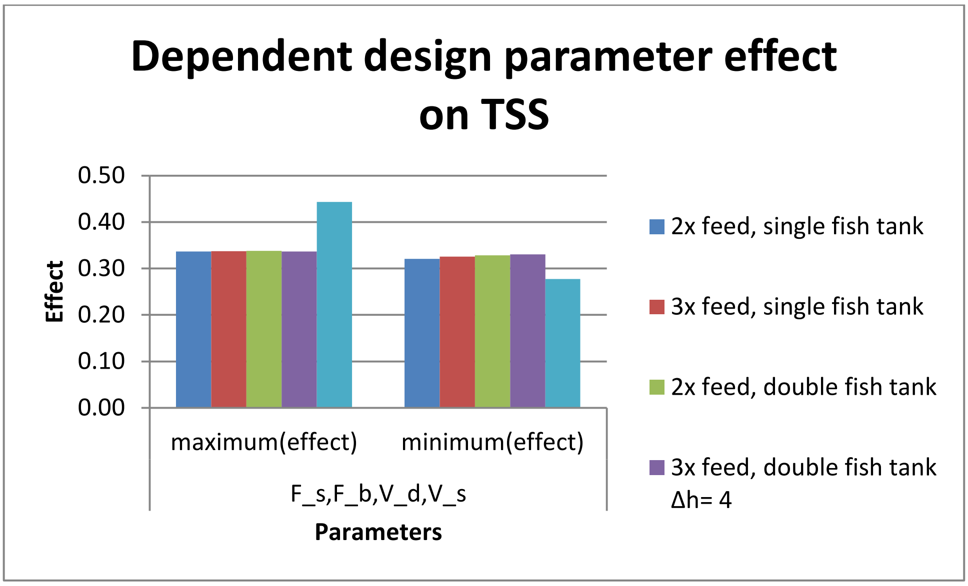

Figure 25 Effect of combined design parameters on TSS concentration in the backwash

The effect of changing all design parameters in the same order resulted in a larger system. The results of this system indicate that maximum and minimum TSS concentrations in the backwash are influenced in comparable order by different feeding strategies. Only a system with a complementary feed of Δ=6h and fed 3 times resulted in significant greater effect on maximum TSS concentration and lower effect on minimum TSS concentration.

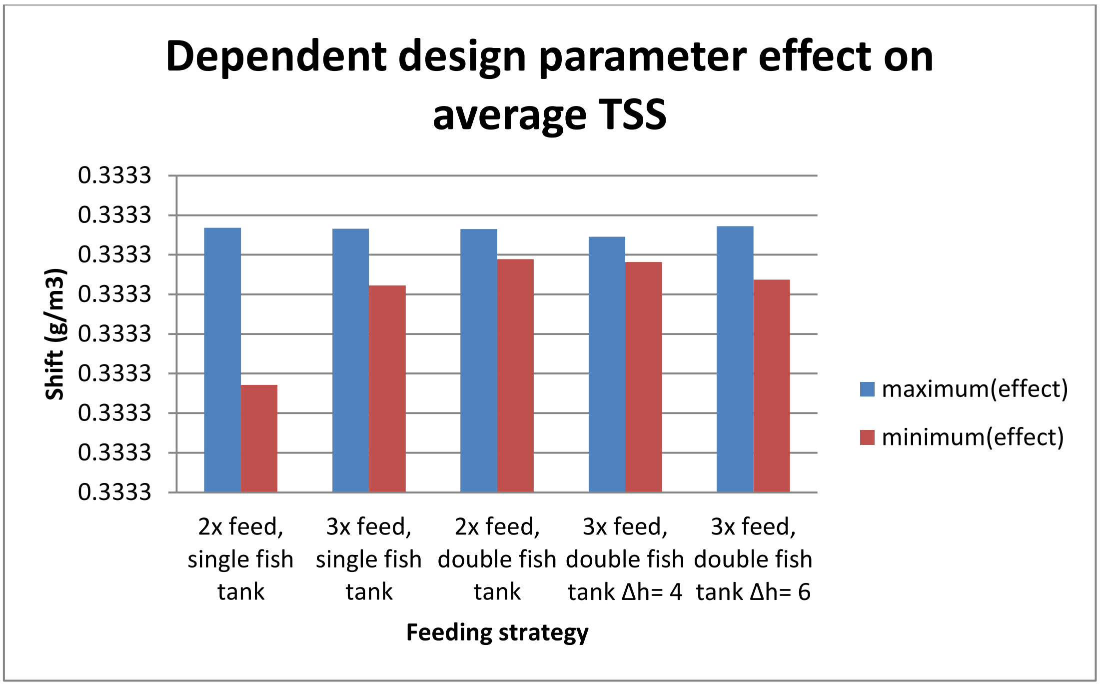

Figure 26 Effect of combined design parameters on the average TSS concentration in the backwash

For a single fish tank system, average TSS concentration in the backwash decreases when the fish are fed more often. For a fish tank system with complementary feed of Δ=4h and Δ=6h fed 3 times, average

TSS concentration does not decrease as much when the fish are fed more often. The effect of all design parameters combined reflect to have a comparable effect on average TSS concentration as the backwash flowrate and settling tank volume.

Due to the fact that changing the combined design parameters backwash flowrate and settling tank volume showed a similar effect on minimum and maximum TSS concentrations in the backwash for each feeding strategy further analysis was performed. Especially because, the backwash is used for discarding waste water to the hydroponics. Where high TSS concentrations in the backwash could lead to damaging the roots of the plants in the hydroponic system. The effect on minimum TSS concentration in the backwash has been tested for different backwash flowrates with the accompanying settling tank volume to maintaining a minimal HRT in the settling tank of 9 hours. The backwash flowrate has been kept between the 0.2-1.5% of the RAS flowrate to maintain proper design requirements.

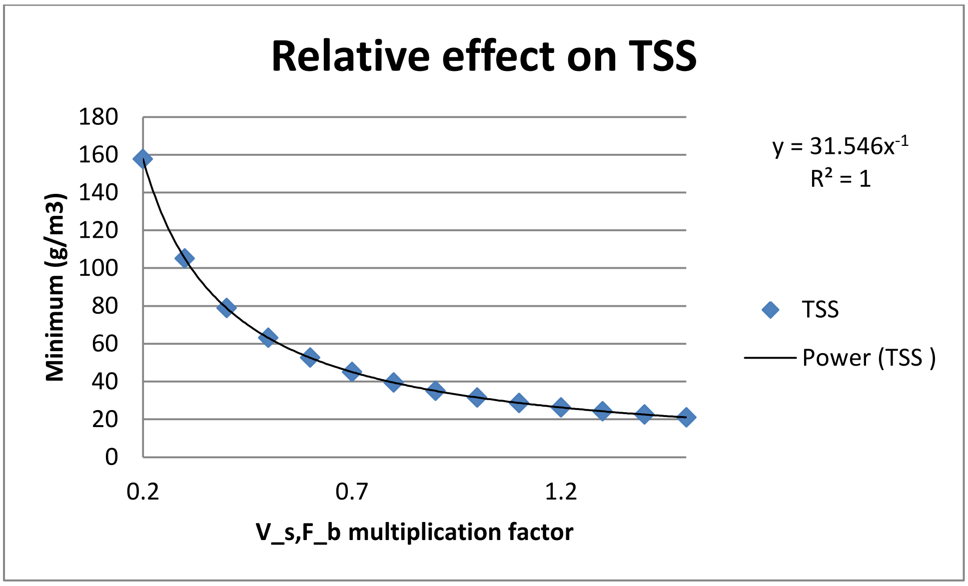

Figure 27 Effect of backwash flowrate with accompanying settling tank volume on the minimum TSS in the backwash

Increasing the backwash flowrate with respect to the settling tank volume can have a great influence on the minimum TSS concentration in the backwash. The minimum TSS concentration is most influenced in systems operating with low backwash flowrates. When operating with greater backwash flowrates the backwash flowrate has little impact, e.g. sizing from 1.4 to 1.5 only deceases 6 % of the minimum TSS concentration in the backwash. The minimum TSS concentration in the backwash can be described as a power function in which x is the multiplication factor of the backwash flowrate and settling tank volume.

The effect of the RAS flowrate on TAN concentrations has also been studied. It has been changed by 50 % and therefore kept within the range to satisfy design requirements. Results can be seen in Figure 28.

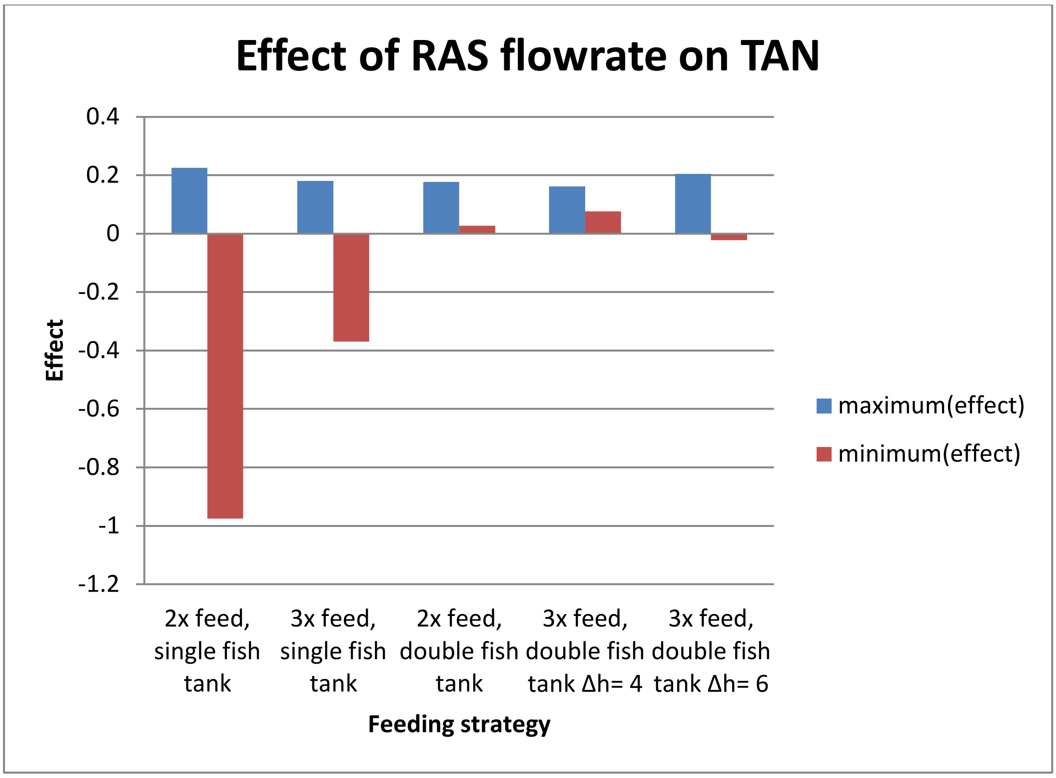

Figure 28 Effect of RAS flowrate on maximum and minimum TAN concentrations in the fish tank system

Figure 28 shows that the RAS flowrate has a negative effect on maximum TAN concentrations and is relatively equal for each feeding strategy. Furthermore, it can be said that the minimum TAN concentrations are reduced the most for fewer feeding frequencies and single fish tank systems. The RAS flowrate has a positive effect on RAS systems fed more than 4 times per day.

