A Systematic View on a Recirculating Aquaculture System: Causality Relation Between Variables

Ágúst Þorri Tryggvason

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
University of Iceland
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Ágúst Þorri Tryggvason

30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Industrial Engineering

Advisor(s)
Guðmundur Valur Oddsson
Harald Ulrik Sverdrup

Examiner
Sigríður Sigurðardóttir

Faculty of Industrial Engineering
School of Engineering and Natural Sciences
University of Iceland
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Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Hjarðarhaga 2-6
107, Reykjavik
Iceland

Telephone: 525 4000

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Abstract

The purpose of this study was to map out the interrelationship between variables in aquaculture by constructing a causal loop diagram (CLD). Key variables from recirculating aquaculture systems (RAS) were chosen based on the previous work of Björnsdóttir (2015) and Vilbergsson (2016) along with other articles that were analyzed to identify cause and effect relation between the key variables. The CLDs were initially constructed based on these four functions: controlling dissolved oxygen and CO_2, feed and solid waste, ammonia and fish production. This literature review resulted in an overview CLD that illustrates the main causalities between variables in aquaculture. Furthermore, indicators were put forth based on whether they indicated success or problems, or whether they could be controlled. The causal loop diagram which was based on this work provides a causality overview between variables in a common aquaculture system, and is intended to be of use in designing and analyzing these systems. This thesis is in the first step of a theory building process and has yet to be validated, but the CLD can hopefully be used as a tool for professionals in the future.

Útdráttur

Megintilgangur þessa verkefnis var að kortleggja innbyrðis tengsl milli breyta í fiskeldi með því að búa til orsakasamhengismynd (CLD). Lykilbreytur í hringrásarfiskeldi (RAS) voru ákvarðaðar út frá fyrri vinnu Björnsdóttir (2015) og Vilbergsson (2016) og einnig voru aðrar greinar greindar til að bera kennsl á tengsl milli orsaka og afleiðinga í lykilbreytum. CLD-myndirnar voru upphaflega byggðar á eftirfarandi fjórum aðgerðum: stýring á uppleystu súrefni og koltvísýringi, úrgangsmyndun, ammoníaki og fisk framleiðslu. Niðurstöður þessa verkefnis leiddi af sér yfirlitsmynd á helstu orsakasamhengjum milli breyta í fiskeldi. Vísar (e. indicator) voru settir fram, byggðir á hvort þeir táknuðu árangur, vandræði eða hvort væri hægt að stjórna þeim. CLD-myndin sem var gerð í þessu verkefni veitir orsakasamhengis yfirsýn yfir algenga uppsetningu á fiskeldishringrásarkerfi og getur vonandi aðstoða á einhvern hátt við að hanna eða greina slík kerfi. Þessi ritgerð er einungis á byrjunarstigi kenningarmyndunar og á eftir að sannreyna, en vonandi geta sérfræðingar notað CLD-myndirnar sem verkfæri í framtíðinni.

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Glossary

RAS: Recirculating aquaculture systems.

CO_2: Carbon dioxide.

CLD: Causal loop diagram.

Rearing tank: Is a tank where fish are bred.

TAN: total ammonia nitrogen

NH_3: Un-ionized ammonia.

NH_4: Ionized ammonia.

NO_2: Nitrite

NO_3: Nitrate

pH value: Indicates if the water is acid or basic and regulates the form that the ammonia takes in the water.

Aeration: When gas (O_2) is pumped into to the rearing tank.

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This work would not have been possible without the assistance of my thesis advisors Guðmundur Valur Oddsson and Harald U. Sverdrup. I would also like to thank Hjalti Gunnar Tryggvason and Eva Hallvarðsdóttir for taking the time to read this thesis over and give me good comments.

1 Introduction

The ocean was long considered to be an endless source of fish products but current estimations show that the maximum sustainable yield has been reached for many species and many species are over fished (Tidwell, 2012). The Food and Aquaculture Organization estimates that food production needs to increase by 60% before 2050 to feed 9 billion people (Mahalik & Kim, 2014) due to a combination of population growth, urbanization and rising income. Aquaculture is a feasible solution to solve this increasing demand. Aquaculture is where aquatic species are bred for consumption. It gives the opportunity to increase the production and prevent overfishing and disturbance of the marine ecosystem. In 2012, 43% of fish supply can be traced to aquaculture and aquaculture has been steadily rising. It is predicted that in the year 2030, 62% of supplied fish will be from aquaculture and this percentage will continue to grow in the following years (Fao, 2014).

