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Modeling and Simulation of Aquaculture Systems

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Abstract: In this work, models for aquaculture are developed with regard to their relevance in an automated recirculation system. The three subsystems fish, water, and feed are determined as modular components. A selection of relevant variables is determined. The relationships between feed, water quality, and fish growth are described on the basis of an initially qualitative description (causal network) and quantified using ODEs. The considered water treatment systems and control devices are used to describe the relationships between filtration, fresh water addition, and water quality. The numerical system model allows simulations of the overall system behavior in time domain including the full growth phase of fish. As example, the conditions using rainbow trout are simulated in a recirculating system. Influences of different variables like water temperature, pH-value, or protein content in dependency of the fish feed variables are shown, as well as the influence of plant parameters. This allows a recording of water quality and also to monitor the optimal fish growth or well-being parameters. The developed model can be extended modularly and allows further considerations and analyses for the control of the plant volume flow or for carbon dioxide gassing.

Keywords: Aquaculture, recirculating systems, water quality, fish growth

1. INTRODUCTION

Aquaculture facilities, which are maintained in commercial operating companies for the production of fish products, must comply with legal regulations and standards and be optimized with regard to the cost/benefit ratio. The optimization of the plants can be carried out if the causal relationships in the operation are known. Recirculating systems usually consist of several artificially constructed tanks, which are not in direct contact with the environment. The special feature is that the water used is circulated between the tanks and various types of water treatment plants, and is thus reused. According to the FAO definition, a maximum of 10 % of the water used is exchanged per day in a recirculation system (FAO (2020)). In modern recirculating systems, about 2 % of the water volume is exchanged per day (IGB (2020)). The disadvantages of this type of system are the high investment costs, complex measuring, control and regulating equipment, and high energy consumption (Güttler (2008)). A profitable operation can only be realized with very high stocking densities, which are possible due to the constant water supply and treatment. In current research projects, the combination of recirculating systems for fish production and hydroponic systems for the cultivation of crops is being investigated. Here, the feed residues and metabolic products of the fish in the form of nitrogen compounds in the water are used as fertilizers for the plants (Rümmler (2015), Goddek and Keesman (2020)). In the operation of recirculating plants, extensive control of water quality and temperature is common, so fish production can be realized independently of natural waters and ecosystems.

The task of this work is to describe the relationships between fish feed, water quality, and fish growth and to explain the significance of the different feed proportions and their effects. Filtering techniques and the use of fresh water in aquaculture facilities are simulated to identify relevant measurement and target parameters, to describe relationships qualitatively, and as a first step quantify them. Simulations of the generated model for one common aquaculture fish is evaluated to generate an overview of the basics of modern plant automation of aquaculture systems.

2. MODELING OF AQUACULTURAL SYSTEMS

2.1 Qualitative modeling

All described relationships between feed intake, water quality and fish growth are shown in Fig. 1. The most important variable in modeling is fish growth, which depends on water quality and feed input (Stiller (2016)). The fish growth describes the change of weight of the individual fish and thus also the development of the total fish mass in the system. The mass of the fish, together with the volume of water present in the fish tank, defines the stocking density. The total mass influences the oxygen consumption as well as the output of carbon dioxide of the fish and thus the oxygen and carbon dioxide content in the water (Sladonja (2011)). Besides carbon dioxide, nitrogen is also excreted by fish as a metabolic end product. The composition of the diet is relevant because the amount of nitrogen excreted depends largely on the protein content of the diet (Avnimelech (1999), Burnell et al. (2019)). The excreted nitrogen combines with hydrogen to form