4.3 Optimizing conditions

Analysing the effect of design parameters on the maximum TAN and minimum TSS concentration helps finding improved conditions to recycle water to the NFT production system. The influence of different RAS flowrates with the accompanying drum filter volume has been analysed. The backwash flowrate has been adjusted for every RAS flowrate maintaining the 0.2-1.5% design requirement. By changing the backwash flowrate the settling tank volume has also been adjusted in the same order. This has been done for the first 3 feeding strategies (Table 3), resulting in Figure 29, Figure 30 and Figure 31.

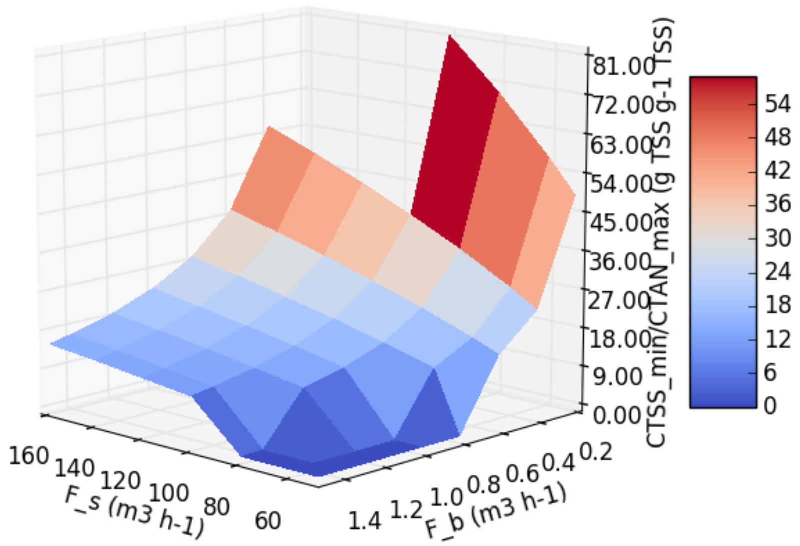

Figure 29 Minimum TSS in relation to maximum TAN determined by design parameters for feeding strategy 1

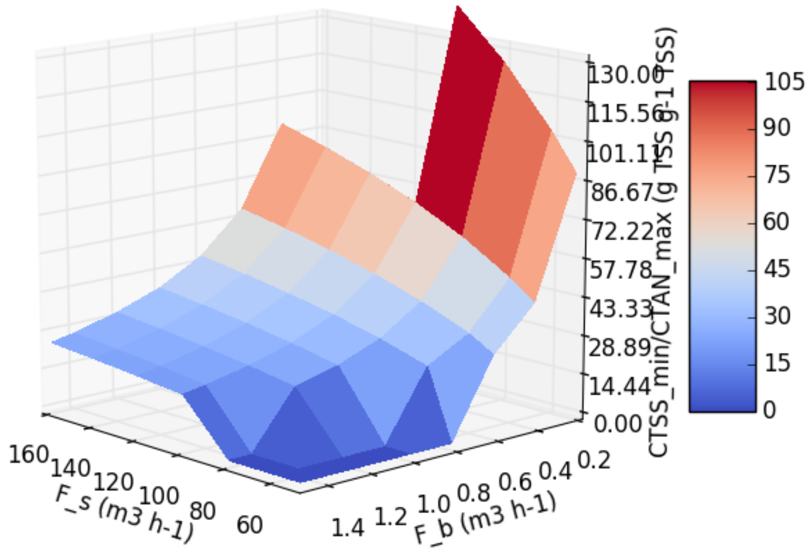

Figure 30 Minimum TSS in relation to maximum TAN determined by design parameters for feeding strategy 2

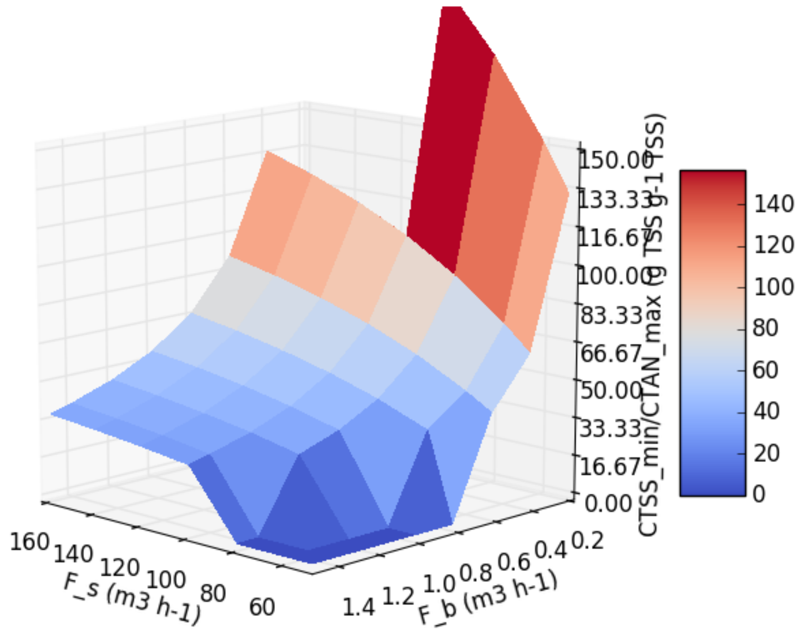

Figure 31 Minimum TSS in relation to maximum TAN determined by design parameters for feeding strategy 3

The TSS:TAN ratio has been analysed for different RAS designs and different feeding strategies in order to determine the appropriate strategy for recycling water. The ratio is based on minimum TSS concentration divided by maximum TAN concentration. It can be seen that for all feeding strategies the backwash flowrate is the most important factor for reducing TSS:TAN ratio. Also, one can determine that applying a higher RAS flowrate has a positive influence on the ratio TSS:TAN ratio. Feeding more frequent has a negative influence on the ratio, increasing it by 1.64-1.85 times. Feeding in complementary has an even more negative effect increasing it by 2.41-2.67 times. Values for backwash flowrate that do not match design requirements for the RAS flowrate have not been analysed, the resulting TSS:TAN ratio has been set to nil.

Unfortunately, TSS and TAN concentration changes reflect same behaviour in the backwash independent from feeding strategy. Maximum TAN concentrations are therefore never reached when minimum TSS concentrations are present (Appendix C). A solution to reach the TSS:TAN ratios given in Figure 29, Figure 30 and Figure 31 would be to recycle backwash water to a second settling tank when maximum TAN concentrations are reached. This second settling tank could potentially reduce TSS concentrations to the levels measured in this RAS model.

A simple solution is to recycle water from another place in the RAS where TSS concentrations are low and TAN concentrations are high. Results in Appendix C indicated that TSS concentrations are minimized after the drum filter and before the fish tank system and TAN concentrations are maximized after the fish tank system and before the trickling filter. Therefore, the strategy for recycling water from the permeate is compared to that of the backwash. The maximum and minimum TAN and TSS concentrations, with the accompanying TSS and TAN concentrations were compared. This resulted in the bad and appropriate strategies for disposing water to the hydroponic system. Results based on hourly excretion for feeding strategies 1, 2 and 3 are given in Figure 32-Figure 39.

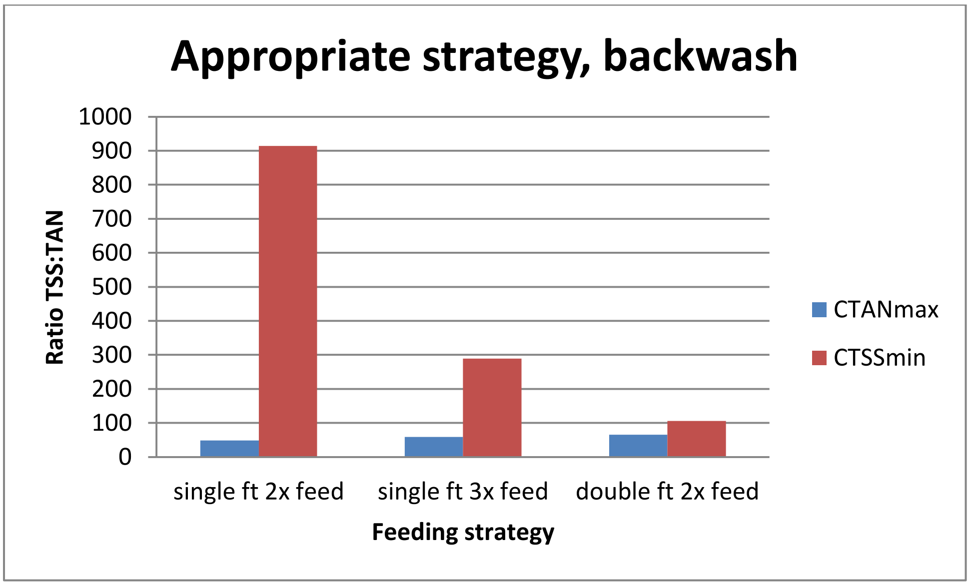

Figure 32 Appropriate strategy for recycling water from the backwash to the hydroponic system in relation to the ratio TSS:TAN for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

