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Aquaponic nutrient model

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A daily material flow analysis approach

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Table of Contents

Abstract

In recirculation aquaculture it is important to keep the amount of water discharged, as small as possible for environmental reasons, which can be achieved by introducing nutrient absorption or conversion. By including plants (e.g. tomatoes) for nutrient uptake, such a system is called aquaponics. There are two different ways to assemble an aquaponic system: either coupled or decoupled.

This study is showing the differences of the nutrient flows inside such systems and their behaviour on a daily basis. Currently available knowledge in literature was used to model material flows in an aquaponic system. Based on the given feed input, the necessary area for soilless plant cultivation (hydroponics) was calculated and incorporated with an recirculating aquaculture system.

1 Introduction

To increase sustainability, the use of water in aquaculture has to be reduced either through integration of other trophic levels or through additional water treatments (Martins et al., 2010). “Aquaponics” is the integration of usually two trophic levels into one system, where one level consists of fish and the other of hydroponic plants (Goddek et al., 2015; Rakocy et al., 2006). The direct re-use of the aquaculture effluent and incorporation with growing plants in an aquaponic system is considered part of the future of European aquaculture (Aller, 2015). Currently there are two different system designs known (see fig. 1). “Coupled systems” consist of one connected water layer like the UVI system (Rakocy et al., 2006), while “decoupled systems” consist of separated aquaculture and hydroponic systems with a controlled connection in between (Goddek et al., 2015).

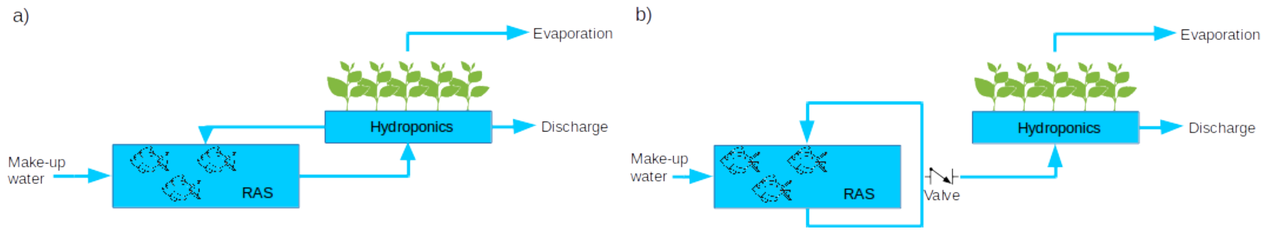

Figure 1: a) coupled b) decoupled aquaponic system

In aquaculture the discharge of water is considered to be an environmental problem which can be tackled by the use of recirculating aquaculture systems (RAS) leading to a reduction of the amount of water per kilogram of feed (Martins et al., 2010). A further reduction can be achieved by integrating greenhouse technology to improve the overall nutrient use efficiency (Kloas et al., 2015; Oberdieck and Verreth, 2009).

The aim of this study is to present and analyse the mass balance inside aquaponic systems with a material flow analysis approach, to better understand the resulting behavior. For this a daily interval has been chosen. Based on available literature a daily material flow analysis (MFA) was created (Brunner and Rechberger, 2004), to investigate the nutrient development inside such systems.

With a daily material flow analysis the spatial hydroponic requirement connected to a RAS has been determined, after a literature study to evaluate the nutrient behaviour in an aquaculture system. These results are used to make a mass balance between the resulting nutrients in the water with the uptake of the hydroponic plants. According to the given production plan an outlook for further investigations is made, to improve the system behaviour and the understanding of it.

Starting with an analysis of the fish feed and its nutrient partition into faeces, fish uptake and release into the water, the mixture of the available substances is determined. Based on this and the plant uptake in the hydroponics, the required area for the plants is calculated based on nitrogen. Due to the expected discharge of water, an differentiation between a coupled and a decoupled aquaponic system is made, to see, whether the system design has an influence on the discharged water and its nutrient content.

2 Materials and methods

2.1 Material flow analysis

Material flow analysis (MFA) is an assessment tool for the investigation of compounds based on the principle of conservation of matter. The objective of MFA is to identify material flows and stocks inside a system and increase the understanding of such, to provide a basis for decision making (Brunner and Rechberger, 2004). This study covers the cycle from system import to system export with an MFA approach to differentiate between coupled and decoupled system designs (Goddek et al., 2015) and to identify the advantages or disadvantages of either design based on literature data. The fish and plants are treated as sinks, which take up nutrients and store them. Energy is not considered in this study (see fig. 2).

Based on the systems of ASTAF-PRO and INAPRO the selected fish species is Nile tilapia (*Oreochromis niloticus*) (Kloas et al., 2015; Slinkert et al., 2015). While the values of the temperature and pH are not relevant for the developed model, they can be expected to be between 24 and 32 °C (DeLong et al., 2009; Eding et al., 2006) and the pH between 6 and 9 (DeLong et al., 2009). Like the system of ASTAF-PRO, in the greenhouse environment tomato plants of the species *Solanum lycopersicum* are used (Kloas et al., 2015).

The plant nutrients consist of 16 chemical elements which can be differentiated in macronutrients (N, K, Ca, Mg, P, S) and micronutrients, also called trace elements (Cl, Cu, Mn, Fe, Zn, Co, Mo, Ni) and sodium and silicon (Maathuis and Diatloff, 2013). Due to the limitation of the used dataset for the tomato substance uptake to N, S, P, K, Ca, Mg and water (Voogt, 1993), it has been enhanced by sodium and chloride, because of their importance in tilapia fish feed (Cnaani et al., 2010).

Sodium and chloride can have either beneficial (Rush and Epstein, 1981) or lethal effects on tomato plants (Rush and Epstein, 1976). In the MFA nutrients are called substances, which include chemical substances and compounds (Brunner and Rechberger, 2004). This study lays focus on the chemical substances (e.g. nitrogen) and does not incorporate different chemical species (e.g. nitrate, ammonia), although the nitrification conversion of these substances is incorporated because of its system importance to maintain the pH level. All compounds are considered to be a good, in the sense of having a certain economic value (Brunner and Rechberger, 2004)

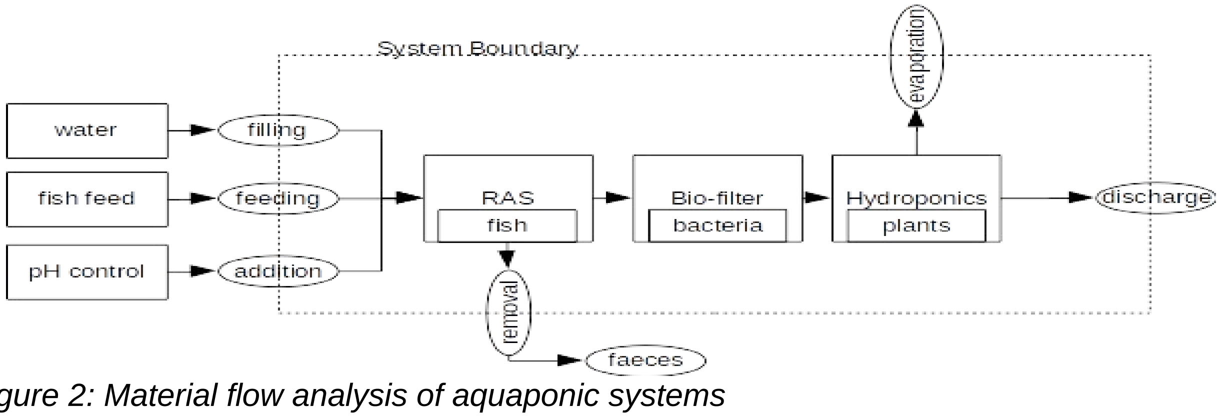

Figure 2: Material flow analysis of aquaponic systems

For the aquacultural system and the hydroponics, the water is essential and the used water (system import) is assumed to be clear of any substances. Therefore, this study focuses on water quantity and quality, in terms of substances, as the connecting link containing the substances while being substance (H_2O) and good, and not on the yields of the respective systems (plants or fish). The nutrients are assumed to be equally distributed inside the water body of the respective system.

2.2 Aquaculture

The nitrogen in aquacultural systems in form of ammoniacal nitrogen, is toxic to tilapia at very low levels (Timmons and Ebeling, 2010). That is why RAS contain a nitrifying bio-filter to convert the total ammoniacal nitrogen (TAN) into less toxic nitrate (NO_3) (DeLong et al., 2009; Eding et al., 2006; Goddek et al., 2015; Masser et al., 1999; van Rijn et al., 2006). The resulting release of H^+-ions by the nitrification process of *Nitrosomonas* and *Nitrobacter* species, leads to a drop in pH for which a compensation is necessary (Eding et al., 2006; Masser et al., 1999; Tyson et al., 2011). This drop in pH and the discharge of water from the system depend on the amount of food consumed by the fish (Einen et al., 1995). Due to the nitrogen uptake by the bacteria a factor of 0.98 is used instead of 1.00, and for hydrogen release 1.98 instead of 2.00 (Eding et al., 2006). In this analysis, the nutrient solution (a solution of substances in a good) provided to the plants is defined by the RAS effluent.

2.3 Hydroponics

Nutrient film technique (NFT), aeroponics and continually aerated nutrient solution are viable growing techniques for systems with a water based solution (Larsen, 1982). ASTAF-PRO and INAPRO operate their hydroponic part of the system with NFT (Kloas et al., 2015; Slinkert et al., 2015). According to Sprengel's law of the minimum, the deficiency of one required mineral prevents further development, even if all other substances are abundantly available (van der Ploeg et al., 1999). To counteract such a shortage, fertilizer would be needed. In this model it is assumed, that a shortage of substances does not affect the uptake of the plants, why a linear uptake is incorporated independent of changes in the substance concentration, as well as time depending nutrient uptakes.

2.4 Aquaponics

Aquaponics is the integration of fish culture with hydroponics (Goddek et al., 2015), while other trophic level combinations also exist (Nobre et al., 2010). The binding link between the systems is the water body, also called effluent or discharge water on the RAS side (Eding et al., 2006), and is an ingoing flow in the hydroponic part, called nutrient solution (Goddek et al., 2015). The difference of coupled and decoupled systems consists in the control of the water flow from the RAS to the plants (Goddek et al., 2015; Kloas et al., 2015). A coupled system, such as the UVI system, has the hydroponic part integrated in the circuit (Rakocy, 2012), while in the decoupled system the hydroponic part is separated from a RAS with a one-way valve (Kloas et al., 2015). In the coupled system, plants directly remove the substances from the water. But in a decoupled system, the amount of water, and subsequently the substances, is controlled by a valve.