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ammonium or ammonia (Brunson et al. (1997)). Up to a pH of about nine, more ammonium than ammonia is present in the water at given water temperatures. The higher the temperature and pH, the more ammonium is converted to ammonia (Brunson et al. (1997)). The pH value is influenced by the carbon dioxide content, the water hardness and the alkalinity. The lower the values for alkalinity and water hardness, the faster changes in pH can occur. Ammonium and ammonia are converted in moving bed biofilm reactors by bacteria in a two-stage process first to nitrite and then to nitrate. Bacterial species involved in the oxidation of ammonium and ammonia to nitrite in freshwater are Nitrosomonas oligotropha and in the oxidation of nitrite to nitrate Nitrospira marina, Nitrospira moscoviensis and species of the genus Nitrobacter (IGB (2020), Burnell et al. (2019)). From the two reaction equations for nitrification Ammonium oxidation
$NH_4^+ + 1.5O_2 \longrightarrow NO_2^- + 2H^+ + H_2O$
and Nitrite oxidation
$NO_2^- + H_2O \longrightarrow NO_3^- + 2H^+ + 2e^-$
it can be seen that in this reaction oxygen is consumed and hydrogen ions are released (Burnell et al. (2019)). The released hydrogen ions consume alkali (Rümmler (2015)). The solids content in the water is affected by the amount of feed (Bergheim and Cripps (2000)). A feed conversion rate of one is assumed. In Burnell et al. (2019) it can be seen that the complete water content of the feed, a large part of the fat and carbohydrate content and less than half of the protein content is converted into fish mass. The remaining protein, fat, and carbohydrate are converted to ammonia and ammonium (described as total ammonia content)), phosphorus and solids. The majority of the resulting ammonia and ammonium results from the protein content of the feed. Nitrogen either enters the water directly from the feed or is excreted by the fish as a metabolic end product and combines with hydrogen to form ammonium (NH_4^+) or ammonia (NH_3) (IGB (2020)). Various species of bacteria nitrate these nitrogen compounds. Oxygen is consumed in the process. In high concentrations, the nitrate endangers fish welfare. In Fig. 1 it is shown for

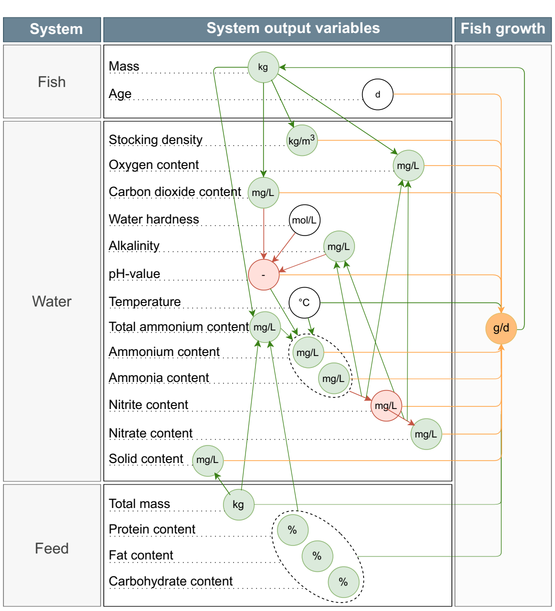

Fig. 1. Qualitative correlations (Brauer (2021))

which of the qualitatively described relationships mathematical descriptions could be found. The variables shown in white are independent of all other variables. The water temperature is considered as a constant parameter. The variables colored in red cannot be calculated. No mathematical descriptions could be found for the pH value and nitrite content. In reality, the pH is controlled by the water exchange in the plant and the addition of sodium hydrogen carbonate, which prevents strong fluctuations. Therefore pH value is considered as a parameter. The green colored variables can be calculated depending on other variables. Fish growth is colored orange because it is possible to calculate it, but it is inaccurate under non-optimal conditions.

2.2 Quantitative modeling

The fish growth is described with the formula sign W and given in g/h. The number of fish in the tank is described as n_{fish}.