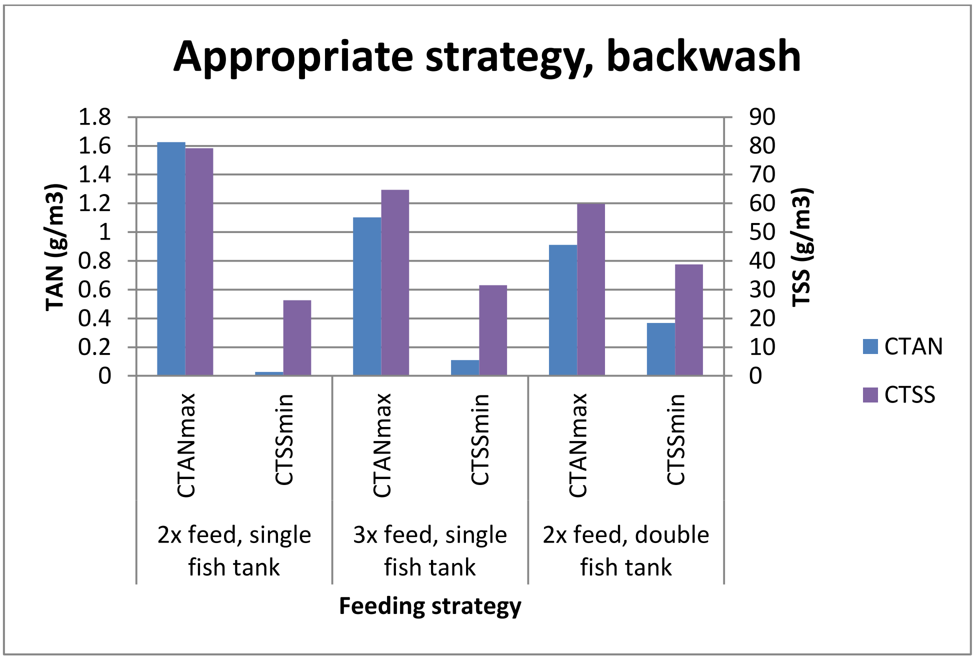

Figure 33 Appropriate strategy for recycling water from the backwash to the hydroponic system in relation to TAN and TSS concentrations for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

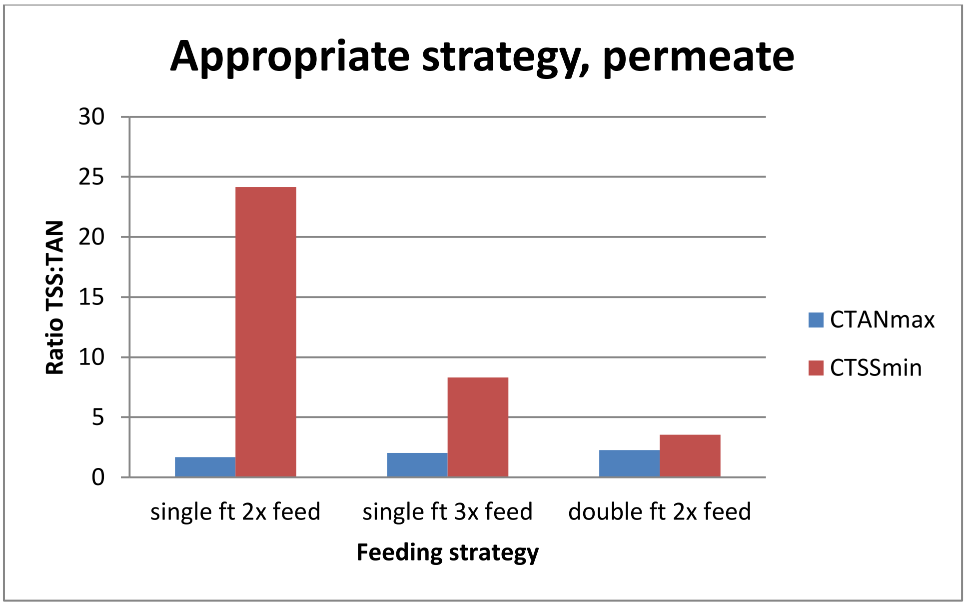

Figure 34 Appropriate strategy for recycling water from the permeate to the hydroponic system in relation to the ratio TSS:TAN for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

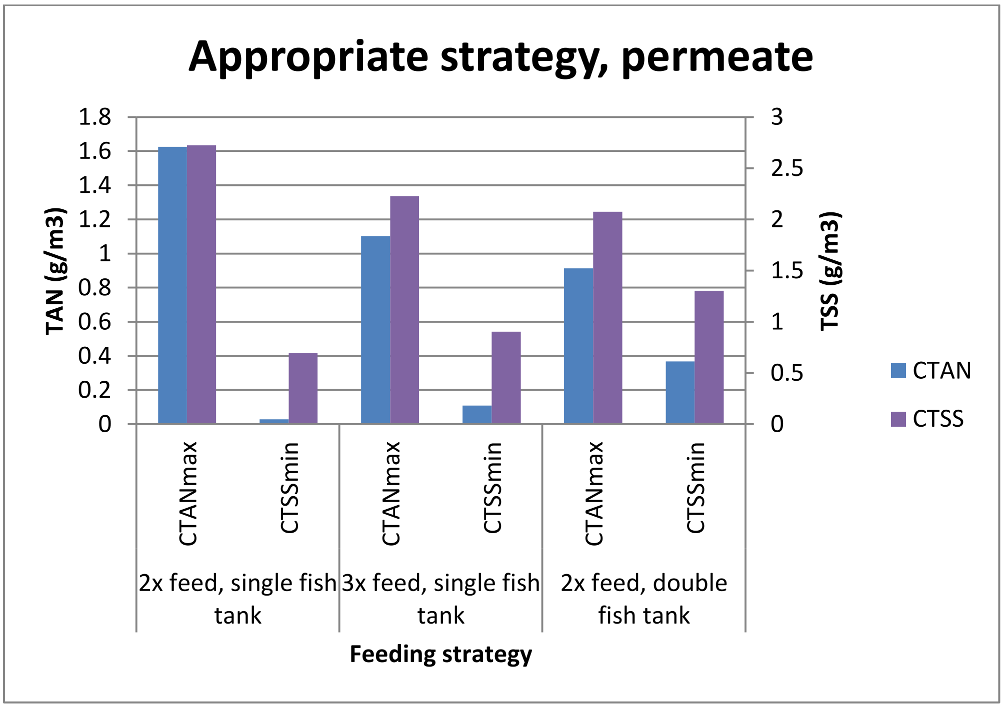

Figure 35 Appropriate strategy for recycling water from the permeate to the hydroponic system in relation to TAN and TSS concentrations for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

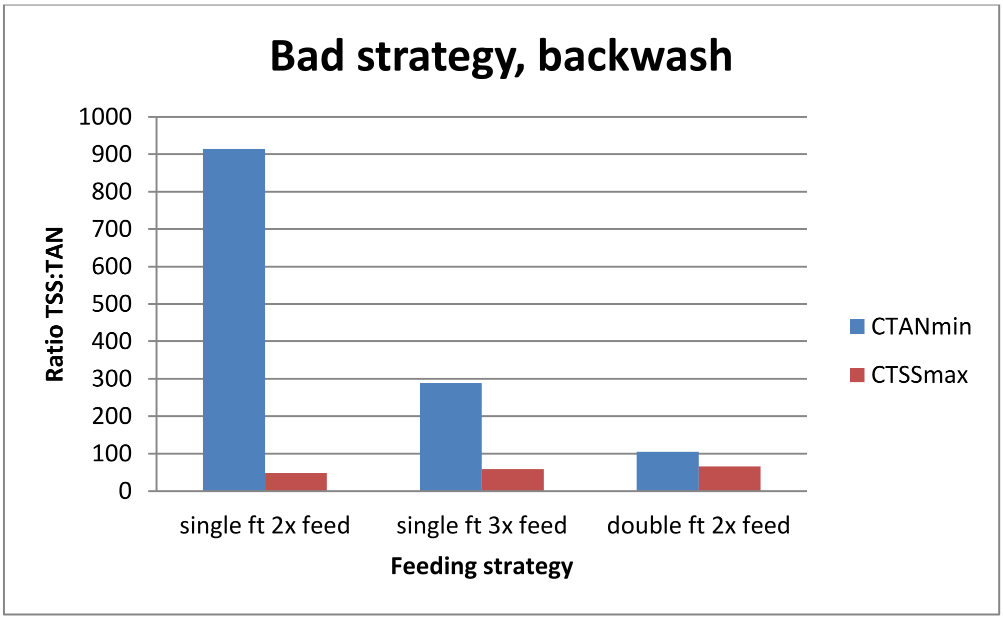

Figure 36 Bad strategy for recycling water from the backwash to the hydroponic system in relation to the ratio TSS:TAN for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