2.5 Water quality

Water quality parameters are usually given by concentrations (mg / L), except salinity which is often given in percent or parts per thousand (ppt) (table 1) (Kamal and Mair, 2005; Timmons and Ebeling, 2010). In a mass balance these information have to be converted into actual masses. In this study, the aquaponic system is based on a RAS with 40 m^3 volume, which is kept constant through make-up water (Slinkert et al., 2015). For the hydroponics a maximal volume of 10 m^3 is given (Slinkert et al., 2015). Due to the fluctuation of the water because of its evaporation or plant transpiration (evapotranspiration), the volume of the hydroponic basin changes over the day (Goddek et al., 2015; Seawright et al., 1998; Slinkert et al., 2015).

	RAS		Hydroponics	
Substance	**Maximal conc. [mg/L]**	**Reference**	**Maximal conc. [mg/L]**	**Reference**
N	100	Eding et al., 2006	434	Kipp, 1997
K	106	Goddek et al., 2014	414	Kipp, 1997
Ca	180	Goddek et al., 2014	533	Kipp, 1997
Mg	44	Goddek et al., 2014	158	Sonneveld and Voogt, 2009
P	17	Goddek et al., 2014	62	Sonneveld and Voogt, 2009
S	50	Timmons and Ebeling, 2010	289	Kipp, 1997; Sonneveld and Voogt, 2009
Cl	18200	Kamal and Mair, 2005	531	Kipp, 1997
Na	11820	Kamal and Mair, 2005	275	Kipp, 1997

Table 1: Water quality requirements for RAS and tomatoes in hydroponics

Depending on the aquaponic system system design, the relevant water quality constraint depends on the overall minimal value (coupled system) or can be differentiated between fish tanks and hydroponics (decoupled system). The water quality is assumed to be stable and not to have any internal processes like precipitation.

2.6 System imports and exports

The import and export processes are limited to the fish feed, pH control, faeces removal and the water, transferred from the aquaculture system to the hydroponics. This study limits the focus on the macro- and micronutrients (N, K, Ca, Mg, P, S, Cl, Na) inside the water which are brought in through the fish feed and taken up by the plants. Other nutrients from gaseous sources (e.g. oxygen, carbon dioxide, elementary nitrogen) are not part of the MFA, likewise energy use (e.g. heating, cooling, light), is not taken into account.

2.7 Assumptions

The aquaponic system is driven by the feed input for the fish. This amount is assumed to be consumed with the same FCR over all cohorts or size classes. Additionally the partition of the substances into uptake, faeces and water (see table 2) are assumed to be constant overall sizes, without any leeching of the feed. In our analysis the faeces are assumed to be removed from the system. Thus, all faecal substances are removed by a solids removal treatment, including the suspended solids. Additionally, the feed spills are assumed to be zero.

The selected values for temperature and pH of the aquaponic system have no importance for the model itself, while maintaining the pH within certain boundaries is essential for the fish and plants. The added substances to maintain the pH (ph control) are included in the MFA for nitrogen. Other substances which might affect the pH are not included in this study.

Substance	**Feed content**	**Reference**
N	51.80 g/kg feed	Moccia et al., 2007
K	2.00 g/kg feed	Shiau and Hsieh, 2001
Ca	8.00 g/kg feed	Köprücü and Özdemir, 2005
Mg	1.80 g/kg feed	Moccia et al., 2007
P	6.83 g/kg feed	Guimarães et al., 2008
S	2.83 g/kg feed	Köprücü and Özdemir, 2005
Cl	18220.00 g/kg feed	Cnaani et al., 2010
Na	11780.00 g/kg feed	Cnaani et al., 2010
Substance	**Body content**	**Reference**
N	36.23 g/kg BW	Gonzales and Brown, 2006
K	0.06 g/kg BW	Gonzales and Brown, 2006
Ca	4.76 g/kg BW	Gonzales and Brown, 2006
Mg	0.13 g/kg BW	Gonzales and Brown, 2006
P	0.26 g/kg BW	Gonzales and Brown, 2006
S	2.45 g/kg BW	Köprücu and Özdemir, 2005
Cl	- g/kg BW	
Na	0.39 g/kg BW	Gonzales and Brown, 2006
Substance	**Faeces content**	**Reference**
N	28.30 g/kg DW	Naylor et al., 1999
K	1.00 g/kg DW	Naylor et al., 1999
Ca	6.53 g/kg DW	Köprücü and Özdemir, 2005
Mg	5.30 g/kg DW	Naylor et al., 1999
P	6.69 g/kg DW	Köprücü and Özdemir, 2005
S	0.38 g/kg DW	Köprücü and Özdemir, 2005
Cl	- g/kg DW	Naylor et al., 1999
Na	- g/kg DW	Naylor et al., 1999

Table 2: The used feed, body and faeces composition (see tables A.1.5, A.2.2 and A.3.2)

Based on the system design of a coupled aquaponic system, it is not possible to maintain different levels of pH for a coupled system. Therefore a pH change for the hydroponic part is not included, despite this is possible in the decoupled system. Due to the scarcity of detailed time differentiating nutrient uptakes of plants and nutrient supply from the fish in aquaponic systems, a 24 hours time frame is used for the mass balances. Due to the low TAN tolerance of the fish, it is assumed to be fully converted into nitrate within 24 hours.

Because of the scarcity of information about the detailed partition of the single nutrients for the uptake of the plants, a constant nutrient ratio is assumed, independent of the development stage. This study does not cover any energy balance. Temperature and light conditions are assumed to be in the optimal range at all times, thus not restricting the growth of fish and plants. Oxygen supply and degassing are not covered in this study, as they would need the inclusion of gaseous balances. Likewise, and for a fair comparison between coupled and decoupled systems, any addition of fertilizer or minerals to change the conductivity are excluded, as well as pH changes by the plants and water re-use in the decoupled system.

2.8 Model equation

The material flow model is based on the conservation of mass without temporal storage and is given by

$$m_{water}=m_{feed}-\frac{m_{body}}{FCR}-m_{faeces}*F_{faeces\,DW} \quad (1)$$

The mass m_{water} released to the water [g / kg feed] equals the imported m_{feed} [g / kg feed] minus the partitioned masses of m_{body} / FCR [g / kg Bodyweight / (g Feed / g Bodyweight)], where the FCR is needed to convert the bodyweight (BW) into the dry weight mass of the feed, minus the mass of the faeces m_{faeces} [g / kg faeces wet weight] multiplied by its dry-weight factor [g faeces wet weight / kg feed].

For the RAS, the masses (see table 2) of the feed ($m_{feed,}$), the body composition (m_{body}), the fish faeces (m_{faeces}) have to be balanced. Due to the distribution of substances inside the fish, the FCR is used to distinguish between dry weight of the feed and the body weight of the fish. Additionally the dry weight factor for the faeces ($F_{faecesDW}$) has been determined, to match the substances of the feed, to the substance content of the faeces (Rafiee and Saad, 2005). With FCR = 1.11 (Kamal and Mair, 2005) and $F_{faecesDW}$ = 0.214 (see table A.2.3) (Rafiee and Saad, 2005) being constants, the masses of each of the substances, have to be conserved. As the feed is pelleted, the moisture content is expected to be close to zero, thus the feed dry weight is assumed to equal the fish feed.

3 Material flow analysis

A material flow analysis of an aquaponic system can be done for different time durations (e.g. day, per cohort, year, production cycle). The best choice of the time frame to look at, depends on the tasks which have to be performed and the available data to incorporate into the balance. Due to the scarcity of knowledge about detailed processes of the digestion in fish and the uptake in plants, as yet a daily interpretation is appropriate.

3.1 Aquaculture

The daily system imports of the RAS are water, fish feed and a base for pH control. The daily exports are water with its soluble and particulate compounds and solids in the form of faeces (see fig. 2). The feed conversion ratio (FCR) is the reported mean at 0 ppt salinty of different tilapia species (Kamal and Mair, 2005). The feeding protocol is based on published data of a feed company (Coppens international bv, The Netherlands, http://www.coppens.eu) and the unpublished production plan of the INAPRO project. Currently there is no detailed faeces analysis for tilapia available, why the findings in rainbow trout are used as a starting point (Moccia et al., 2007; Naylor et al., 1999). Due to the difference in macronutrient recommendation per species (Figueiredo-Silva et al., 2013), these data have been adapted with other findings in Nile tilapia (Cnaani et al., 2010; Kandeepan, 2013; Köprücü and Özdemir, 2005; Moccia et al., 2007; Ng and Romano, 2013; Robinson et al., 1987; Shiau and Hsieh, 2001). Also there is no specific dataset available for the conversion of the substances of the diet weight into the respective dry matter weight for Nile tilapia, therefore it is assumed to be equal over all nutrients.

The fish take up nutrients through the ingested feed (Clement and Lovell, 1994; Dale et al., 2004; Gonzales and Brown, 2006; Köprücü and Özdemir, 2005). For the protein nitrogen conversion the Kjeldahl method has been used (Eding et al., 2006; Köprücü and Özdemir, 2005). Due to the differences in reported sulphur body content, the smallest one has been used (Gonzales and Brown, 2006; Köprücü and Özdemir, 2005), while other substance values have been calculated from the corresponding mass balance. By applying the mass balance formula (Eq. 1) to all documented nutrients, the following partition results (see fig. 3 and table A.4 for numerical results).