Fish mass The total mass of all fish in the tank is referred to as

$$M_{ges} = \frac{1kg}{1000g} \cdot \int_0^T W \ dt,$$

where T is the observation or simulation time. The mass of a single fish is calculated by

$$M_{fish} = \frac{M_{ges}}{n_{fish}}.$$

Stocking density The tank volume is denoted as V_T. The stocking density is denoted as

$$B = \frac{M_{ges}}{V_T}.$$

Oxygen and carbon dioxide content Oxygen content is denoted as X_{O_2}, carbon dioxide content as X_{CO_2}. The oxygen consumption S of the fish is assumed to be constant throughout the day, depending on the mass of the fish, and given as a species-specific literature value. For the carbon dioxide output of the fish, it is assumed that each oxygen molecule (O_2) described by the oxygen consumption is excreted as a carbon dioxide molecule (CO_2). It must be taken into account that the two molecules have different molar masses, which is why the carbon dioxide output of the fish is given by Linden et al. (2009) as

$$K_{fish} = \frac{44mg_{CO_2}}{32mg_{O_2}} \cdot M_{ges} \cdot S.$$

The carbon dioxide content in water is given by

$$X_{CO_2} = \frac{1}{V_T + V_R} \cdot \frac{1m^3}{1000L} \cdot \int_0^T K_{fish} \ dt$$

with the size V_R describing the volume of the moving bed filter. In addition to the oxygen consumption of the fish, the oxygen consumption during nitrification in the moving bed filter also influences the oxygen content in the water. According to Davis (2015), under real conditions, a consumption of about 4.57 kg of oxygen is observed during the nitrification of one kilogram of ammonium and ammonia. The oxygen content in the water is given by

$$X_{O_2} = \frac{1}{V_T + V_R} \cdot \frac{1m^3}{1000L} \cdot \int_0^T -S \cdot M_{ges}$$
$$-4.57 \cdot \frac{d}{dt} NH_{x,Bac} \ dt.$$

The time-dependent mass of ammonium and ammonia nitrified by bacteria is denoted as $\frac{d}{dt}NH_{x,Bac}$. The oxygen content is controlled using loss-free input of pure oxygen. According to Piedrahita et al. (2000), an aerated counterflow cascade unit is modeled through which the plant volume flow passes, causing desorption processes to occur at different carbon dioxide contents and carbon dioxide to be transferred from the water to the gas phase.

Feed quantity The feed rate $M_{feed,day}$ is the mass of feed introduced into the system each day to feed the fish. The number of feedings per day, the size of feed pellets, and the protein content of the feed has to be considered. The feed quantity per feeding can be calculated using the table value $F_{\%}$ by

$$M_{feed} = \frac{M_{feed,day}}{n_{feed}} = \frac{F_{\%} \cdot M_{ges}}{100 \cdot n_{feed}}$$

with n_{feed} as the number of feedings per day (FAO (2021)).

Nitrogen Excretion The nitrogen excretion of fish is modeled after Burnell et al. (2019). The amount of nitrogen excreted per feed can be calculated as a function of feed quantity, protein content, and the protein fraction of the feed converted to biomass with

$$M_{N,feed} = M_{feed} \cdot 0.16 \cdot 0.75 \cdot (P_F - P_b).$$

On average about 16 % nitrogen is contained in the protein fraction and about 75 % of the nitrogen present as a metabolic end product is excreted via the gills of the fish and thus enters the water as dissolved nitrogen. The remaining 25 % is excreted via excrement as bound nitrogen. The values for the protein content P_F are contained in the feed tables. The variable P_b describes the protein content of the biomass produced during growth and is assumed to be 0.17. This means that about 0.17 kg of protein is needed to produce one kilogram of fish weight. The nitrogen excreted through the gills does not leave the body immediately after feeding, but nitrogen excretion is dynamic. The nitrogen excretion is expressed as a transfer function

$$G(s) = \frac{1}{(1+pT_1)(1+pT_2)}$$

based on the gastric emptying rate of the fish with the values $T_1 = 1$ h and $T_2 = 2$ h (Linden and Wik (2004)). The time behavior of nitrogen excretion after a feeding can be determined by multiplying the nitrogen excretion per feeding by the transfer function.

Total ammonium, ammonium, and ammonia content A practical, but for the present consideration nevertheless sufficiently exact description supplies the tabulated values after Brunson et al. (1997). With these, the ammonium and ammonia content can be determined mathematically as a function of temperature, pH value and the total ammonium content. The value T_W from the tables given in Brunson et al. (1997) is multiplied by the total ammonium content to determine the ammonia content of the water, resulting in

$$X_{NH_3} = X_{NH_x} \cdot T_W.$$

The ammonium content is given by

$$X_{NH_4^+} = X_{NH_x} - X_{NH_3}$$

with X_{NH_x} as the total ammonium content in water.