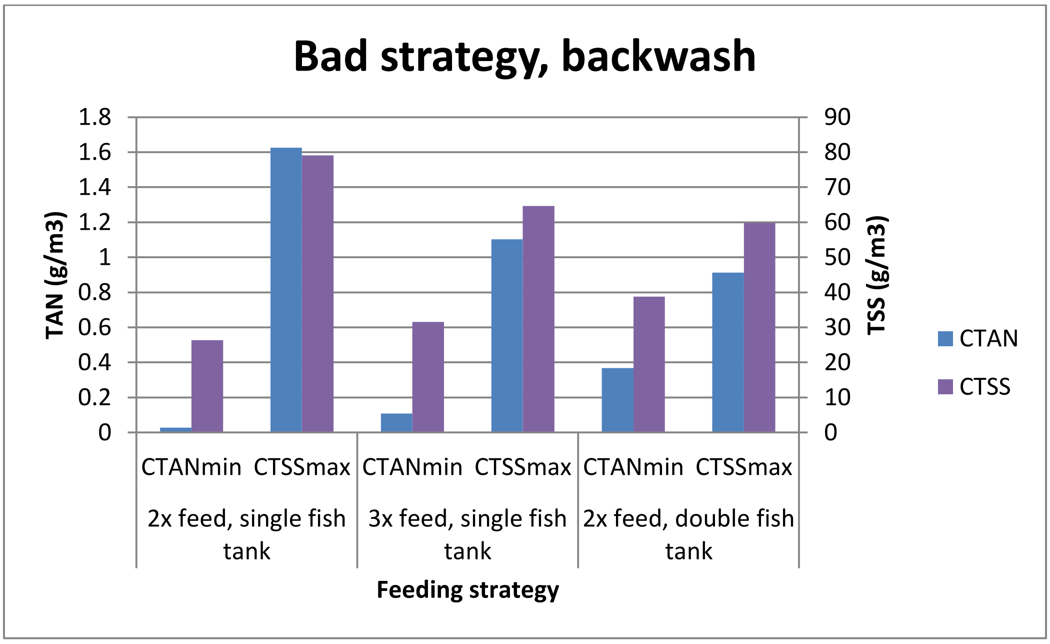

Figure 37 Bad strategy for recycling water from the backwash to the hydroponic system in relation to TAN and TSS concentrations for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

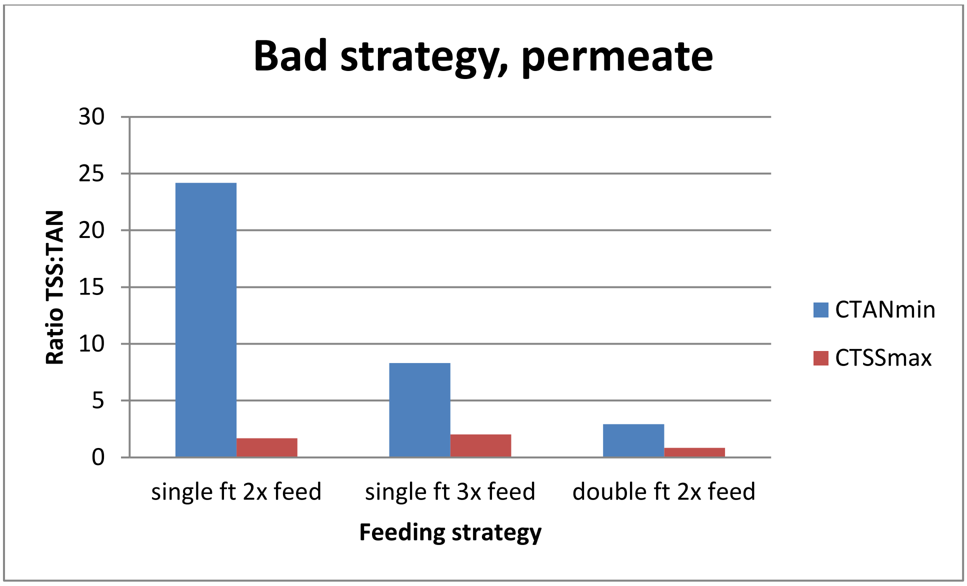

Figure 38 Bad strategy for recycling water from the permeate to the hydroponic system in relation to the ratio TSS:TAN for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

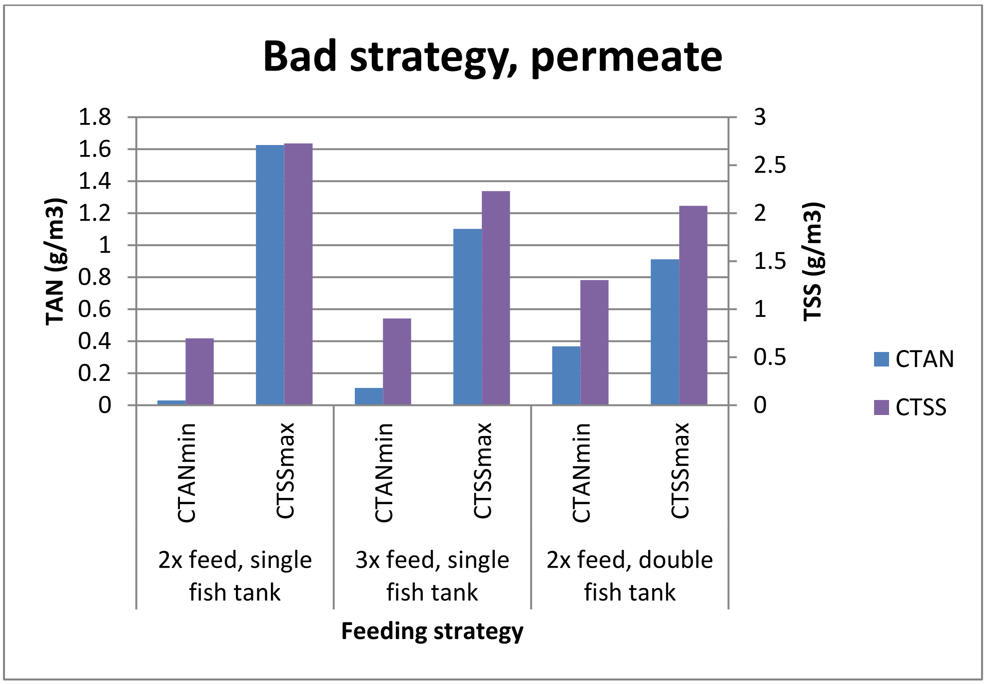

Figure 39 Bad strategy for recycling water from the permeate to the hydroponic system in relation to TAN and TSS concentrations for 3 feeding strategies by minimizing TSS concentrations and maximizing TAN concentrations

Figure 32, Figure 34, Figure 36 and Figure 38 show that the appropriate and bad strategy for recycling water to the hydroponic system from the permeate is always better than from the backwash, independent from feeding strategy. Furthermore, the impact of a bad strategy for recycling water from the permeate or the backwash to the hydroponic system is decreased when feeding frequency is increased or when a system with complementary feeding time is applied. Also, results show that maximizing TAN concentrations and not minimizing TSS concentrations is the appropriate strategy for recycling water from the permeate or the backwash to the hydroponic system.

5 Conclusion

A functional model has been made which describes the hourly excretion by tilapia and its influence on TAN and TSS concentrations within different compartments of a commercial RAS. Different feeding strategies were tested to examine their influence on TAN and TSS concentrations. By changing the design parameters for each feeding strategy, the system dynamics have been manipulated in order to optimize water quality sent to the hydroponic system(high TAN concentrations and low TSS concentrations have been aimed for). By minimizing the TSS:TAN ratio an appropriate strategy for recycling water to the hydroponic system has been proposed.

Effect of modelling hourly excretion

For a single fish tank system fed 2 times per day, TAN concentrations between the fish tank system and the trickling filter fluctuate between 1.625-0.029 mg L^{-1} and TSS concentrations in the backwash fluctuate between 79.130-26.344 mg L^{-1} (Figure 20 and Figure 21). These different concentrations result in fluctuations in the TSS:TAN ratios found in the backwash. Fluctuating in single fish tank systems from 2728.6-16.2 for fish fed 2 times per day and 593.1-28.6 for fish fed 3 times per day.

For complementary systems, TSS:TAN ratios fluctuate over time from 162.4-42.6 for fish fed 2 times per day. These fluctuations make it important to incorporate hourly excretion of the fish in order to determine the appropriate strategy for recycling water to the hydroponic system.

Impact of feeding strategy

When the feeding frequency is increased minimum concentrations increase and maximum concentrations decrease for TAN and TSS. This observation has also been made for complementary systems (chapter 4.1). By applying a complementary system for fish fed 2 times per day minimum TAN concentrations have been increased by 1269% and maximum TAN concentrations have been decreased by 56% (Figure 21). However, the problem remains that maximum TAN concentrations in the fish tank systems do not decrease significantly (Figure 47 and Figure 48). This is caused by the fact that the amount of feed fed to the fish remains a ratio between the fish tank system volume and therefore decreases in the same order(e.g. fish fed half the amount of feed consist of half the fish population and are therefore kept in half the fish tank system volume). Consequently, this does not result in a system in which more fish can be grown or RAS flowrates can be reduced. Fish fed more frequent results in higher minimum TAN and TSS concentrations and lower maximum TAN and TSS concentrations. This is caused by the fact that less feed is given per fed, which results in lower amounts of excretion (Figure 20 and Figure 21). Furthermore, more frequent feeding results in shorter post–prandial excretion therefore increasing minimum concentrations (chapter 3.2). Increasing feeding frequencies does result in lower maximum concentrations and can contribute to systems in which more fish can be grown per fish tank system volume or RAS flowrates can be reduced. Decreasing feeding frequencies and using single fish tank systems results in higher fluctuations between maximum and minimum TAN and TSS concentrations. This in turn results in a lower TSS:TAN ratios and is therefore increasingly interesting for timing proper water recycling strategies to the hydroponic systems.

Impact of design parameters

Design parameters that influence the TSS:TAN ratio are the RAS flowrate and the backwash flowrate and their accompanying design parameter to maintain proper HRTs (chapter 4.2). Increasing the backwash flowrate decreases the minimum TSS concentration in the backwash (Figure 24). Additionally, by increasing the RAS flowrate minimum TSS concentrations in the backwash are slightly decreased and maximum TAN concentrations after the fish tank system are decreased (Figure 25 and Figure 28). The resulting TSS:TAN ratio in the backwash is therefore lowest when applying low RAS flowrates and high backwash flowrates unrelated to the feeding strategy that is applied (Figure 29, Figure 30 and Figure 31).