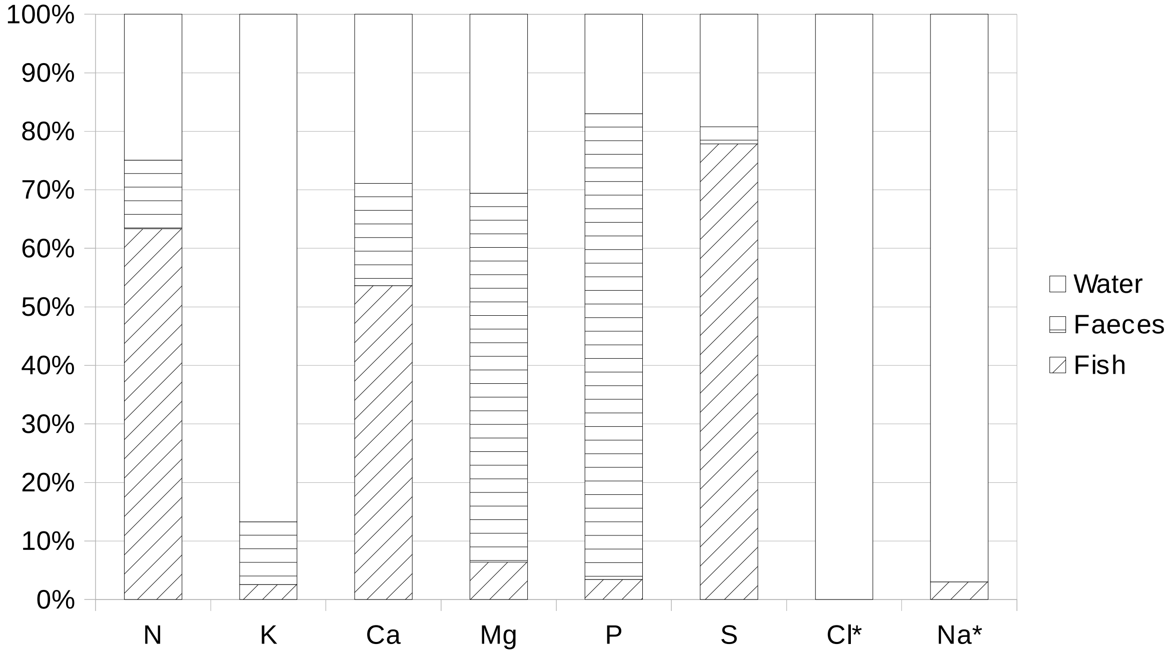

Figure 3: Feed substance partition into fish, faeces and water for N, K, Ca, Mg, P, S, Cl and Na. (*) incomplete dataset

The results of the partition for nitrogen differ from literature for tilapia (Endut et al., 2009; Rafiee and Saad, 2005). This is a consequence of the different species used in the studies, as trout (Moccia et al., 2007; Naylor et al., 1999) and red tilapia (Endut et al., 2009; Rafiee and Saad, 2005) differ from each other and have a different body and faecal composition, also Nile tilapia is expected to have a different composition.

As it can be seen for chloride, the whole mass is appearing in the water and none in the faeces and the body (see fig. 3). The original datasets for faeces and body composition do either not include chloride or chloride is not present in the body (Moccia et al., 2007; Naylor et al., 1999).

According to the production plan, the average daily feed import is an average of the cohort feed input. The cohort has a length of 45 days and the average feed import into the system is 21.9 kg/day (fig. 4). The fluctuations of the system feed input are beyond a daily interval, therefore these fluctuations, as well as the strong decrease on day 44 (fig. 4), are not included in this analysis.

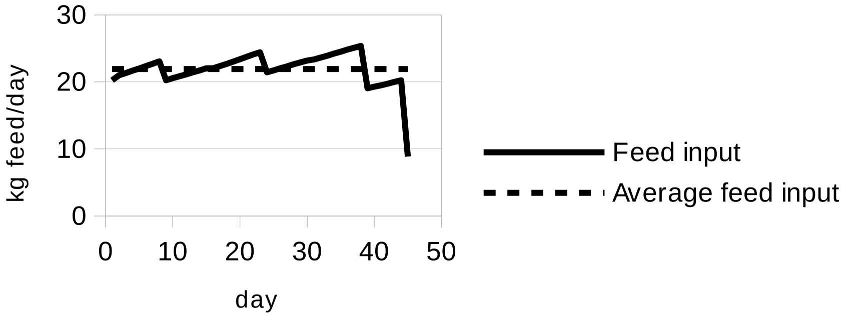

Figure 4: Averaged cohort feed plan

It is assumed that within one day, all the ammoniacal nitrogen is converted into nitrate by the nitrification processes in the bio-filter. Because of the release of TAN by the fish in relation to feeding, all the nitrate has its origin in the TAN (Eding et al., 2006). Based on the overall nitrification, the necessary pH compensation can be calculated, to keep its level constant. Per mol of TAN, 2 mol of hydrogen ions (H+) are released (Eding et al., 2006). Due to the bacterial biomass gain, this number is in reality slightly smaller with 1.98 mol H/mol NH_4-N (Eding et al., 2006). To counteract this alkalinity consumption, sodium bicarbonate ($NaHCO_3$) (Eding et al., 2006) or limestone ($CaCO_3$) (Goddek et al., 2015) can be used. For every alkali metal (e.g. Na^+, K^+, etc.) and alkaline earth metal (Mg^{2+}, Ca^{2+}, etc.) a bicarbonate and a carbonate compound exists. This degree of freedom can be used to counteract a shortage of nutrients supplied by the RAS effluent and therefore improve the overall suitability of the substance solution. The ratio of the nutrients is constant, as the fish feed composition does not change (fig. 5 and table A.4).

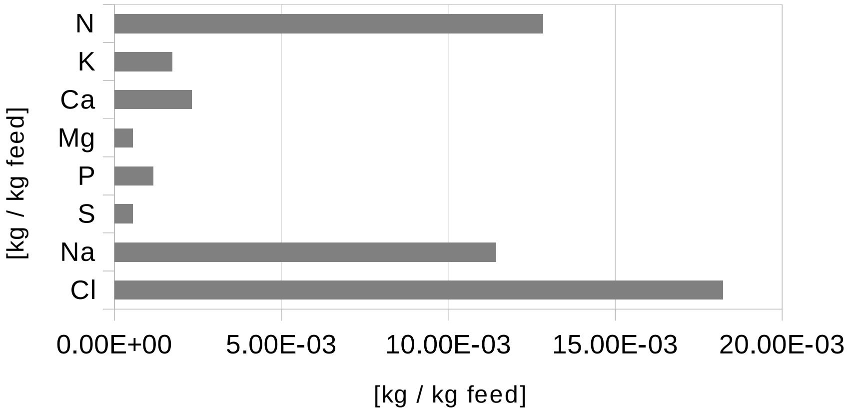

Figure 5: The ratio [kg/kg feed] between the substances

The effluent provided to the hydroponics depends on the water quality requirement for the tilapia and nutrients added through the fish feed. The minimal discharge per kilogram of feed $Q_{discharge}$ [L / kg feed], can be calculated by dividing the amount of substance per kilogram feed $m_{substance}$ [g / kg feed] by $c_{max,substance}$ [g / L]. That is,

$$Q_{discharge} = \frac{m_{substance}}{C_{max,\,substance}} \tag{2}$$

This discharge follows from a steady state mass balance and gives the minimal amount of water needed, to transport a certain substance out of the system (fig. 6).

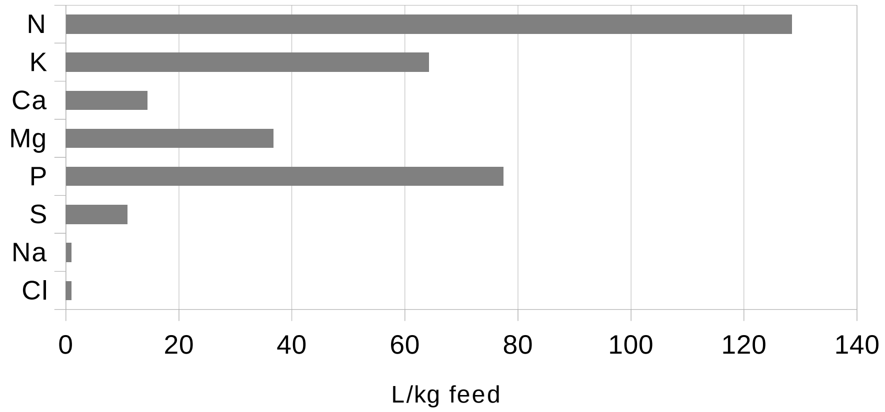

Figure 6: Minimal RAS discharge requirement based on feed partition and maximal allowable water concentration (see table A.5.2)

The requirement for discharge is because of the nitrogen (in form of nitrate) (also Eding et al., 2006), while the other substances stay below the maximal concentration tolerable for tilapia (see Eq. (2) and table A.5.2).

Based on the average feed input of 21.9 kg/day and the minimal discharge of 128.4 L/kg feed, a total daily discharge of 2812.2 L/day is required for the RAS.

3.2 Hydroponics

There have been reports of greenhouse tomato yields of 56.2 kg/m^2 (De Gelder et al., 2005). A fixed substance partition for N, S, P, K Ca, Mg and water uptake (Voogt, 1993) is most valuable for this study, as it provides insight in the actual uptake ratio and does not compare different substances against each other. As the model is based on a daily material flow, the average substance uptake over the whole growth period has been taken into account, including the water evaporation. Seasonal or daily changes have not been taken into account. Based on the data from Voogt (1993) and De Gelder et al. (2005), a daily uptake per m^2 of 0.404 g-N, 0.110 g-S, 0.098 g-P, 0.707 g-K, 0.295 g-Ca and 0.069 g-Mg is predicted (see tables A.6.2 and A.6.3). Due to the lack of data for sodium and chloride, no uptake is considered.

Tomatoes do not only take up nutrients, but also evaporate water in which the nutrients are solved. The amount of evaporated water is assumed to be 2.9 mm/m^2/day. Due to the high sensitivity of tomatoes to sodium and chloride in the provided substance solution, these nutrients are the drivers for the required discharge. Based on maximal allowable concentrations in the hydroponic system, the discharge driver is sodium (274.8 mg / L) or chloride (531.0 mg / L). The nutrients provided and the maximal allowable concentration, allow the calculation of the minimal required discharge (Eq. 2), resulting in a minimal discharge for chloride of 751 L / day and for sodium of 911 L / day. Thus, every day approximately 1 m^3 waste water has to be discharged.

3.3 Aquaponics

Given the mass of the substances in the effluent from the RAS and the substance uptake of the tomatoes, the spatial requirement for the hydroponic area can be calculated from

$$A_{substance,req} = \frac{m_{substance,effluent}}{m_{substance,uptake}} \tag{3}$$

where $A_{substance,req}$ [m^2] is the minimal spatial requirement the substance mass in the effluent $m_{substance,effluent}$ [g / day] and $m_{substance,uptake}$ [g / m^2 / day] the uptake of the substance by the plants.