Nitrification Reactor In Burnell et al. (2019) an aquaponic system is described, in which the nitrate-containing water from the reactor is directed to the hydroponics section of the system and then returned to the recirculating system for fish rearing at a lower nitrate level. This consideration is adapted so that the water volume flow between the recirculation and hydroponic system is set equal to zero, leaving a pure recirculation system with fish tank and reactor. This does not change the operation of the nitrification reactor. In the nitrification reactor ammonium and ammonia are converted into nitrate by bacteria in a two-stage oxidation process (Rümmler (2015), Burnell et al. (2019)). The maximum daily nitrification of the bacteria μ_{max} is calculated by multiplying the total surface area A and the specific maximum daily nitrification $NH_{x,Nit}$. For $NH_{x,Nit}$ a value of 1.2 is assumed (Burnell et al. (2019)). The real nitrification rate depends on the maximum possible daily nitrification μ_{max}, the reactor volume V_R and the total ammonia content of the water in the nitrification reactor $X_{NH_x,R}$ and is modeled as monod kinetics. The parameter saturation constant K_S corresponds to the total ammonium content in the water at which the nitrification rate μ is exactly half the maximum possible daily nitrification μ_{max}. For K_S a value of 0.6 is assumed (Burnell et al. (2019)). The change of the total ammonium content during nitrification in the reactor is given by

$$\frac{d}{dt} X_{NH_x,R} = -\mu_{max} \cdot \left(\frac{X_{NH_x,R}}{K_S + X_{NH_x,R}} \right) \cdot \frac{1}{V_R}.$$

The change in nitrate content during nitrification in the reactor is given by

$$\frac{d}{dt} X_{NO_3^-,R} = +\mu_{max} \cdot \left(\frac{X_{NH_x,R}}{K_S + X_{NH_x,R}} \right) \cdot \frac{1}{V_R}.$$

It is assumed that the biofilm on the carrier bodies is constantly fully developed. The total ammonium content in the fish tank is influenced by the ammonium and ammonia excretions of the fish as well as the water exchange through the plant volume flow. The plant volume flow continuously transports a portion of the process water between the fish tank and the reactor. The total ammonium content in the nitrification reactor is affected by the water exchange through the plant volume flow and by nitrification. The nitrate content in the fish tank is influenced exclusively by the water exchange.

Solids content Solids enter the water through the excrements of the fish and through the feed intake. The fish feed must be constantly slightly overdosed so that the fish are always completely satiated and no growth capacities remain unused. The uneaten feed sinks to the bottom of the fish tank, decomposes and remains as solids in the water. The amount of solids in the water depends on the species of fish being kept and the composition of the feed used. The solids input per feed is given by

$$M_{solids,feed} = 0.15 \cdot M_{feed} \cdot \frac{1kg}{1000000mg}.$$

About 15 % of the total solids input enters the water through the decomposition of feed residues, within a few minutes after feeding Basilico (2020). In the simulation, it is assumed that this happens instantaneously. The remaining 85 % of the total solids enter the water through the excreted feces Basilico (2020). This occurs over a period of several hours and is dependent on the rate of digestion of the fish. The time behavior of excretion of excrement, like the time behavior of nitrogen excretion, is given by the transfer function following the gastric emptying rate. A drum filter is used, which filters solid particles with a constant filtering efficiency, regardless of the ambient conditions and their size.

Alkalinity During the nitrification of ammonium and ammonia, alkali nitrate is consumed. Under experimental conditions, it was found that the oxidation of one kilogram of ammonium and ammonia to nitrate consumes about 7.05 kg alkalinity (Sladonja (2011)). The alkalinity of the water can be expressed by

$$X_{Alk} = \frac{1m^3}{1000L} \cdot \int_0^T -\frac{1}{V_T+V_R} \cdot 7.05 \cdot \frac{d}{dt} NH_{x,Bac}\, dt.$$

The alkalinity of the water is influenced by introducing an alkaline chemical Rümmler (2015).