Recommendations

Firstly, it is important to incorporate hourly excretion in the model since TAN and TSS concentration fluctuate significantly for each feeding strategy (Appendix C). By doing so the appropriate time can be determined to recycle water to the hydroponic system. Secondly, it is advised not to use complementary fish tank systems, since complementary systems showed a negative effect on the TSS:TAN ratio (65.5 instead of 48.7; 66.0 instead of 58.7) (Figure 31) and did not have any significant effect on reducing TAN concentrations in the fish tank system, which would enable the possibility to increase the fish production capacity (Figure 47 and Figure 48). Thirdly, feeding more frequently also has an adverse effect on the TSS:TAN ratio increasing the TSS:TAN ratio from 10.8 for 2 fed per day to 19.1 for 3 fed per day (Figure 30). Although, maximum TAN concentrations are reduced significantly from 1.625 mg L^{-1} for 2 fed per day to 1.102 mg L^{-1} for 3 fed per day (Figure 20), by decreasing the RAS flow rate TAN concentrations can be increased again (Figure 28). The TSS:TAN ratio can then be brought back to approximately 12.9. Due to the higher yield of fish by feeding more frequently and the possibility to reduce the RAS flowrate to reduce TSS:TAN ratios it is not advised to reduce the feeding frequency. Fourthly, independent from the feeding strategy it is advised to increase the backwash flowrate with the required settling tank volume to its maximum capacity to reduce minimum TSS in the backwash (Figure 24). The RAS flowrate should be kept as low as possible to increase TAN concentrations as much as possible, keeping in mind that TAN should not reach toxic concentrations. However, recycling the backwash water does require an extra settling tank, since the aforementioned TSS and TAN concentrations do not occur at the same in the backwash. The extra settling tank can therefore be used to reduce the TSS further to reach the ratios shown by Figure 29, Figure 30 and Figure 31. Fifthly, it is advised to use the permeate instead of the backwash to recycle water, since equivalent TAN and lower TSS concentrations occur in this flow (Figure 33 and Figure 35), resulting in better TSS:TAN ratios (Figure 32 and Figure 34). Lastly, to improve TSS:TAN ratios further when recycling water, the RAS flowrate can be decreased temporarily to increase TAN concentrations and slightly increase TSS concentration in the permeate assuming good performance of the drum filter.

Model limitations

Each module of the system was based on data from literature [3, 4, 9, 47]. The excretion model from literature describes gastric evacuation based on V_0, which is assumed to be constant in this model.. Furthermore, it is assumed that the excretion of TAN reflects same dynamics as the gastric evacuation. The drum filter volume in this system does not influence the drum filter efficiency significantly. In reality this is not the case, a smaller drum filter should result in lower TSS retention efficiencies due to a lower HRT and a smaller surface area for solids capture. In this module it is assumed that the drum filter efficiency is maintained the same when the dimension is increased in the same proportion as the RAS flowrate. In reality each system should be considered separately according to literature [37]. The module that describes the settling tank efficiency is based on a model from literature that describes the settling tank efficiency in a RAS for salmon and rainbow trout. This could result in an overestimation of the settling efficiency since faeces of tilapia have a form of faecal casing making it less dense and therefore less susceptible for settling [35]. Furthermore, it is assumed that the TAN excreted in the particulates is retained by the settled tank and stay within the particulates. In reality they can be degraded by organisms in the sludge, resulting in an increase in TAN concentrations. The module that describes the trickling filter is based on a model from literature, which gives an approximation for the dynamics of a trickling filter. The model from literature is based on a few parameters, such as D_w, D_e, D and L_w. The value of these parameters have been taken from other experimental work. The value of these parameters can differ from research to research and therefore give an approximation. The main problem is that L_w decreases when the turbulence increases due to a higher RAS flowrate. The module that has been made for the trickling filter does not take turbulence into account and can therefore over or underestimate the nitrification rate of the trickling filter [47]. The r_{TAN}^{max} is based on the optimal conditions for nitrifying bacteria in a biofilm without a stagnant layer. This can give an overestimation of reality, since the r_{TAN}^{max} in reality is influenced by multiple factors [5]. The maximum value found in this research was 0.925 g TAN m^{-2} d^{-1}, which lies close to the reported 0.9 g TAN m^{-2} d^{-1} [51].

The model describing the TSS concentration in the backwash and the system in chapter 3.2 corresponds to values found in literature [7, 38]. The model describing the TAN concentrations does not exceed the maximum TAN concentrations that forms a toxic environment for tilapia [2]. Furthermore, the great fluctuations in TAN concentrations due to modelling hourly excretion found in this study has also been described in previous studies [21, 22, 52]. It can therefore be said that the model resembles dynamics found in real systems. However, the model still needs to be validated in order to prove precision.

6 Acknowledgement

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Uncategorized References

1. INAPRO. *inapro-project*. [cited 2016 28-12].
2. Timmons, M.B. and J.M. Ebeling, *Water Quality Design Targets*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 88-95.
3. Summerfelt, S., J. Bebak-Williams, and S. Tsukuda, *Controlled systems: water reuse and recirculation.* Fish Hatchery Management, Second Ed.. American Fisheries Society, Bethesda, MD, 2001.
4. Bergheim, A., S.J. Cripps, and H. Liltved, *A system for the treatment of sludge from land-based fish-farms.* Aquatic Living Resources, 1998. **11**(4): p. 279-287.
5. Chen, S., J. Ling, and J.-P. Blancheton, *Nitrification kinetics of biofilm as affected by water quality factors.* Aquacultural Engineering, 2006. **34**(3): p. 179-197.
6. Tidwell, J., *Hydroponic subsystems*, in *Aquaculture production systems*. 2012, John Wiley & Sons. p. 360-362.
7. Goddek, S., et al., *Navigating towards decoupled aquaponic systems: A system dynamics design approach.* Water, 2016. **8**(7): p. 303.
8. Li, L. and A. Yakupitiyage, *A model for food nutrient dynamics of semi-intensive pond fish culture.* Aquacultural Engineering, 2003. **27**(1): p. 9-38.
9. Riche, M., et al., *Effect of feeding frequency on gastric evacuation and the return of appetite in tilapia Oreochromis niloticus (L.).* Aquaculture, 2004. **234**(1-4): p. 657-673.
10. Wik, T.E., B.T. Lindén, and P.I. Wramner, *Integrated dynamic aquaculture and wastewater treatment modelling for recirculating aquaculture systems.* Aquaculture, 2009. **287**(3): p. 361-370.
11. KHATER, E.-S.G.E.-S., *SIMULATION MODEL FOR DESIGN AND MANAGEMENT OF WATER RECIRCULATING SYSTEMS IN AQUACULTURE*. 2012, BENHA UNIVERSITY.

12. Riche, M., et al., *Effect of feeding frequency on consumption, growth, and efficiency in juvenile tilapia (Oreochromis niloticus).* 2004.
13. Eding, E., *Question on fish feed and biofilter load*, M.v.d. Ham and D. Lastiri, Editors. 2016, Wageningen University & Research.
14. Wik, T., *On Modeling the Dynamics of Fixed Biofilm Reactors. With focus on nitrifying trickling filters*. 1999: Chalmers University of Technology.
15. Pérez, F. and B.E. Granger, *IPython: A System for Interactive Scientific Computing.* Computing in Science and Engineering. **9**(3): p. 21-29.
16. Forsberg, O., *The impact of varying feeding regimes on oxygen consumption and excretion of carbon dioxide and nitrogen in post-smolt Atlantic salmon Salmo salar L.* Aquaculture research, 1997. **28**(1): p. 29-41.
17. Losordo, T.M. and A.O. Hobbs, *Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems.* Aquacultural Engineering, 2000. **23**(1): p. 95-102.
18. Timmons, M.B. and J.M. Ebeling, *Production Terms*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 87.
19. Brunty, J., et al., *The influence of feed protein intake on tilapia ammonia production.* Aquacultural engineering, 1997. **16**(3): p. 161-166.
20. Riche, M., et al., *Effect of feeding frequency on gastric evacuation and the return of appetite in tilapia Oreochromis niloticus (L.).* Aquaculture, 2004. **234**(1): p. 657-673.
21. Zakêœ, Z.a. and K. Demska-Zakêœ, *The influence of feeding frequency on the metabolic rate of perch Perca fluviatilis L.* 2002.
22. Lee, S.-M., U.-G. Hwang, and S.H. Cho, *Effects of feeding frequency and dietary moisture content on growth, body composition and gastric evacuation of juvenile Korean rockfish (Sebastes schlegeli).* Aquaculture, 2000. **187**(3): p. 399-409.
23. El-Sayed, A.-F.M. and M. Kawanna, *Effects of photoperiod on the performance of farmed Nile tilapia Oreochromis niloticus: I. Growth, feed utilization efficiency and survival of fry and fingerlings.* Aquaculture, 2004. **231**(1): p. 393-402.
24. Biswas, A.K. and T. Takeuchi, *Effect of different photoperiod cycles on metabolic rate and energy loss of fed and unfed adult tilapia Oreochromis niloticus: Part II.* Fisheries science, 2002. **68**(3): p. 543-553.
25. El-Sayed, A.F.M. and M. Kawanna, *Effects of photoperiod on growth and spawning efficiency of Nile tilapia (Oreochromis niloticus L.) broodstock in a recycling system.* Aquaculture Research, 2007. **38**(12): p. 1242-1247.
26. Rad, F., et al., *Effects of different long-day photoperiods on somatic growth and gonadal development in Nile tilapia (Oreochromis niloticus L.).* Aquaculture, 2006. **255**(1): p. 292-300.
27. Timmons, M.B. and J.M. Ebeling, *Waste Characteristics*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 251-253.
28. Pedersen, L.-F., et al., *Effects of feed loading on nitrogen balances and fish performance in replicated recirculating aquaculture systems.* Aquaculture, 2012. **338**: p. 237-245.
29. Timmons, M.B. and J.M. Ebeling, *Design Examples*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 101-114.
30. Timmons, M.B. and J.M. Ebeling, *Design Example: Trickling Tower*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 348-353.
31. Timmons, M.B. and J.M. Ebeling, *Design Examples*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 127-129.
32. Timmons, M.B. and J.M. Ebeling, *Design Example - Solids Capture*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 224.
33. Patterson, R. and K. Watts, *Micro-particles in recirculating aquaculture systems: microscopic examination of particles.* Aquacultural engineering, 2003. **28**(3): p. 115-130.
34. Khater, E.-S.G., et al., *Solids removal in a recirculating aquaculture system.* MJ of Agric. Eng, 2011. **28**(4): p. 1178-1196.
35. Timmons, M.B. and J.M. Ebeling, *TSS Physical Characteristics*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 183-184.
36. Chen, S., et al., *Suspended solids characteristics from recirculating aquacultural systems and design implications.* Aquaculture, 1993. **112**(2-3): p. 143-155.
37. Timmons, M.B. and J.M. Ebeling, *Removal Mechanisms*, in *Recirculating Aquaculture*, M.B. Timmons and J.M. Ebeling, Editors. 2010, Cayuga Aqua Ventures: Ithaca, NY. p. 185-213.
38. Kelly, L., A. Bergheim, and J. Stellwagen, *Particle size distribution of wastes from freshwater fish farms.* Aquaculture International, 1997. **5**(1): p. 65-78.
39. Cripps, S.J., *Serial particle size fractionation and characterisation of an aquacultural effluent.* Aquaculture, 1995. **133**(3): p. 323-339.
40. McMillan, J., et al., *Pumping effect on particle sizes in a recirculating aquaculture system.* Aquacultural Engineering, 2003. **27**(1): p. 53-59.
41. Vermue, M., *Drum filters*, M.v.d. Ham, Editor. 2016, Wageningen University & Research.
42. A., K.A., *The effect of feed ingredients on the settling velocity of feces in tilapia (Oreochromis niloticus L.).* Iranian Journal of Fisheries Sciences 2012. **12**(2): p. 5.
43. Khater, E., *Settleable solids at different settling velocities*, in *SIMULATION MODEL FOR DESIGN AND MANAGEMENT OF RECIRCULATING SYSTEMS*. 2015. p. 208-209.
44. Bratby, J., *Introduction*, in *Coagulation and Flocculation in Water and Wastewater Treatment*. 2006, IWA Publishing: London. p. 240-241.