Substance	RAS effluent [g/day]	Predicted uptake [g/m2/day]	Spatial requirement [m2]
N	281.2	0.4	695.4
K	38.0	0.7	53.7
Ca	50.7	0.3	171.8
Mg	12.1	0.1	175.6
P	25.4	0.1	258.5
S	11.9	0.1	108.6

Table 3: Minimal spatial requirement per substance (sodium and chloride have been left out, as they are not taken up by the model)

From the spatial requirement (see table 3) it can be seen, that the effluent of the RAS is extremely short in potassium, compared to other substances, especially nitrogen. The same has been reported earlier in other studies (Graber and Junge, 2009; Kloas et al., 2015).

The sensitivity of tomatoes to salinity is depending on the cultivar, but also on the ratio of the available substances (Satti and Al-Yahyai, 1995). To improve the fitting of the RAS effluent to the tomato uptake, pH control can be used. Due to the decreased calcium content of tomato fruits with increased salinity (Satti and Al-Yahyai, 1995), the use of sodium bicarbonate ($NaHCO_3$) does not seem useful, as it would increase the sodium content of the solution. Potassium bicarbonate seems like the best choice, to improve to overall ratio of the solution.

A daily amount of 281.2 g-N is supplied to the RAS in the form of fish feed, which will result as TAN in the water. The conversion of ammonia into nitrate requires an pH compensation, to prevent the pH from dropping, due to the H^+-ion release of the nitrification process. Based on the atomic weight of nitrogen of 14 g / mol and the daily input of 281.2g-N / day, daily 20.09 mol-N/day have to be converted. Due to the biomass of the nitrifying bacteria, an alkalinity compensation 1.98 mol-H / mol-N has to be introduced (instead of 2.00) (Eding et al., 2006). Thus 39.78 mol-H / day have to be bound. Given the atomic weight of potassium of 39.1 g / mol, potassium bicarbonate ($KHCO_3$) is used in this study, which has a molar weight of 100.1 g / mol. The addition of 39.8 mol equals a total weight of 3982.1 g-$KHCO_3$ / day, which adds 1555.2 g-K / day. As an alternative also magnesium carbonate might be added, which results in 1676.7 g-$MgCO_3$ / day or 483.3 g-Mg / day, given the atomic weight of magnesium of 24.3 g / mol. The shortage of potassium, calcium and magnesium can thus be counteracted by strategic choosing of (bi-)carbonate compounds (see table A.7).

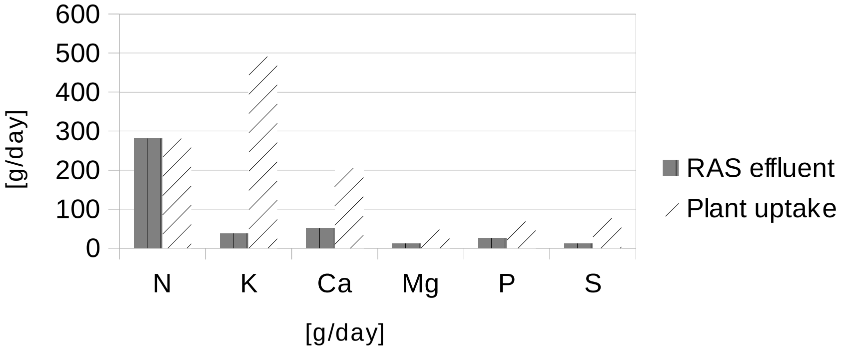

Figure 7: Daily system substance balance (see tables 4 and A.5.3)

Based on the findings for nitrogen, a spatial area of the hydroponic system of 695 m^2 was calculated, under the assumption that the shortages of substances are not limiting for the plants (see table 4 and fig. 7).

Substance	Uptake [g/m^2/day]	Area [m^2]	Daily uptake [g/day]
N	0.404	695	281.1
S	0.110	695	76.3
P	0.098	695	68.4
K	0.707	695	491.4
Ca	0.295	695	204.9
Mg	0.069	695	47.7
Water	2920.030	695	2029420.9

Table 4: Daily substance uptake by the plants

3.3.1 Decoupled aquaponic systems

Based on the discharge requirement for nitrogen and a maximal nitrogen concentration of 100 mg-N/L in the RAS (40 m^3), a total of 4000 g-N (100 mg-N / L * 40000 L) can accumulate. With 12.8 g-N / kg feed a total of 311.5 kg feed (4000 g-N / 12.8 g-N / kg feed) can be added into the RAS before discharge to the decoupled hydroponic system is required, which corresponds the feeding of 14.2 days (311.5 kg feed / 21.9 kg feed / day). Due to the constant water replacement and discharge, the composition of the effluent is constant, based on the assumption of a maximal concentration of nitrogen and using Eq. (2), a discharge of (128.4 L / kg feed * 21.9 kg feed / day =) 2812.2 L/day from the RAS is needed (table A.5.2).

Substance	Substance added netto [g/kg feed]	Daily feeding [kg feed/day]	System volume [m3]	Days [day]	RAS Discharge concentration [mg/L]
N	12.8	21.9	40.0	14.2	100.0
K	1.7	21.9	40.0	14.2	13.5
Ca	2.3	21.9	40.0	14.2	18.0
Mg	0.6	21.9	40.0	14.2	4.3
P	1.2	21.9	40.0	14.2	9.0
S	0.5	21.9	40.0	14.2	4.2
Na	11.4	21.9	40.0	14.2	89.0
Cl	18.2	21.9	40.0	14.2	141.8

Table 5: Substance composition of the RAS effluent in the decoupled aquaponics

All the values of the effluent are within the water quality requirements of the hydroponics (see table A.8.2). With the above mentioned concentrations, it can be expected to get a daily flow of effluent from the RAS of 2812.22 L / day, as shown earlier. The amount of water left in the hydroponic tank (2812 L – 2029 L = 783 L) requires additional water to not exceed the maximally allowed concentrations for sodium in the plant nutrient solution (see table 1), which requires a minimal discharge of 911 L/day to prevent accumulation (see table 6). Thus (911 L – 783 L =) 128 L of water have to be added to the hydroponics to not exceed the maximal allowable sodium concentration.

Substance	Substance amount [g/day]	Maximal concentration [mg/L]	Volume [L]	Substance system mass [g]	Days before discharge [days]	Minimal discharge volume [L]
Na	250.2	274.8	40000.0	10992.0	43.9	910.6
Cl	398.9	531.0	40000.0	21240.0	53.3	751.2

Table 6: Minimal discharge volume for a coupled aquaponic system based on sodium and chloride accumulation

A maximum of 783 L / day * 274.8 mg-Na / L = 215.2 g-Na / day can be discharged by the given water volume. The minimal water discharge for a decoupled aquaponic system with the given substance composition for the fish feed is 911 L / day / 21.9 kg feed / day = 41.6 L / kg feed due to sodium.

3.3.2 Coupled Aquaponics

Based on the findings for the decoupled system, the substance concentration of the water is the same after 14.22 days. Also the plant uptake is the same, as the hydroponic area is also 695 m^2. Based on the assumption that discharge of the sodium and chloride takes place before they accumulate, the discharge of the system would need at least 2711.4 L / day (see table A.9.1), which is similar to the standalone RAS discharge requirement. In an aquaponic system the cause of the discharge is sodium, while in the RAS it is nitrate (Eding et al., 2006). To improve the situation (see tab. 7), the accumulation of sodium and chloride has to be tolerated.

Substance	Maximal daily Concentration [mg/L]	Theoretical discharge [L/day]	Loss per day [g/day]
N	93.0	2812.2	261.4
K	11.6	2812.2	32.6
Ca	16.3	2812.2	45.8
Mg	-8.0	2812.2	-22.5
P	3.9	2812.2	11.0
S	3.0	2812.2	8.6
Na	89.0	2812.2	250.2
Cl	141.8	2812.2	398.9

Table 7: Lost substances in a coupled aquaponic system without sodium accumulation

Accumulating sodium and chloride before discharge, increases efficiency due to lower water usage. This has a negative effect on the tomatoes, as they prefer as little sodium and chloride as possible (see tables A.6.1a and A.6.1b) (Komosa and Górniak, 2015; Satti and Al-Yahyai, 1995). This would result in a daily discharge of 2711.4 L/day.

Due to the requirement of minimal water level in a coupled aquaponic system because of the fish, a minimal water strategy (complete discharge) as in the decoupled system is not possible. Thus an accumulation of sodium and chloride is necessary, to keep the discharge as little as possible ('little' means as much substance per litre as possible).

The analysis for a coupled system with sodium an chloride accumulation shows, that after a maximal period of 44 days the discharge is necessary, to keep the sodium level below the maximal concentration (see tab. A.9.2). At this concentration, a minimum of 911 L/day is required to discharge the daily imported sodium, which equals 41.6 L / kg feed.

4 Discussion

The material flow analysis has proven to be useful to investigate the aspects needed in aquaponic systems. Due to the limited number of inputs (fish feed, water, pH control) in such systems, the composition of each is extremely important. The data needed to form such a complete analysis is scarce, but results from Kloas et al. (2015) show similarity to the results of this study. To further improve the used numbers, experiments are needed to identify further differences in the known system designs. The dry weight factor of the faeces (Rafiee and Saad, 2005) and the composition of the faeces (Moccia et al., 2007; Naylor et al., 1999) are based on single datasets (Eq. 1), thus these may not be accurate for this analysis. The model (see table A.4) results in some compounds (Fe, Mn, Si, B, Se) in negative mass balances, due to either errors of the measurements or the differences in fish species.

In general we know, that the FCR is highly dependent on the used feed, while the faeces depend on the used binder in the fish feed. Thus, the factors for FCR and faeces dry weight in the mass balance (Eq. 1) contain uncertainties and need verification for Nile tilapia through experiments. Additional knowledge from fish nutrition might also affect the substances in the body composition, due to their high plasticity (see table A.3.1). But the actual origin of the plasticity is at the moment unknown. The big number of substances requires a validation for each of the substances.

In this study the water processes have been excluded. It is necessary to include further details about the behaviour of substances in the water. Due to a continuous water flow, changes can be expected in different system parts depending on the water flow. Solids removal is part of the RAS. But we know, that faeces can decompose if they are not removed in short time and affect the function of the bio-filter. Thus the removal of the faeces is important. The necessary pH control for counteracting the bio-filter conversion enables some degree of freedom in the control of the substance solution. But further knowledge in plant-fish interaction is necessary to investigate the interaction between the faecal treatment and the plants inside an aquaponic system to include it in a model.