Various types of aquaculture exist. Aquaculture can be intensive, semi-intensive and extensive, depending on the quantity of fish per volume of water and water source. There are some concerns about how extensive and semi-intensive systems influence the eco system. The aquaculture is known to cause pollution, spread diseases and have fish escape their ponds. An example is when chemicals are poured into the sea cage to reduce other harmful chemicals. Therefore, extensive and semi-intensive systems might not be the best solution to solve this increased demand in food production. The focus of this thesis is on intensive systems, or more specifically, a recirculating aquaculture systems (RAS), where you need to constantly interfere with the system to keep it running (Timmons, Ebeling, & Center, 2007).

RAS has gained increased attention in recent years and they are believed to be the future of the aquaculture industry. RAS was developed to respond to the increasing environmental standards and limited access to water and are quite expensive to build so fish need to be stocked quite densely for the system to be economically profitable. RAS has major advantages over typical aquaculture systems such as enabling reuse of 90-99% the water in a closed system where the water flows through different treatment steps to be purified in a year-round production. These systems allow the operator to control the environment to make optimal water quality for the fish to grow in. Reduction of water usage in RAS offers many advantages such as improved waste management and nutrient recycling (Badiola, Mendiola, & Bostock, 2012; Martins et al., 2010). RAS uses only a small portion of water compared to a typical flow-through system and therefore it is possible to maximize the fish production in a controlled system while minimizing the environmental impact from the production. To be able to continuously reuse the water it has to flow through different filtrations to remove solids, ammonia, CO_2 and other chemicals. It is also important to control aspects like temperature, pH value and dissolved oxygen concentration (Dalsgaard et al., 2013).

However, a recirculating aquaculture system is a complex system and needs to be understood before it can be managed. The reason for this complexity is due to the required sustainability of the system (Bjørndal, Lane, & Weintraub, 2004).

This thesis is based on the previous work of Björnsdóttir (2015) and Vilbergsson (2016). Björnsdóttir (2015) analyzed hundreds of articles and mapped the production functions of aquaculture production systems and grouped them into three groups: Input functions, treatment functions and output functions as can be seen in figure 1. Treatment functions are various methods applied to optimize the water quality of the rearing tank to gain maximum fish growth rate and to make sure that the fish will be of sufficient quality.

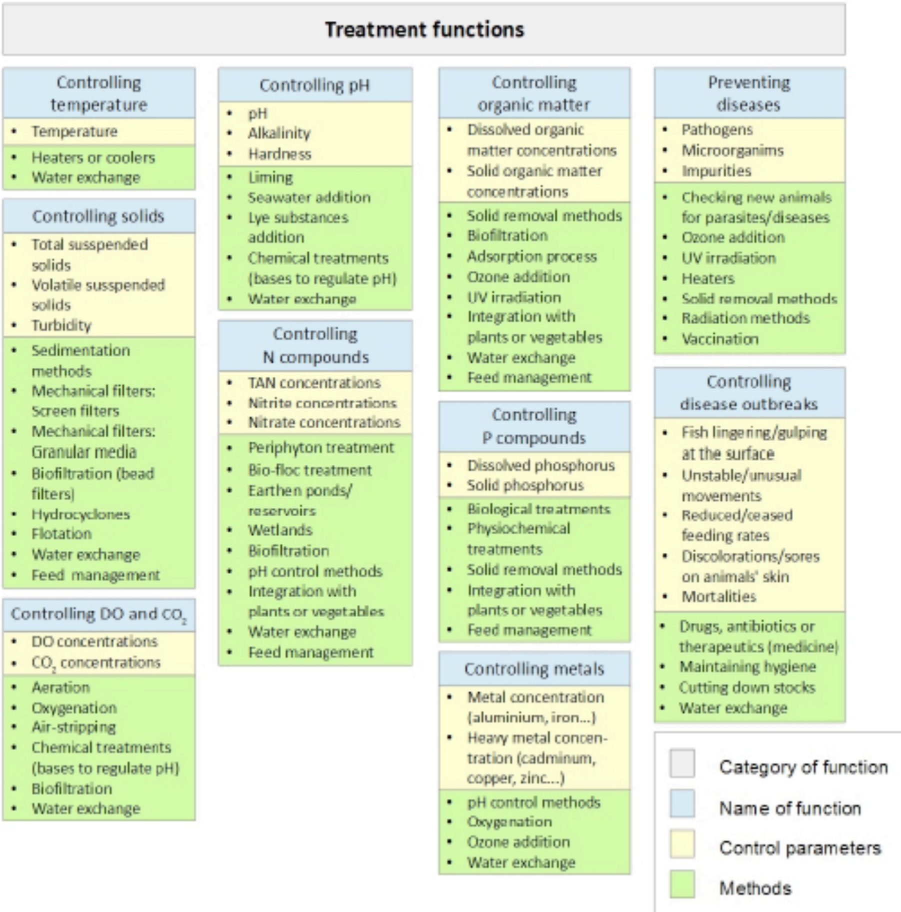


Figure 1: Treatment funcitons identified by (Björnsdóttir, 2015).