45. Cripps, S.J. and A. Bergheim, *Solids management and removal for intensive land-based aquaculture production systems.* Aquacultural engineering, 2000. **22**(1): p. 33-56.
46. Gujer, W. and M. Boller, *Design of a nitrifying tertiary trickling filter based on theoretical concepts.* Water Research, 1986. **20**(11): p. 1353-1362.
47. Hamdi, M., *Biofilm thickness effect on the diffusion limitation in the bioprocess reaction: Biofloc critical diameter significance.* Bioprocess engineering, 1995. **12**(4): p. 193-197.
48. Stewart, P.S., *Diffusion in biofilms.* Journal of bacteriology, 2003. **185**(5): p. 1485-1491.
49. Schramm, A., et al., *Structure and function of a nitrifying biofilm as determined by in situ hybridization and the use of microelectrodes.* Applied and Environmental Microbiology, 1996. **62**(12): p. 4641-4647.
50. Greiner, A.D. and M.B. Timmons, *Evaluation of the nitrification rates of microbead and trickling filters in an intensive recirculating tilapia production facility.* Aquacultural Engineering, 1998. **18**(3): p. 189-200.
51. Ebeling, J.M., *Biofiltration-Nitrification Design Overview.*
52. TWAROWSKA, J., P. WESTERMAN, and T. LOSORDO, *Water treatment and waste characterization evaluation of an intensive recirculating fish production system.* Aquacultural engineering, 1997. **16**(3): p. 133-147.

7 Appendices

7.1 Appendix A

Symbol list:

Compartments within the RAS:

Concentrations within different compartments of the RAS are defined by the subscript x in the variable list. The compartments found in the RAS can be defined by the following subscripts:

f = out of the fish tank system
f,c = out of the combined fish tank system
t = out of the trickling filter
s = to the settling tank
d = to the trickling filter
b = in the backwash
a = to the aquaponic system
r = retained by the settling tank
i = certain level of the trickling filter

Variables:

t = time post-prandial (h)
R_f = amount of feed added every fed (g feed)
V_T = volume of feed at time t
P_T = fraction of feed undigested at time t
$P_{T,T+\tau}$ = percentage of excreted feed between two time points (% h^{-1})
P_{TAN} = waste production TAN by fish (g TAN h^{-1})
P_{TSS} = waste production TSS by fish (g TSS h^{-1})
$C_{TAN,x}$ = concentration TAN in compartment x (g m^{-3})
$C_{TSS,x}$ = concentration TSS in compartment x (g m^{-3})
$C_{NO3,x}$ = concentration NO_3 in compartment x (g m^{-3})
η_d = drum filter efficiency (-)
V_s = volume of settling tank (m3)
η_s = efficiency of the settling tank (-)
$M_{TSS}(t_2)$ = TSS captured in the sludge of the settling tank at time t_2 (kg)
$r_{TAN,i}$ = consumption rate of TAN in a certain level of the trickling filter (g m^{-3} h^{-1})
t_2 = final time of system (h)
$M_{NO3}(t_2)$ = total amount of NO_3 within the system at time t_2 (g)
$C_{NO3}(t_2)$ = concentration of NO_3 within the system at time t_2 (g m^{-3})
effect = relative effect of changing a design parameter (-)
Δ = feeding interval (h)

Parameters:	**Value**
V_0 = volume of feed at time 0	
b = the instantaneous evacuation rate	
τ = time step (h)	1
PC = protein content in feed (%)	0.35
X_{TAN} = an approximation of TAN excreted	0.092
X_{TSS} = an approximation of TSS excreted	0.25
F_s = flowrate through the RAS (m^3 h^{-1})	100

n_f = number of fish tanks	
V_f = total fish tank system volume (m^3)	50
HRT_f = total hydraulic retention time of the fish tanks (h)	0.5
$V_{f,d}$ = half of the total fish tank system volume (m^3)	25
$F_{s,d}$ = half of the total flowrate through the RAS (m^3 h^{-1})	50
d = fraction of F_s used for backwash	0.01
ε = machine epsilon	10^{-8}
V_d = drum filter volume (m3)	1.6
HRT_d = hydraulic retention time of the drum filter (h)	
F_b = flow rate used for the backwash (m^3 h^{-1})	1
d = fraction of F_s used for backwash	0.01
HRT_s = hydraulic retention time of the settling tank (h)	9
μ_{max} = maximum growth rate at 25 °C (h^{-1})	0.0521
k_s = half saturation constant at 25 °C (g m^{-3})	0.144
n_t = number of CSTR trickling filters modelled (-)	5
V_t = total trickling filter volume (m^3)	9.81
$V_{t,i}$ = volume of one block of a trickling filter (m^3)	2
L_w = thickness of the stagnant layer (m)	$2*10^{-4}$
D = average thickness of the biofilm (m)	$2*10^{-4}$
D_w = diffusion coefficient of TAN through water (m^2 h^{-1})	$7.09*10^{-6}$
D_e = diffusion coefficient of TAN through the biofilm (m^2 h^{-1})	$5.46*10^{-6}$
$Y_{N/T}$ = stoichiometric ratio (mol NO_3 mol TAN^{-1})	0.98
MW_{TAN} = molar weight TAN (g mol^{-1})	18
r_{TAN}^{max} = maximum consumption rate TAN (g m^{-3} h^{-1})	31.66
t_1 = initial time at which the system starts (h)	0

*Commonly used percentage in commercial aquaculture

Estimated Parameters:*	**Value**
a = volume of feed at time 0	95.7
c = the instantaneous evacuation rate	0.318
p_1 = maximum fraction of solids retained by the drum filter	0.86
p_2 = exponential relation in retention of solids in the drum filter	1.47
p_3 = maximum fraction of solids retained by the drum filter	0.889
p_4 = exponential relation in retention of solids in the drum filter	0.046

7.2 Appendix B

	single fish tank		double fish tank		
feeding time	double feed	triple feed	double feed	triple feed (Δ=4h)	triple feed (Δ=6h)
0:00			x (ft2, 6.875 kg)		x (ft2, 4.583 kg)
1:00					
2:00				x (ft2, 4.583 kg)	
3:00					
4:00					
5:00					
6:00	x(13.75 kg)	x(9.166 kg)	x (ft1, 6.875 kg)	x (ft1, 4.583 kg)	x (ft1, 4.583 kg)
7:00					
8:00					
9:00					
10:00				x (ft1, 4.583 kg)	
11:00					
12:00	x(13.75 kg)	x(9.166 kg)	x (ft1, 6.875 kg)		x (ft1, 4.583 kg)
13:00					
14:00				x (ft1, 4.583 kg)	
15:00					
16:00					
17:00					
18:00		x(9.166 kg)	x (ft2, 6.875 kg)	x (ft2, 4.583 kg)	x (ft1, 4.583 kg), x (ft2, 4.583 kg)
19:00					
20:00					
21:00					
22:00				x (ft2, 4.583 kg)	x (ft2, 4.583 kg)
23:00					