Most of the hydroponic research is based on controlled nutrient solutions without any incorporation of suspended solids. The availability of the nutrients from the RAS has to be verified, as this study does not focus on the different chemical species. This difference might make it necessary to evaluate other approaches than NFT, such as aeroponics, to provide the plants the needed substances that might be beneficial as a response to the high sodium and chloride content. The results of this study show the influence of the system design on the sodium discharge requirement and might be further improved to reduce the necessary water discharge. Because of the trade-off between water usage and high sodium and chloride concentration (salinity), the overall development of the minimal water discharge in the coupled and decoupled system is with 911 L / 21.9 kg feed = 41.6 L / kg feed higher, than reported in current low water exchange RAS (30 L / kg feed), which include denitrification (Martins et al., 2009). Because of the linear relationship between the substance concentrations, a lower maximal daily concentration of sodium can be achieved by increasing the spatial area of the plants (with addition of nitrogen fertilizer), a higher allowable maximal concentration for sodium or a reduction of the sodium content of the fish feed. Due to the link of the FCR to sodium chloride (Cnaani et al., 2010), a new feed composition also affects other aspects of the system design. It is also necessary to consider other fish species with less sodium chloride affinity to prevent these imports to the system (e.g. rainbow trout (Moccia et al., 2007)).

The system design of the decoupled aquaponic system can be used to provide the hydroponics a higher concentrated nutrient solution with less salinity by accumulating the nutrients before the discharge to the hydroponics, although this requires make-up water to compensate for the evaporation. In the coupled system there is no system differentiation between RAS and hydroponics, as they share the common water layer. In both system types the pH control provides a degree of freedom to steer the nutrients provided to the plants beyond the fish feed. Further degrees of freedom may be in the pH relevant processes of the plants, which have been excluded from the model.

By providing the best possible nutrient solution, the plants are assumed to grow ideally as the deficit of nutrients is as little as possible. With ideal growth, also the best possible nutrient removal and assumed yield should be achieved. By properly selecting the pH control with calcium, potassium and magnesium, additional fertilizer can be limited to sulphur and phosphorous, which are the second and third limiting nutrients (see fig. 7). Although at the moment the ideal composition of the selected compounds for pH control has to be determined through experiments. If the provided nutrient solution meets the needs perfectly, the environmental impact of the discharged water is assumed to be minimal (only sodium and chloride), due to maximal nutrient removal. This removal increases profits as they are converted into yields and decrease fertilizer use.

The maximal allowable concentrations are based on literature, which may not be suitable for aquaponic systems. To further decrease water usage (41.6 L / kg feed), more detailed knowledge is needed for the water quality requirements of the single parts (fish and plants). Especially in the decoupled system such information is needed for sodium, to prevent the use of additional water. Without make-up water need because of sodium, the achievable water discharge is 783 L / day / 21.9 kg feed / day = 35.8 L / kg feed based on the given maximal allowable nitrate concentration.

The fish feed (fish production plan), the pH control and the spatial requirement of the hydroponics share a linear relationship (see Fig. 7 and tables 1 and A.7). Thus the size of a system is defined by the amount of fish feed per day. The harmonization of the RAS (feed and pH control) to the nutrient requirements of the plants (including fertilizer) is a requirement on system design level independent of coupled of decoupled system design.

With the conditions of this study, a system recommendation on water usage is not possible. But for the substance loading of the discharged water, the decoupled system is better (see tables A.8.2 and A.9.1), as all substances except sodium and chloride are removed by the plants (table 8).

Substance	**Coupled [mg/L]**	**Dcoupled [mg/L]**
N	97.9	0.1
K	12.2	-42.1
Ca	17.2	-19.5
Mg	-8.4	-526.2
P	4.1	-197.0
S	3.2	-39.3
Na	93.7	274.7
Cl	149.4	437.8

Table 8: Discharge concentrations of aquaponic systems (negative values represent depleted substances)

5 Conclusion

Hydroponics are a viable way to reduce substance loading of RAS effluents. The discharged concentrations are depending on the system design and further investigation of the detailed substance behaviour is needed, to fully understand the system. Many details of internal processes are currently unknown. To further reduce the discharged water, the development of aquaponic fish feed is necessary to optimise the nutrient composition of the fish to the tomato plants. More substances have to be incorporated in models and experiments, to identify critical system substances besides sodium and chloride. Understanding the internal processes requires more research on fish nutrient behaviour and experiments on nutrient interaction in the water depending on the nutrient concentrations. Future research should focus on system design, fish feed composition and plant uptake to improve the overall performance of aquaponic systems, including pH control to steer the nutrient solution.

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A Appendix tables

A.1 Feed analysis

A.1.1 Premix analysis

The substance analysis of the premix gives an insight into the substances of fish feed for Nile tilapia (Guimarães et al., 2008).

Mineral Premix				
Na2SeO3	0.7	mg/kg diet	172.8	g/mol
MnO	50	mg/kg diet	70.9	g/mol
ZnO	150	mg/kg diet	81.3	g/mol
FeSO4	20	mg/kg diet	151.9	g/mol
CoSO4	0.5	mg/kg diet	155	g/mol
I2Ca	1	mg/kg diet	293.9	g/mol
NaCl	1000	mg/kg diet	58.3	g/mol
CaCO3	18500	mg/kg diet	100.1	g/mol
CaHPO4	30000	mg/kg diet	136.1	g/mol
Cr2O3	1000	mg/kg diet	152	g/mol
Sum				
Na	22.9	g/mol	392.981	mg/kg diet
Se	79	g/mol	0.320	mg/kg diet
Mn	54.9	g/mol	38.717	mg/kg diet
Zn	65.3	g/mol	120.480	mg/kg diet
Fe	55.8	g/mol	7.347	mg/kg diet
S	32.1	g/mol	4.330	mg/kg diet
I	126.9	g/mol	0.864	mg/kg diet
Ca	40.1	g/mol	16250.314	mg/kg diet
Cl	35.4	g/mol	607.204	mg/kg diet
P	31	g/mol	6833.211	mg/kg diet
Cr	52	g/mol	684.211	mg/kg diet

Table A.1.1: Premix analysis

A.1.2 Sulphur analysis based on feed protein composition

Sulphur analysis based on feed protein composition, as the provided sulphur content of the premix analysis has to be incomplete based on the mass balance assumption (Köprücü and Özdemir, 2005).

	per kg feed	**uptake**	**excretion**	**Molar weight**	**Sulphur**
	%	**%**	**%**	**g/mol**	**g/mol**
Methionine	0.7	86.6	13.4	149.21	32.1
Cysteine	0.5	86.2	13.8	121.15	32.1

		uptake	**excretion**	**Sulphur uptake**	**Sulphur excretion**
		g/kg feed	**g/kg feed**	**g-S/kg feed**	**g-S/kg feed**
Methionine		6.06	0.94	1.30	0.20
Cysteine		4.31	0.69	1.14	0.18

Table A.1.2: Sulphur analysis based on feed protein composition

A.1.3 Sodium chloride analysis

The estimated sodium chloride content of the tilapia feed is based on the findings on improved FCR based on dietary salt supplementation. An addition of 3 % salt improved the FCR (Cnaani et al., 2010), as the composition of the diet is assumed to be based on current knowledge.

	Molar weight	**Total amount**	
	g/mol	**%**	**g**
Na	22.9	1.18	11.78
Cl	35.4	1.82	18.22
Sum	58.3	3	30

Table A.1.3: Sodium chloride analysis

A.1.4 Feed substance overview

The reports about substance composition for tilapia feed only cover part of the nutrients. Thus a the knowlegde from different sources has been combined, based on the literature (see table A.1.1, A.1.2 and A.1.3) (Cnaani et al., 2010; Guimarães et al., 2008; Köprücü and Özdemir, 2005; Rafiee and Saad, 2005; Robinson et al., 1987; Shiau and Hsieh, 2001).

Substance	Amount	Reference
N	5.18 %	Moccia et al., 2007
	3.40 %	Rafiee and Saad, 2005
K	0.88 %	Moccia et al., 2007
	0.53 %	Rafiee and Saad, 2005
	2000.00 mg/kg diet	Shiau and Hsieh, 2001
Ca	1.53 %	Moccia et al., 2007
	0.80 %	Köprücü and Özdemir, 2005
	1.74 %	Rafiee and Saad, 2005
	16250.31 mg/kg diet	Guimarães et al., 2008
Mg	0.18 %	Moccia et al., 2007
	0.43 %	Rafiee and Saad, 2005
P	1.12 %	Moccia et al., 2007
	1.48 %	Rafiee and Saad, 2005
	6833.21 mg/kg diet	Guimarães et al., 2008
	5000.00 mg/kg diet	Robinson et al., 1987
S	4.33 mg/kg diet	Guimarães et al., 2008
	2830.00 mg/kg diet	Köprücü and Özdemir, 2005
Cl	- mg/kg DW	Moccia et al., 2007
	607.20 mg/kg diet	Guimarães et al., 2008
	18220.00 mg/kg diet	Cnaani et al., 2010
Cu	0.0024 %	Rafiee and Saad, 2005
	20.67 mg/kg DW	Moccia et al., 2007
Mn	78.00 mg/kg DW	Moccia et al., 2007
	0.003 %	Rafiee and Saad, 2005
	38.72 mg/kd diet	Guimarães et al., 2008
Fe	186.00 mg/kg DW	Moccia et al., 2007
	0.1094 %	Rafiee and Saad, 2005
	7.35 mg/kg diet	Guimarães et al., 2008
Zn	156.67 mg/kg DW	Moccia et al., 2007
	0.0056 %	Rafiee and Saad, 2005
	120.48 mg/kg diet	Guimarães et al., 2008
Co	1.50 mg/kg DW	Moccia et al., 2007
Mo	2.50 mg/kg DW	Moccia et al., 2007
Ni	4.00 mg/kg DW	Moccia et al., 2007
Na	392.98 mg/kg diet	Guimarães et al., 2008
	11780.00 mg/kg diet	Cnaani et al., 2010
Si	-	
B	-	
C	49210.00 mg/kg DW	Moccia et al., 2007
H	-	
O	-	
As	1.00 mg/kg DW	Moccia et al., 2007
Cd	1.00 mg/kg DW	Moccia et al., 2007
Cr	1.33 mg/kg DW	Moccia et al., 2007
	684.21 mg/kg diet	Guimarães et al., 2008
Hg	0.05 mg/kg DW	Moccia et al., 2007
Pb	5.00 mg/kg DW	Moccia et al., 2007
Se	1.00 mg/kg DW	Moccia et al., 2007
	0.32 mg/kg diet	Guimarães et al., 2008
Al	-	
Ba	-	

Table A.1.4: Feed substance overview

A.1.5 Used feed substance composition

In literature there a different reports on substance combinations used for tilapia feed. This plasticity makes it difficult to select the right value. Based on table A.1.4 the substances have been selected to fulfill the mass balance (Eq. 1 and table A.4).