Fish growth Fish growth describes how the total body weight of all fish in the tank changes per day and depends on the feed conversion ratio (FCR) and the feed mass (Davis (2015)). The feed conversion ratio is a measure of how much mass of feed is needed to realize a certain growth of the fish. Most of the absorbed energy can be converted into biomass (Davis (2015)). The feed conversion rate depends on the fish species, the life stage of the animals, the living conditions and the amount of feed supplied. In case of less than optimal water conditions or other sources of stress, the feed conversion rate will increase. The amount of energy used to perform the vital functions is constant under uniform water quality, so the feed conversion rate increases even if the feed input is reduced (IGB (2020)). Assuming near-optimal living conditions during the simulation, a constant feed conversion rate is assumed for the respective fish species, which does not change with different life stages of the animals. The maximum possible fish growth W can be given by

$$W_{max} = \frac{1000g}{1kg} \cdot \frac{1d}{24h} \cdot FCR \cdot M_{feed,day},$$

assuming that the fish grow at a constant rate throughout the day. The real fish growth is obtained by multiplying the maximum possible fish growth and a coefficient for the water quality by

$$W = W_{max} \cdot \epsilon_{water}.$$

pH value and nitrite content The pH value is needed to calculate the division of the total ammonium content into ammonium and ammonia content. To keep this possible, the pH-value is considered as parameter, fixed at the beginning of the simulation. The nitrite content is not taken into account.

3. SIMULATION RESULTS

The volume of the fish tank is 6 m^3, the reactor volume is 3 m^3. The plant volume flow is set at 600 L/min. There are 1100 fish in the fish tank with a starting weight of 100 g each. The total ammonium content in the tank at the start of the simulation is 0 mg/L, oxygen content is 7 mg/L, nitrate, carbon dioxide, and solids content are 0 mg/L each, and alkalinity is 70 mg/L. The feed conversion rate is 1.2 (IGB (2020), Davidson et al. (2010a)). The control loop flow rates are set at 8 mg/L for oxygen, 70 mg/L for alkalinity, and 75 mg/L for nitrate. The specific oxygen consumption of fish is assumed to be constant at 2000 mg/kg·d (Stiller (2016)). The simulation duration is 1200 h, i.e. 50 days. The limits up to which water quality can be considered optimal are selected to suit the needs of rainbow trout. For the ammonia content, the limits are between 0.02 and 0.07 mg/L (Burnell et al. (2019)). In the present case, a limit value of 0.02 mg/L is set. The ammonium content should be kept below 1 mg/L (Burnell et al. (2019)). The nitrate content should be kept at the highest 75 mg/L (Davidson et al. (2010b)). The limit of carbon dioxide content is 25 mg/L (Davidson et al. (2010a)). The solid content should not exceed 15 mg/L (Barrows et al. (2013)). Up to these limits, the respective growth coefficient has a value of one. The progression of these coefficients is described by a second cut-off point at which a value of zero is reached and thus no more fish growth takes place. A linear progression is assumed between the two points. For the two critical variables, the respective lethal concentrations are used for the second test point. A lethal effect of the non-critical variables is not expected and only significant exceedances of the limits lead to reduced fish growth (Sladonja (2011)). In some cases, even a carbon dioxide content of about 60 mg/L does not lead to reduced fish growth (Barrut et al. (2012)). For the non-critical variables, the assumption is made that the growth coefficient reaches a value of zero when the current value of the respective variable is three times the threshold. This is only a rough estimate that cannot accurately predict reduced fish growth.

The further discussion is now focused without loss of generality to one fish species. The rainbow trout belongs to the salmonids and is the fifth most popular food fish in Germany (IGB (2020)). In 2017, more than 800,000 t of rainbow trout were produced in aquaculture facilities worldwide (FAO (2019)). The freshwater trout reaches a maximum body length of 80 cm and a maximum body weight of 5 kg (IGB (2020)). Freshwater trout are carnivorous (IGB (2020)). The protein content of the feed used is therefore usually between 45 and 53 % (FAO (2021)). Rainbow trout can easily be kept at stocking densities of up to 100 kg/m^3 and prefer water temperatures between 6 and 20 °C (IGB (2020)). In the simulation performed, a water temperature of 18 °C and a pH of 7.5 are assumed.