7.3 Appendix C

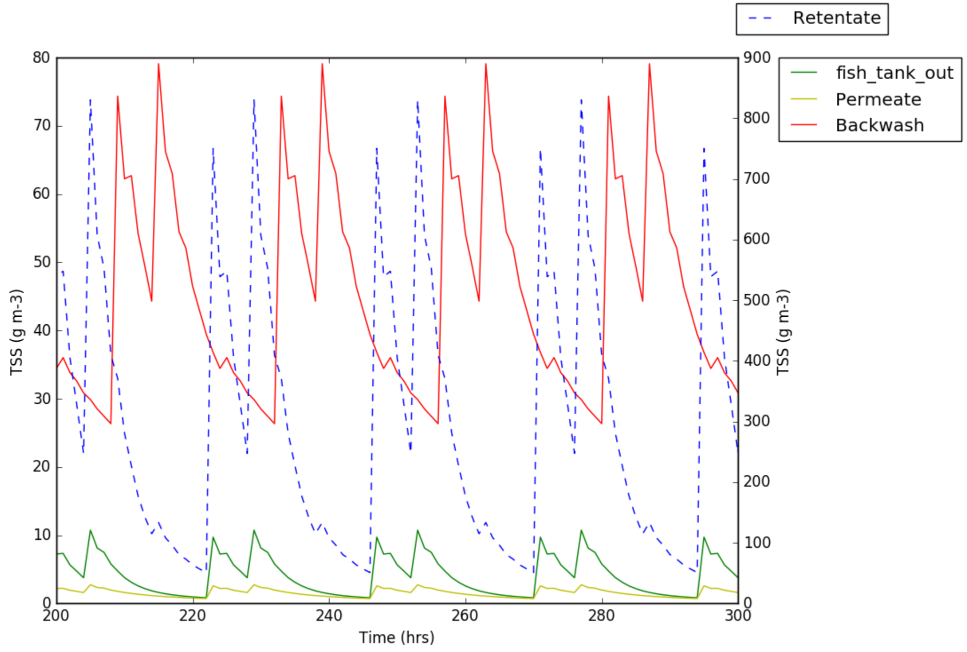

Figure 41 TSS feeding strategy 1

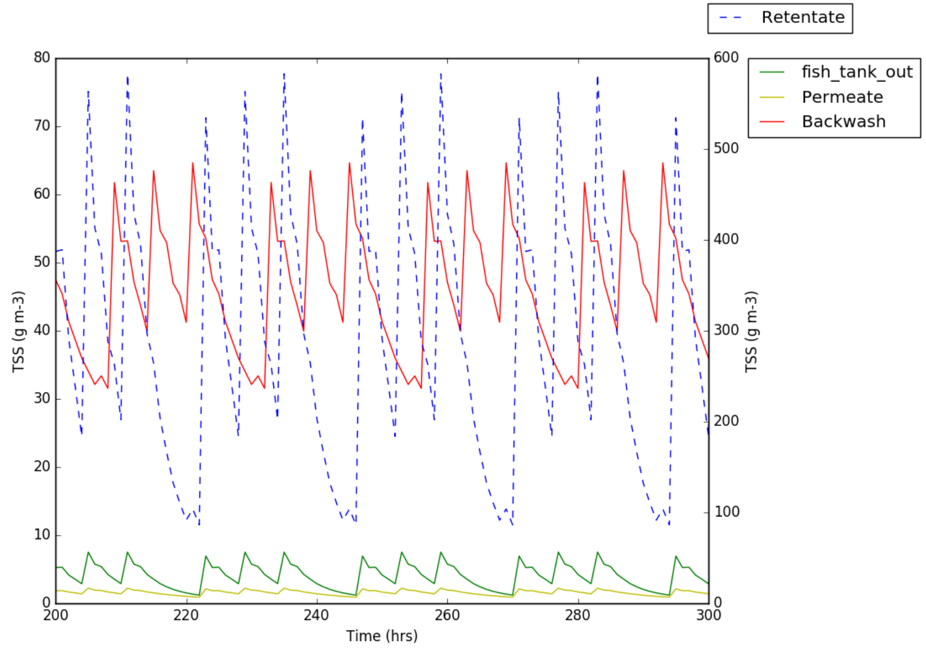

Figure 40 TSS feeding strategy 2

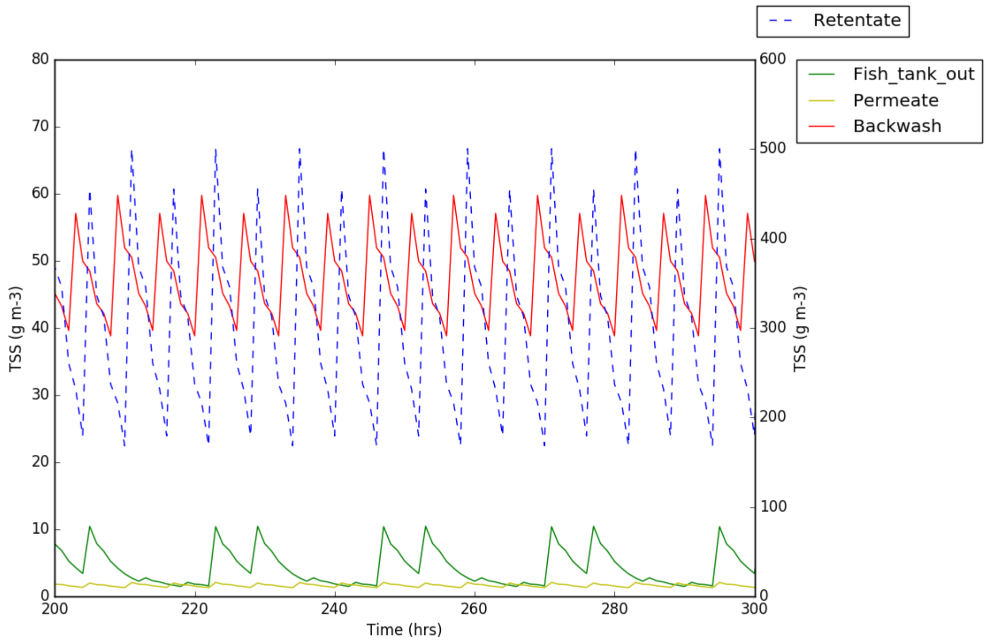

Figure 42 TSS feeding strategy 3

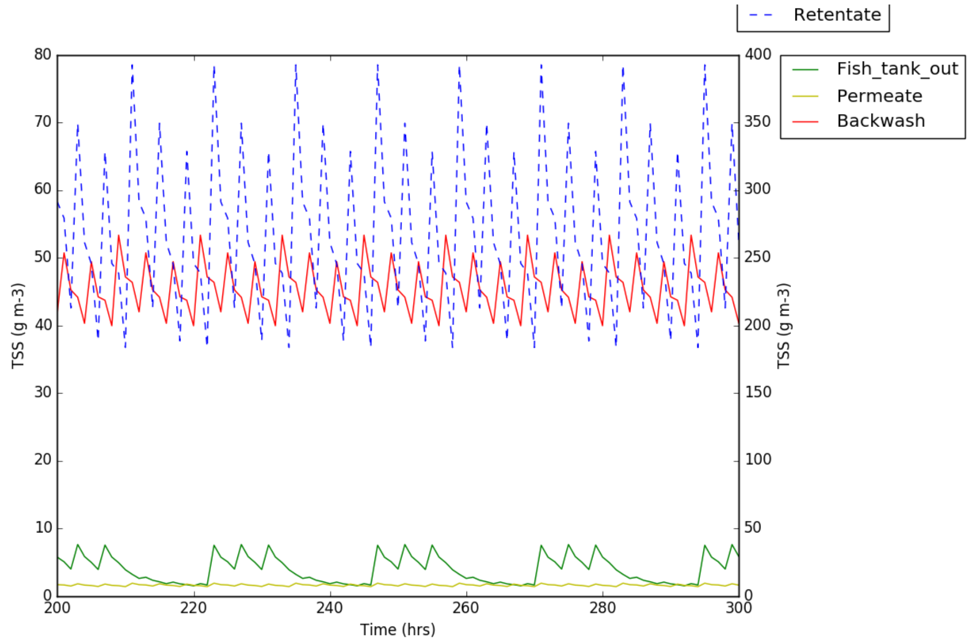

Figure 43 TSS feeding strategy 4

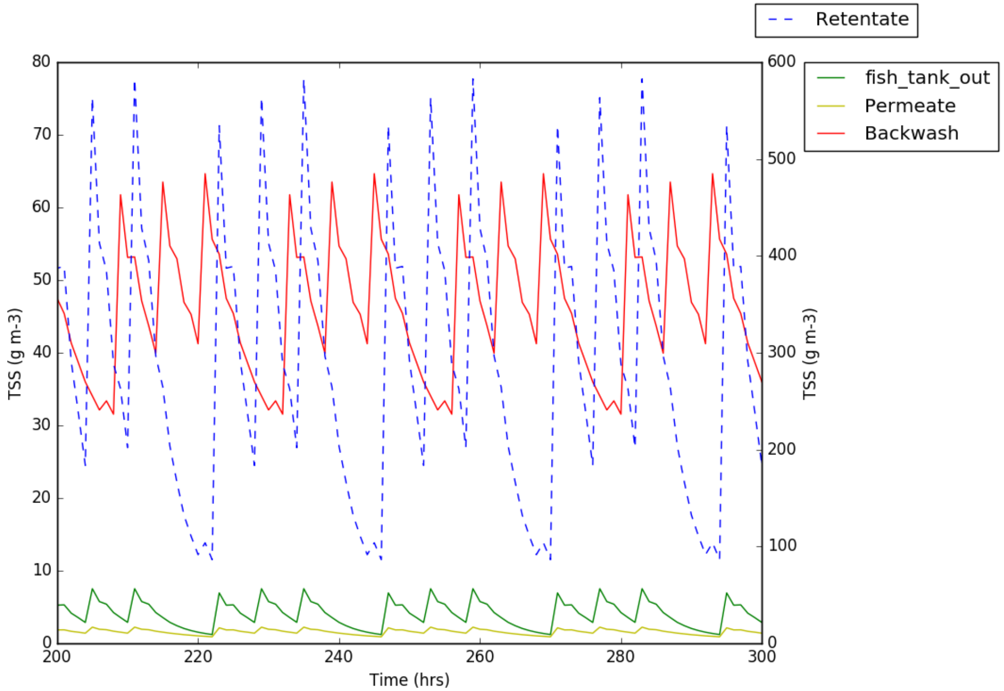

Figure 44 TSS feeding strategy 5