Substance	Amount		Reference
N	51.80	g/kg feed	Moccia et al., 2007
K	2.00	g/kg feed	Shiau and Hsieh, 2001
Ca	8.00	g/kg feed	Köprücü and Özdemir, 2005
Mg	1.80	g/kg feed	Moccia et al., 2007
P	6.83	g/kg feed	Guimarães et al., 2008
S	2.83	g/kg feed	Köprücü and Özdemir, 2005
Cl	18.22	g/kg feed	Cnaani et al., 2010
Cu	0.02	g/kg feed	Moccia et al., 2007
Mn	0.08	g/kg feed	Moccia et al., 2007
Fe	0.19	g/kg feed	Moccia et al., 2007
Zn	0.16	g/kg feed	Moccia et al., 2007
Co	0.00	g/kg feed	Moccia et al., 2007
Mo	0.00	g/kg feed	Moccia et al., 2007
Ni	0.00	g/kg feed	Moccia et al., 2007
Na	11.78	g/kg feed	Cnaani et al., 2010
Si	-	g/kg feed	
B	-	g/kg feed	
As	0.00	g/kg feed	Moccia et al., 2007
Cd	0.00	g/kg feed	Moccia et al., 2007
Cr	0.68	g/kg feed	Guimarães et al., 2008
Hg	0.00	g/kg feed	Moccia et al., 2007
Pb	0.01	g/kg feed	Moccia et al., 2007
Se	0.00	g/kg feed	Guimarães et al., 2008

Table A.1.5: Used feed substance composition

A.2 Faeces composition

A.2.1 Faeces composition overview

Based on the reports in literature a review of reports of faeces composition has been made (Köprücü and Özdemir, 2005; Naylor et al., 1999).

Substance	Feces content	Reference
N	2.83 %	Naylor et al., 1999
K	0.1 %	Naylor et al., 1999
Ca	6.99 %	Naylor et al., 1999
	6.528 g/kg DW	Köprücü and Özdemir, 2005
Mg	0.53 %	Naylor et al., 1999
P	2.54 %	Naylor et al., 1999
	6.687 g/kg DW	Köprücü and Özdemir, 2005
S	- %	Naylor et al., 1999
	0.38 g/kg DW	Köprücü and Özdemir, 2005
Cl	- mg/kg DW	Naylor et al., 1999
Cu	33.4 mg/kg DW	Naylor et al., 1999
Mn	487.8 mg/kg DW	Naylor et al., 1999
Fe	1942 mg/kg DW	Naylor et al., 1999
Zn	604.9 mg/kg DW	Naylor et al., 1999
Co	1.82 mg/kg DW	Naylor et al., 1999
Mo	- mg/kg DW	Naylor et al., 1999
Ni	4.94 mg/kg DW	Naylor et al., 1999
Na	- mg/kg DW	Naylor et al., 1999
Si	- mg/kg DW	Naylor et al., 1999
B	-	Naylor et al., 1999
C	-	Naylor et al., 1999
H	-	Naylor et al., 1999
O	-	Naylor et al., 1999
As	2.2 mg/kg DW	Naylor et al., 1999
Cd	1.13 mg/kg DW	Naylor et al., 1999
Cr	3.86 mg/kg DW	Naylor et al., 1999
Hg	0.05 mg/kg DW	Naylor et al., 1999
Pb	5.54 mg/kg DW	Naylor et al., 1999
Se	0.5 mg/kg DW	Naylor et al., 1999
Al	-	Naylor et al., 1999
Ba	-	Naylor et al., 1999

Table A.2.1: Faeces composition overview

A.2.2 Used faeces composition

Based on the review of available data (see table A.2.1) and the mass balance approach (table A.4), a representative faeces composition has been chosen from Rainbow trout (Naylor et al., 1999) and Nile tilapia (Köprücü and Özdemir, 2005).

Substance	Faeces content		Reference
N	28.30	g/kg DW	Naylor et al., 1999
K	1.00	g/kg DW	Naylor et al., 1999
Ca	6.53	g/kg DW	Köprücü and Özdemir, 2005
Mg	5.30	g/kg DW	Naylor et al., 1999
P	6.69	g/kg DW	Köprücü and Özdemir, 2005
S	0.38	g/kg DW	Köprücü and Özdemir, 2005
Cl	-	g/kg DW	Naylor et al., 1999
Cu	0.03	g/kg DW	Naylor et al., 1999
Mn	0.49	g/kg DW	Naylor et al., 1999
Fe	1.94	g/kg DW	Naylor et al., 1999
Zn	0.60	g/kg DW	Naylor et al., 1999
Co	0.00	g/kg DW	Naylor et al., 1999
Mo	-	g/kg DW	Naylor et al., 1999
Ni	0.00	g/kg DW	Naylor et al., 1999
Na	-	g/kg DW	Naylor et al., 1999
As	0.00	g/kg DW	Naylor et al., 1999
Cd	0.00	g/kg DW	Naylor et al., 1999
Cr	0.00	g/kg DW	Naylor et al., 1999
Hg	0.00	g/kg DW	Naylor et al., 1999
Pb	0.01	g/kg DW	Naylor et al., 1999
Se	0.00	g/kg DW	Naylor et al., 1999

Table A.2.2: Used faeces composition

A.2.3 Faeces dry weight factor

The faeces dry weight factor is based on one report for Red tilapia (Rafiee and Saad, 2005), as no other dataset has been found.

Fish groups [g]	feed input [g]	dry sludge [g]	dry solid [g]	faeces **[%]**
20	2025	182.5	349.1	**26.25%**
40	2167	113.5	444.8	**25.76%**
80	2702	159.41	334.8	**18.29%**
120	3579	169.1	436.2	**16.91%**
180	2868	224.1	440	**23.16%**
Total	**13341**	**848.61**	**2004.9**	**21.39%**

Table A.2.3: Faeces dry weight factor

A.3 Tilapia body composition

A.3.1 Reported body compositions for Nile tilapia

The reported substance contents for Nile tilapia (Clement and Lovell, 1994; Dale et al., 2004; Gonzales and Brown, 2006; Köprücü and Özdemir, 2005).

	Dale et al., 2004	**Gonzales and Brown, 2006**	**Clement and Lovell, 1994**	**Köprücu and Özdemir, 2005**
	whole body	**whole body**	**fillet**	**Uptake**
Substance	**mg/100g DW**	**mg/100g DW**	**mg/100g raw fillet ****	**mg/100g**
N	3425 *	3623.13	3248.00 *	
K	380	5.69	324.00	
Ca	8400	476.15	17.50	147.20
Mg	150	12.75	26.26	
P	4100	25.87	169.00	231.30
S		600.00		244.61
Cl				
Cu	0.09	0.05	0.09	
Mn	0.139	0.02	0.01	
Fe	1.87	0.03	1.76	
Zn	0.675	1.35	0.70	
Co		0.06	0.04	
Mo		0.57	0.01	
Ni				
Na	380	39.47	34.70	
Si			0.16	
B		0.04	0.06	
C				
H				
O				
As				
Cd				
Cr		7.10	0.04	
Hg				
Pb			0.01	
Se		0.71		
Al			0.36	
Ba			0.05	

* Kjeldahl protein calculation

** the fillet represents 36% of the body

Table A.3.1: Reported body compositions for Nile tilapia

A.3.2 Used body composition for Nile tilapia

The used body composition based on the found body substance composition (see table A.3.1) and the mass balance approach (see table A.4) (Clement and Lovell, 1994; Gonzales and Brown, 2006; Köprücü and Özdemir, 2005).

Substance	Body content		Reference
N	3623.13	mg/100g	Gonzales and Brown, 2006
K	5.69	mg/100g	Gonzales and Brown, 2006
Ca	476.15	mg/100g	Gonzales and Brown, 2006
Mg	12.75	mg/100g	Gonzales and Brown, 2006
P	25.87	mg/100g	Gonzales and Brown, 2006
S	244.61	mg/100g	Köprücu and Özdemir, 2005
Cl	-	mg/100g	
Cu	0.09	mg/100g	Clement and Lovell, 1994
Mn	0.02	mg/100g	Gonzales and Brown, 2006
Fe	0.03	mg/100g	Gonzales and Brown, 2006
Zn	1.35	mg/100g	Gonzales and Brown, 2006
Co	0.04	mg/100g	Clement and Lovell, 1994
Mo	0.01	mg/100g	Clement and Lovell, 1994
Ni	-	mg/100g	
Na	39.47	mg/100g	Gonzales and Brown, 2006
Si	0.16	mg/100g	Clement and Lovell, 1994
B	0.06	mg/100g	Clement and Lovell, 1994
C	-	mg/100g	
H	-	mg/100g	
O	-	mg/100g	
As	-	mg/100g	
Cd	-	mg/100g	
Cr	7.10	mg/100g	Gonzales and Brown, 2006
Hg	-	mg/100g	
Pb	-	mg/100g	
Se	705.00	mg/100g	Gonzales and Brown, 2006
Al	0.36	mg/100g	Clement and Lovell, 1994
Ba	0.05	mg/100g	Clement and Lovell, 1994

Table A.3.2: Used body composition for Nile tilapia

A.4 Overall substance partition

By combining the information from tables A.1.5, A.3.2, A.2.2, A.2.3 the following substance partition can be found based on formulas 1), 2) and 3). The negative values for Fe, Mn, Si, B and Se are a consequence of the standard deviation in the original dataset or the different species used in the study (Moccia et al., 2007; Naylor et al., 1999).