Stocking density and total fish mass In Fig. 2 the changes of the stocking density and the calculated total mass of the fish as well as the best possible development of the total mass at optimal water quality are shown. The stocking density at the beginning of the simulation is about 18 kg/m^3 and reaches a final value of about 46 kg/m^3. This is well below the maximum appropriate stocking density of 100 kg/m^3. The calculated total mass deviates slightly from the optimal behavior. This indicates that from a specific time point on, the growth coefficient is not at one and thus the water quality is not optimal.

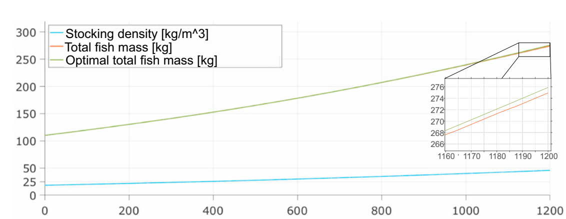

Fig. 2. Stocking density and total fish mass

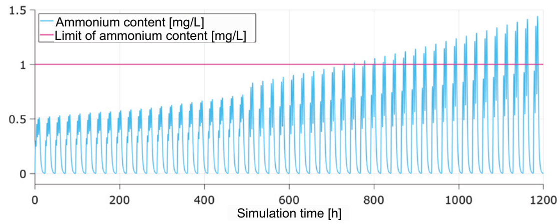

Fig. 3. Ammonium content

Ammonium content In Fig. 3 the variation of ammonium content and the threshold value up to which the fish growth is not affected by the ammonium content are presented. A nearly sinusoidal behavior can be seen, in which each low point is followed by several high points in close succession. A continuous increase of these local high points can be observed. A sudden increase of the local maximum values at a simulation duration of about 500 h can be noticed. In each of the first 500 h of the simulation, four feedings per day are realized and successive high points can be seen in the ammonium content. After 500 h simulation time, three feedings per day and therefore three high points are visible. The limit value of the ammonium content is exceeded for the first time after about 700 h. From this point on, further, periodically repeated, overruns of the limit value follow. Between the local maxima, the ammonium content drops significantly and repeatedly reaches a value of zero (see Fig. 3).

Ammonia content The ammonia content and the corresponding limit value are shown in Fig. 4. The curve is comparable to the curves of the ammonium content and also approximately sinusoidal. The frequencies, phase positions and number of closely following high points are identical, only the amplitudes differ. The ammonia content does not exceed the limit value at any time, so that the conditions are optimal at all times and the value of the growth coefficient is constant at one.

Carbon dioxide content The Fig. 5 show the behavior of the carbon dioxide content during the simulation. The limit value of the carbon dioxide content is 25 mg/L and is not shown because the carbon dioxide content, which increases abruptly at the beginning of the simulation and then linearly, reaching a maximum value of under 0.04 mg/L, is well below this limit value. The low values result from the moderate stocking density and the high amount of fresh water given to the system.

Solids content The solids content and the corresponding limit value are presented in Fig. 6. The curve of the solids content is also approximately sinusoidal, and the phase, amplitude and number of high points following one

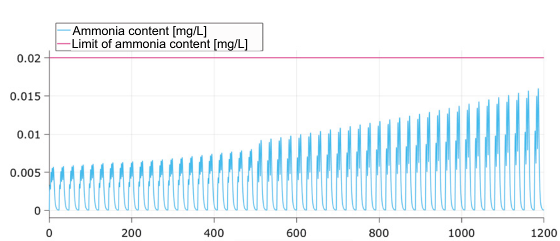

Fig. 4. Ammonia content

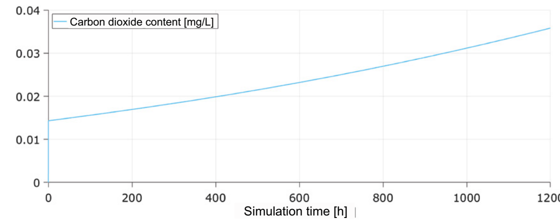

Fig. 5. Carbon dioxide content

another closely are identical to those of the ammonium and ammonia content. The solid content reaches a maximum value of about 4 mg/L, which is well below the limit value of 15 mg/L.