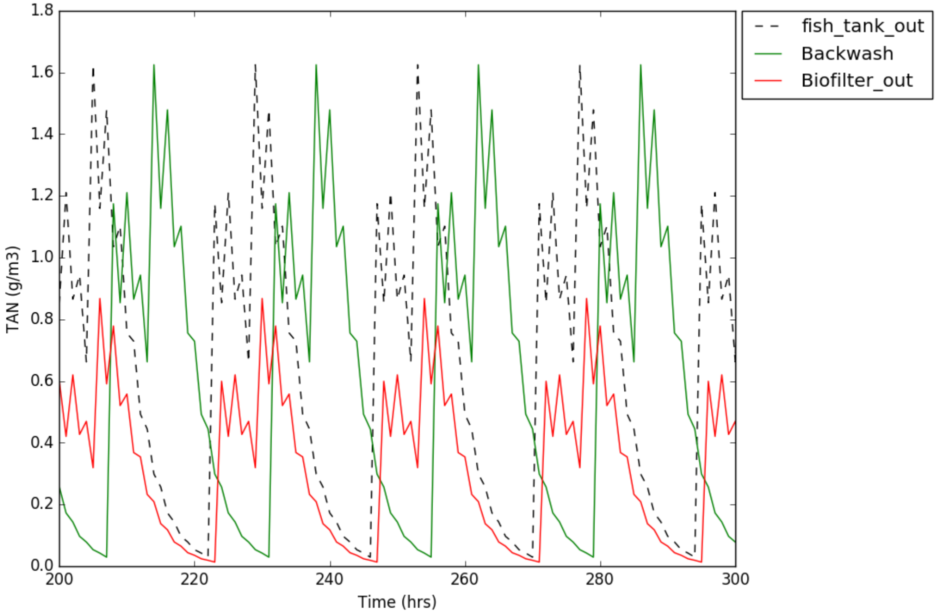

Figure 46 TAN feeding strategy 1

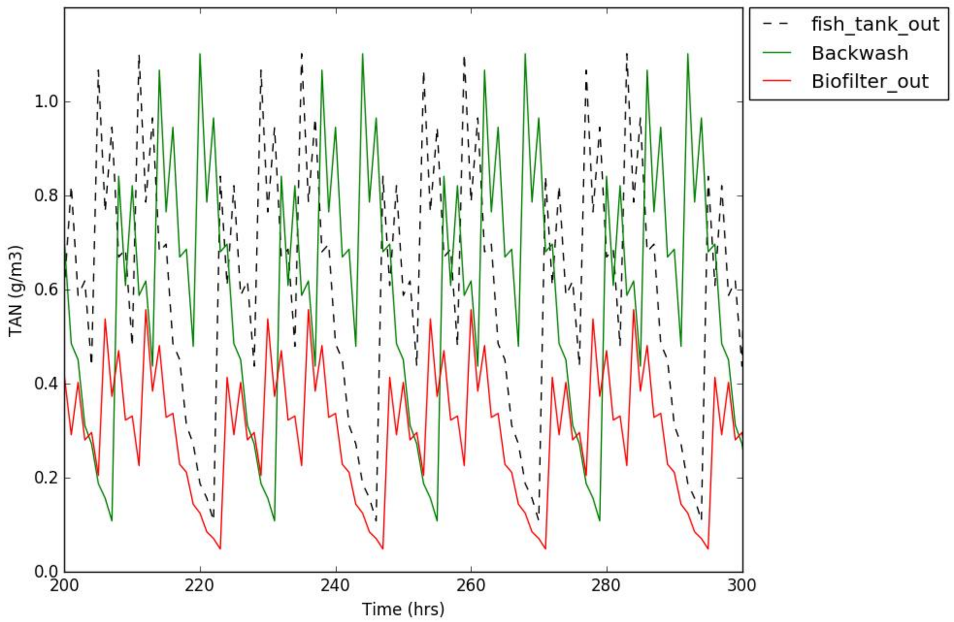

Figure 45 TAN feeding strategy 2

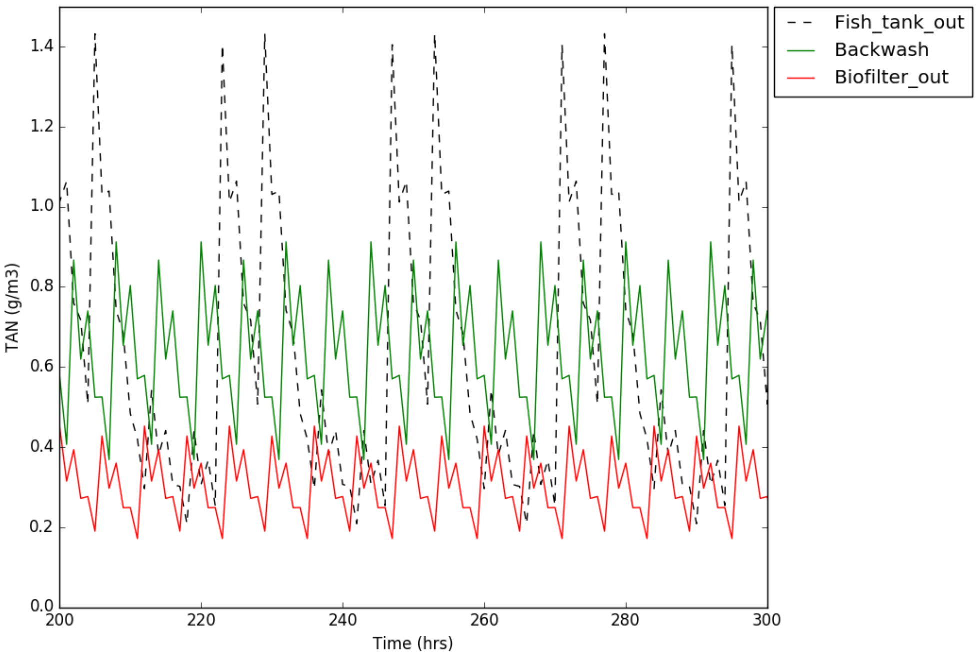

Figure 48 TAN feeding strategy 3

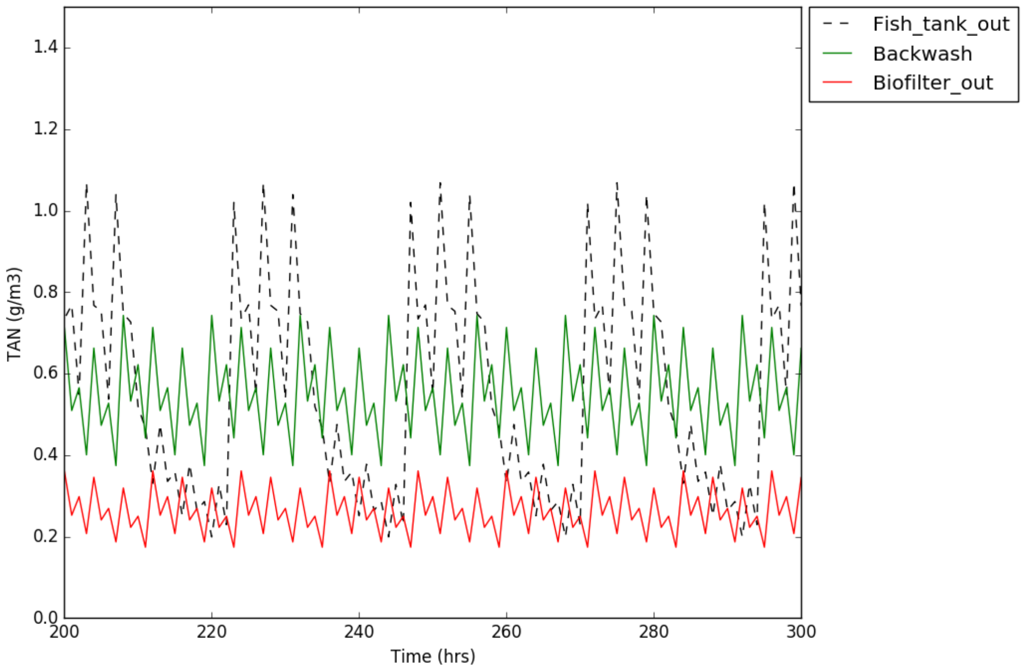

Figure 47 TAN feeding strategy 4

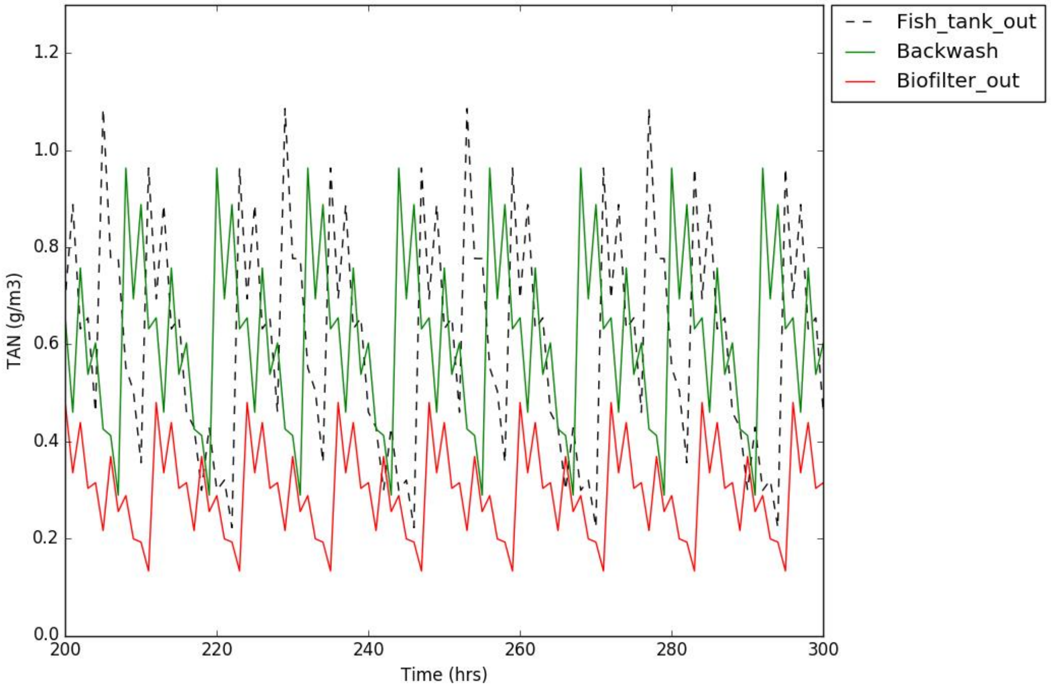

Figure 49 TAN feeding strategy 5