1) $$m_{bodyF} = \frac{\frac{m_{body} * 10}{1000}}{FCR}$$

2) $$m_{faecesDW} = m_{faeces} * F_{FaecesDW}$$

3) $$m_{water} = \left(m_{feed} - m_{bodyF} - m_{faecesDW}\right) * F_{nitrification}$$

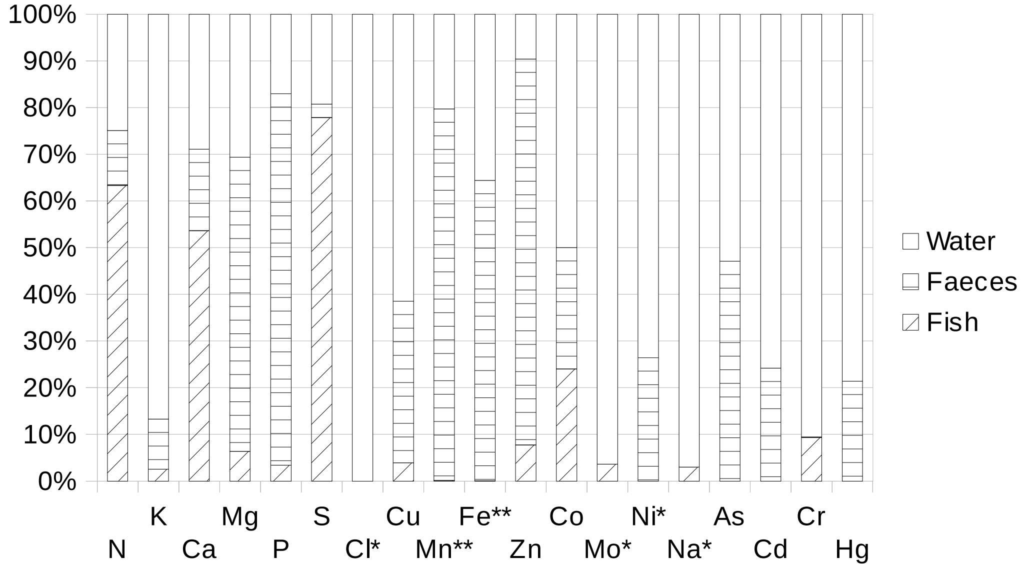

*Figure A.4: Feed substance partition into fish, faeces and water without Si, B, C, H, O due to data scarcity (*) incomplete dataset; **) overall balance is negative)*

Sub-Stance	**Feed composition (table A.1.5)** [g/kg feed] m.feed	**Body composition (table A.3.2)** [mg/100g] m.body	**Faeces composition (table A.2.2)** [g/kg DW] m.faeces	**FCR** [-]	**Fish uptake 1)** [g/kg feed] m.bodyF	**F,FaecesDW (table A.2.3)** [-] F.FaecesDW	**Faeces content 2)** [g/kg feed] m.faecesDW	**Nitrification correction** [-] F.nitrification	**Water Substances 3)** [g/kg feed] m.water
N	51.80	3623.13	28.30	1.11	32.64	0.214	6.06	0.98	12.841
K	2.00	5.69	1.00	1.11	0.05	0.214	0.21	1.00	1.735
Ca	8.00	476.15	6.53	1.11	4.29	0.214	1.40	1.00	2.313
Mg	1.80	12.75	5.30	1.11	0.11	0.214	1.13	1.00	0.551
P	6.83	25.87	25.40	1.11	0.23	0.214	5.44	1.00	1.161
S	2.83	244.61	0.38	1.11	2.20	0.214	0.08	1.00	0.545
Cl	18.22	-	-	1.11	0.00	0.214	0.00	1.00	18.216
Cu	0.02	0.09	0.03	1.11	0.00	0.214	0.01	1.00	0.013
Mn	0.08	0.02	0.49	1.11	0.00	0.214	0.10	1.00	-0.027
Fe	0.19	0.03	1.94	1.11	0.00	0.214	0.42	1.00	-0.230
Zn	0.16	1.35	0.60	1.11	0.01	0.214	0.13	1.00	0.015
Co	0.00	0.04	0.00	1.11	0.00	0.214	0.00	1.00	0.001
Mo	0.00	0.01	-	1.11	0.00	0.214	0.00	1.00	0.002
Ni	0.00	-	0.00	1.11	0.00	0.214	0.00	1.00	0.003
Na	11.78	39.47	-	1.11	0.36	0.214	0.00	1.00	11.428
Si	0.00	0.16	-	1.11	0.00	0.214	0.00	1.00	-0.001
B	0.00	0.06	-	1.11	0.00	0.214	0.00	1.00	-0.001
C	492.10	-	-	1.11	0.00	0.214	0.00	1.00	492.100
H	0.00	-	-	1.11	0.00	0.214	0.00	1.00	0.000
O	0.00	-	-	1.11	0.00	0.214	0.00	1.00	0.000
As	0.00	-	0.00	1.11	0.00	0.214	0.00	1.00	0.001
Cd	0.00	-	0.00	1.11	0.00	0.214	0.00	1.00	0.001
Cr	0.68	7.10	0.00	1.11	0.06	0.214	0.00	1.00	0.619
Hg	0.00	-	0.00	1.11	0.00	0.214	0.00	1.00	0.000
Pb	0.01	-	0.01	1.11	0.00	0.214	0.00	1.00	0.004
Se	1	705	0.5	1.11	6.35	0.214	0.11	1.00	-5.458
Al	-	0.36	-	1.11	0.00	0.214	0.00	1.00	-
Ba	-	0.05	-	1.11	0.00	0.214	0.00	1.00	-

Table A.4: Overall substance partition (mass balance)

A.5 Water quality concentrations in fish rearing systems

A.5.1 RAS water concentration limits

In literature there are some information about the concentrations used in RAS, which have been collected (Goddek et al., 2015; Kamal and Mair, 2005; Timmons and Ebeling, 2010)

Substance	Concentration	Reference
NO3-N	0-400 mg/L	Timmons and Ebeling, 2010
	20-137 mg/L	Goddek et al., 2014
	100 mg/L	Eding et al., 2006
K	<5 mg/L	Timmons and Ebeling, 2010
	27-106 mg/L	Goddek et al., 2014
Ca	4-160 mg/L	Timmons and Ebeling, 2010
	24-180 mg/L	Goddek et al., 2014
Mg	<15 mg/L	Timmons and Ebeling, 2010
	6-44 mg/L	Goddek et al., 2014
P	0.01-3.0 mg/L	Timmons and Ebeling, 2010
PO4-P	8-17 mg/L	Goddek et al., 2014
SO4-S	<50 mg/L	Timmons and Ebeling, 2010
	6 mg/L	Goddek et al., 2014
Cl	<0.003 mg/L	Timmons and Ebeling, 2010
	18200 mg/L	Kamal et Mair, 2005
Cu	0.18*10E-3 mg/L	Timmons and Ebeling, 2010
	0.03-0.05 mg/L	Goddek et al., 2014
Mn	<0.01 mg/L	Timmons and Ebeling, 2010
	0.06-0.8 mg/L	Goddek et al., 2014
Fe	<0.15 mg/L	Timmons and Ebeling, 2010
	0.2-2.5 mg/L	Goddek et al., 2014
Zn	2.4*10E-3 mg/L	Timmons and Ebeling, 2010
	0.34-0.44 mg/L	Goddek et al., 2014
Co	- mg/L	Timmons and Ebeling, 2010
Mo	- mg/L	Timmons and Ebeling, 2010
	0.01 mg/L	Goddek et al., 2014
Ni	<0.1 mg/L	Timmons and Ebeling, 2010
Na	<75 mg/L	Timmons and Ebeling, 2010
	11820 mg/L	Kamal et Mair, 2005
	14-17	Goddek et al., 2014
Si	- mg/L	Timmons and Ebeling, 2010
B	0 mg/L	Timmons and Ebeling, 2010
	0.09-0.19 mg/L	Goddek et al., 2014
As	<0.05 mg/L	Timmons and Ebeling, 2010
Cd	0.01 mg/L	Timmons and Ebeling, 2010
Cr	- mg/L	Timmons and Ebeling, 2010
Hg	<0.02 mg/L	Timmons and Ebeling, 2010
Pb	<0.02 mg/L	Timmons and Ebeling, 2010
Se	<0.01 mg/L	Timmons and Ebeling, 2010
Al	<0.01 mg/L	Timmons and Ebeling, 2010
Ba	<5 mg/L	Timmons and Ebeling, 2010

Table A.5.1: RAS water concentration limits

A.5.2 RAS minimal discharge requirement

Based on the water concentration limits (table 1) and Eq. (2), the minimal required discharge per kilogram of feed can be calculated.

Substance	Feed substances [g/kg feed]	Fish water quality [mg/L]	Minimal discharge requirement [L/kg feed]
N	12.841	100	128.4
K	1.735	27	64.2
Ca	2.313	160	14.5
Mg	0.551	15	36.7
P	1.161	15	77.4
S	0.545	50	10.9
Cl	18.216	18200	1.0
Na	11.431	11820	1.0

Table A.5.2: RAS minimal discharge requirement

A.5.3 Daily supplied substance mass by feed

The defined feed supply combined with the substances released into the water (table A.4) gives the daily supplied substance mass to the RAS.

Substance	Feed substances [g/kg feed]	Average feed input [kg feed/day]	Daily substance mass released into water [g/day]
N	12.841	21.902	281.242
K	1.735	21.902	37.994
Ca	2.313	21.902	50.667
Mg	0.551	21.902	12.067
P	1.161	21.902	25.436
S	0.545	21.902	11.931
Cl	18.216	21.902	398.970
Na	11.431	21.902	250.372

Table A.5.3: Daily supplied substance mass by feed

A.6 Hydroponics

A.6.1 Hydroponic water concentration limits

Plants do not only require a certain amount of substances, but also concentration of these substances within certain boundaries (Kipp, 1997; Sonneveld and Voogt, 2009).

Substance	**concentration**				**Reference**
EC	2.50	-	5.50	mS/cm	Kipp, 1997
	4.00			dS/m	Sonneveld and Voogt, 2009
NH4-N	1.40	-	7.00	mg/L	Kipp, 1997
	0.00	-	7.00	mg/L	Sonneveld and Voogt, 2009
K	207.23	-	414.46	mg/L	Kipp, 1997
	254.15	-	391.00	mg/L	Sonneveld and Voogt, 2009
Na	2.29	-	274.80	mg/L	Kipp, 1997
Ca	264.66	-	533.33	mg/L	Kipp, 1997
	320.80	-	481.20	mg/L	Sonneveld and Voogt, 2009
Mg	72.90	-	145.80	mg/L	Kipp, 1997
	65.61	-	157.95	mg/L	Sonneveld and Voogt, 2009
NO3-N	210.00	-	434.00	mg/L	Kipp, 1997
	238.00	-	392.00	mg/L	Sonneveld and Voogt, 2009
Cl	3.54	-	531.00	mg/L	Kipp, 1997
S	144.45	-	288.90	mg/L	Kipp, 1997
	128.40	-	288.90	mg/L	Sonneveld and Voogt, 2009
P	21.70	-	40.30	mg/L	Kipp, 1997
	21.70	-	62.00	mg/L	Sonneveld and Voogt, 2009
Fe	0.73	-	2.12	mg/L	Kipp, 1997
	0.50	-	1.40	mg/L	Sonneveld and Voogt, 2009
Mn	0.11	-	0.41	mg/L	Kipp, 1997
	0.16	-	0.55	mg/L	Sonneveld and Voogt, 2009
Zn	0.23	-	0.69	mg/L	Kipp, 1997
	0.33	-	0.65	mg/L	Sonneveld and Voogt, 2009
B	0.27	-	0.81	mg/L	Kipp, 1997
	0.38	-	0.70	mg/L	Sonneveld and Voogt, 2009
Cu	0.03	-	0.07	mg/L	Kipp, 1997
	0.03	-	0.10	mg/L	Sonneveld and Voogt, 2009
Mo	0.03	-	0.08	mg/L	Kipp, 1997
	0.03	-	0.08	mg/L	Sonneveld and Voogt, 2009

Table A.6.1a: Hydroponics water quality concentration limits

Kipp (1997) does not only give the boundaries for the concentrations, but also includes an optimal value for each of the substances.