4. DISCUSSION

From the simulation results it can be seen that the stocking density at the end of the simulation is about 46 kg/m^3, which is below the corresponding maximum values, so that it is considered as rather moderate stocking density. The fish growth of the rainbow trout is almost optimal. Carbon dioxide and solids levels are consistently below the respective limits and do not affect fish growth. The growth of the rainbow trout is only affected by the ammonium content exceeding the limit value, but only slightly. About 98.9 % of the total ammonium is present as ammonium and about 1.1 % is present as ammonia. The maximum value of the total ammonium content is dependent on the feed input, the number of feedings per day, the protein content of the feed given, and the consequent increase in nitrogen output. The exceedances of the limits indicate that the plant parameters must be changed in order to ensure optimal water quality with the total mass of fish present. An increase in plant flow rate or reactor volume may be considered to increase the rate of nitrification of nitrogen compounds in the water. The losses in carbon dioxide content are unrealistically low. The maximum value is under 0.04 mg/L and significantly below the limit value of 25 mg/L. This is supported by the assumptions that the entire plant volume flow always flows through the unit for carbon dioxide gasification and that a constant air supply is maintained in this unit. Energy saving and thus an increase in efficiency could be realized by controlling the carbon dioxide content by means of a variable air supply in the unit. The solids input is independent of the feed composition, but is determined solely by the feed quantity. The maximum value is below the corresponding limit value, so an increase in stocking densities is possible. The values of ammonium, ammonia, and solids content increase after each feeding until they reach a local maximum value. For each day of the simulation, there is a group of short consecutive maximum values. The number of these local

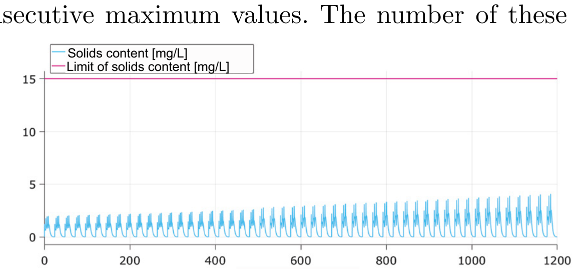

Fig. 6. Solids content

maxima corresponds to the number of feedings per day. Between the individual feedings on a day, the values of the water quality variables briefly drop to a local minimum value. In the time ranges representing the night, i.e. in the ranges between the groups of maximum values, the values of the variables drop significantly and repeatedly reach a value of zero. This is usually not the case in reality and also in models of closed-loop systems described in the literature and therefore to be classified as unrealistic (Barrows et al. (2013), Linden and Wik (2004)). This may be due to the fact that no realistic values were chosen for the transfer function presented, which models the gastric emptying rate of the fish and thus also describes the discharge of nitrogen and excrements, i.e. solids. The parameters T_1 and T_2 were assigned the values 1 h and 2 h. Reducing these values lead to a more uniform excretion of the metabolic end products of the fish, which results in lower maximum values of the variables.

5. SUMMARY AND CONCLUSION

In this paper, the recirculating system is selected for more detailed consideration. The description of the overall system is realized by the three subsystems fish, water and feed. To each of these systems, system output variables are assigned to describe the respective system, whereby a selection of the relevant variables is made. The selected variables are presented and the relationships between feed, water quality, and fish growth are described qualitatively in the first step and then quantified. The significance of the individual feed components is described in the behavior of this. This modeling results in a simulation-capable model whose parameters and initial conditions are freely selectable. One simulation is carried out in which the rainbow trout is assumed in a recirculation system. The results also allow conclusions to be drawn as to whether the dimensioning of the plant parameters is suitable for achieving optimal water quality and thus optimal fish growth. This first step of describing an aquacultural system needs to be validated.

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