Substance	Concentration				Reference
	ideal	min	max		
EC	3.70	2.50	5.50	mS/cm	Kipp, 1997
NH4-N	1.40	1.40	7.00	mg/L	Kipp, 1997
K	312.80	207.23	414.46	mg/L	Kipp, 1997
Na	138.55	2.29	274.80	mg/L	Kipp, 1997
Ca	401.00	264.66	533.33	mg/L	Kipp, 1997
Mg	109.35	72.90	145.80	mg/L	Kipp, 1997
NO3-N	322.00	210.00	434.00	mg/L	Kipp, 1997
Cl	267.27	3.54	531.00	mg/L	Kipp, 1997
S	218.28	144.45	288.90	mg/L	Kipp, 1997
P	31.00	21.70	40.30	mg/L	Kipp, 1997
Fe	1.40	0.73	2.12	mg/L	Kipp, 1997
Mn	0.27	0.11	0.41	mg/L	Kipp, 1997
Zn	0.46	0.23	0.69	mg/L	Kipp, 1997
B	0.54	0.27	0.81	mg/L	Kipp, 1997
Cu	0.05	0.03	0.07	mg/L	Kipp, 1997
Mo	0.05	0.03	0.08	mg/L	Kipp, 1997

Table A.6.1b: Hydroponic water quality requirement including optimal range

A.6.2 Hydroponic substance uptake

The tomato uptake of substances and water evaporation has been reported (Voogt, 1993).

Substance	Unit	Average	Exp 1	Exp2	Exp3	Exp4	Exp5
NO3	mmol/m^2	**6143.8**	5145	5400	5642	6324	8208
SO4	mmol/m^2	**728.4**	578	810	620	650	984
H2PO4	mmol/m^2	**675.8**	452	648	744	715	820
K	mmol/m^2	**3847**	2973	3618	3782	4680	4182
Ca	mmol/m^2	**1564.6**	1307	1242	1302	1430	2542
Mg	mmol/m^2	**601**	355	486	496	520	1148
Water	mm	**621**	475	540	620	650	820
	Plants/m^2	**2.14**	2.2	2.2	2.1	2.1	2.1
Yields	kg/m^2	**40**	32	26	48	46	48
Start growth			01/15/99	01/15/99	12/20/98	12/20/98	12/20/98
End growth			10/30/99	10/01/99	10/25/99	11/07/99	11/01/99
Number of days		**298.8**	288	259	309	322	316

Table A.6.2: Hydroponic substance uptake

A.6.3 Predicted plant uptake

The predicted plant uptake is based on findings on overall yield (De Gelder et al., 2005) and the uptake of each substance and water (Voogt, 1993). The yield factor is based on the yield of Voog (1993) divided by the yield of De Gelder et al. (2005) which is 40 kg / m2 / 56.2 kg / m2 = 1.405.

Substance	Average uptake/day (Voogt, 1993)	Predicted yield (De Gelder et al., 2005)	Yield factor	Predicted uptake
N	0.288 g/m2/day	56.2 kg/m2	1.405	0.404 g/m2/day
S	0.078 g/m2/day	56.2 kg/m2	1.405	0.110 g/m2/day
P	0.070 g/m2/day	56.2 kg/m2	1.405	0.098 g/m2/day
K	0.503 g/m2/day	56.2 kg/m2	1.405	0.707 g/m2/day
Ca	0.210 g/m2/day	56.2 kg/m2	1.405	0.295 g/m2/day
Mg	0.049 g/m2/day	56.2 kg/m2	1.405	0.069 g/m2/day
Water	2.078 mm/m2/day	56.2 kg/m2	1.405	2.920 mm/m2/day

Table A.6.3: Predicted plant uptake

A.7 pH control table

Eding et al. (2006) report the needed calculations for pH compensation for the nitrification of the bio-filter. Based on these calculations and the information from Goddek et al. (2015), the necessary amount have been calculated for potassium, sodium, magnesium and calcium. The calculation is based on the compensation of 1.98 mol HCO_3^- / mol NH_4-N of Eding et al. (2006).

Substance	**Daily substance mass [g/day]**	**atomic weight [g/mol]**	**Daily amount [mol/day]**	**Daily alkalinity**	**Aklinity factor [-]**
N	281.24	14.00	20.09	39.78	1
KHCO3	3982.14	100.12	39.78	39.78	1
K	1555.15	39.10	39.78	39.78	1
NaHCO3	3341.15	84.00	39.78	39.78	1
Na	914.04	22.98	39.78	39.78	1
MgCO3	1676.74	84.31	19.89	39.78	2
Mg	483.27	24.30	9.94	19.89	2
CaCO3	1990.37	100.08	19.89	39.78	2
Ca	797.10	40.08	9.94	19.89	2

Table A.7: pH control table

A.8 Decoupled System

A.8.1 RAS effluent concentration

Through the given water volume and the added feed per day, the length before reaching the maximal concentration can be calculated. The lowest number of days is showing the critical nutrient, thus a discharge after 14.2 days is needed because of the nitrogen substance.

Substance	Substance added netto [g/kg feed]	Daily feeding [kg feed/day]	Substance per day [g/day]	Water quality RAS [mg/L]	System volume [m3]	# days before discharge [day]
N	12.841	21.902	281.242	100	40	14.2
K	1.735	21.902	37.994	106	40	111.6
Ca	2.313	21.902	50.667	180	40	142.1
Mg	0.551	21.902	12.067	44	40	145.9
P	1.161	21.902	25.436	17	40	26.7
S	0.545	21.902	11.931	50	40	167.6
Na	11.428	21.902	250.302	11820	40	1888.9
Cl	18.216	21.902	398.970	18200	40	1824.7

Table A.8.1: RAS effluent concentration

A.8.2 Decoupled hydroponics uptake

Because of the installed valve, the hydroponic and fish part are separated from each other. Thus each part of the system can be adressed by its own specific maximal concentration of substances. This separation allows a strategy to have a minimal amount of water in the system, to prevent accumulation of nutrients. The concentration of accumulating substances (e.g. sodium and chloride) changes due to the evaporation of water by the plants. To remove these not take up nutrients, the discharge has to be triggered. Based on the maximal concentration and the amount of substance, the minimal water discharge is calculated. In the situation, where the water volume in the hydroponics has to be kept as low as possible, the minimal discharge also represents the minimal water level.

Substance	RAS Discharge concentration [mg/L]	Volume [L]	Substance mass [g]	Plant uptake [g/m2/day]	Area [m2]	Plant uptake [g/day]	Left substances [g/day]	Maximal concentration [mg/L]	Minimal water level [L/day]
N	99.982	2812.22	281.170	0.404	695	281.090	0.080	434	-
K	13.507	2812.22	37.985	0.110	695	76.340	-38.355	414.46	-
Ca	18.012	2812.22	50.654	0.098	695	68.397	-17.743	533.33	-
Mg	4.290	2812.22	12.063	0.707	695	491.438	-479.374	157.95	-
P	9.042	2812.22	25.429	0.295	695	204.933	-179.504	40.3	-
S	4.241	2812.22	11.928	0.069	695	47.746	-35.819	288.9	-
Na	88.983	2812.22	250.238	0.000	695	0	250.238	274.8	910.620
Cl	141.834	2812.22	398.867	0.000	695	0	398.867	531	751.163
			Nutrient solution [L]	**Plant evaporation [L/m2/day]**	**Area [m2]**	**Plant evaporation [L/day]**	**Left water [L/day]**		
Water			2812.22	2.92	695	2029.4	783	-	

Table A.8.2: Decoupled hydroponics uptake

A.9 Coupled aquaponic water concentrations

A.9.1 Non-accumulation discharge requirement

Based on the assumption to discharge the same amount of sodium and chloride as added through the feed, the minimal required discharge can be calculated.

Substance	Substance added netto [g/kg feed]	Daily feeding [kg feed/day	Substance per day [g/day]	System volume [L]	End water concentration [mg/L]	Minimal discharge [L/day]
N	12.841	21.902	281.242	38556	96.436	2916.355
K	1.735	21.902	37.994	38556	12.033	3157.526
Ca	2.313	21.902	50.667	38556	16.913	2995.772
Mg	0.551	21.902	12.067	38556	-8.296	-1454.542
P	1.161	21.902	25.436	38556	4.066	6255.938
S	0.545	21.902	11.931	38556	3.162	3773.304
Na	11.428	21.902	250.302	38556	92.316	2711.378
Cl	18.216	21.902	398.970	38556	147.146	2711.378

Table A.9.1: Non-accumulation discharge requirement for coupled aquaponics

A.9.2 Accumulation discharge requirement

Based on the maximal allowable substance concentration (see table 1), the following minimal

Substance	Substance added netto [g/kg feed]	Daily feeding [kg feed/day	Substance per day [g/day]	System volume [L]	Maximal concentration [mg/L]	Maximal accumulation time [day]
N	12.8	21.9	281.2	40000	100.0	14.2
K	1.7	21.9	38.0	40000	106.0	111.6
Ca	2.3	21.9	50.7	40000	180.0	142.1
Mg	0.6	21.9	12.1	40000	44.0	145.9
P	1.2	21.9	25.4	40000	17.0	26.7
S	0.5	21.9	11.9	40000	50.0	167.6
Na	11.4	21.9	250.3	40000	274.8	43.9
Cl	18.2	21.9	399.0	40000	531.0	53.2

Table A.9.2: Accumulation discharge requirement for coupled aquaponics