Vilbergsson (2016) identified and mapped out the means used to resolve the treatment functions: controlling dissolved oxygen and CO_2, solids, organic matter and nitrogen (N) compounds as can be seen in the example in figure 2 to control dissolved oxygen and CO_2.

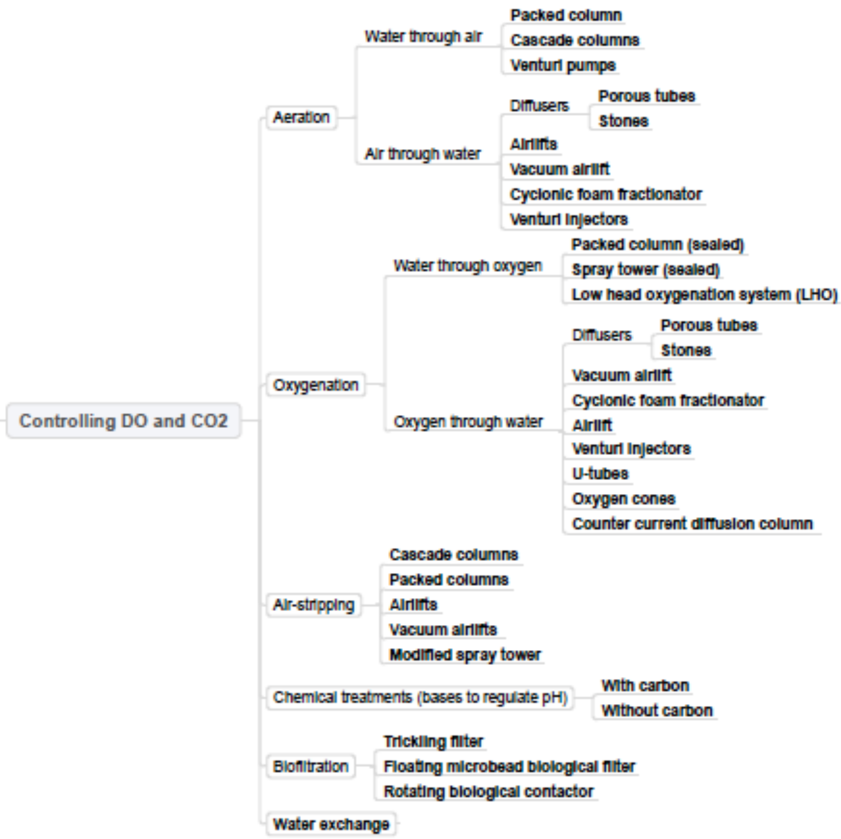


Figure 2: Taxonomy of means identified by Vilbergsson (2016).

There is a lot of literature available that describes the functionality of aquaculture but few articles describe the underlying mechanism visually. This thesis aims at constructing a causal loop diagram between relationships of key variables in recirculating aquaculture systems. Dozens of articles were analyzed to identify the effect between key variables in the system. The next step would be to simulate these relations but that is outside of the scope of this thesis.

System analysis was used in this thesis to construct a causal loop diagram (CLD). It is a good tool when dealing with such a complicated system. It gives a good holistic overview of the system and helps to see how different variables interfere with one another. The CLD will be presented first as specific parts in the system, more exactly as fish production, dissolved oxygen, feed and waste in the water and total ammonia nitrogen. These parts are then combined to form the overview CLD of the whole system. Specific variables will then be listed as success, problematic or control variables and presented in different colors in the overview CLD. This will hopefully help aquaculture managers to figure out how everything is linked together and changing one thing may change the whole system.

1.1 Aims and research questions

A recirculating aquaculture system is a complex system and in order to be able to build a high performing recirculating aquaculture system it is of vital importance to understand the underlying mechanisms of that system. System analysis was used in this thesis to be able to increase the knowledge of cause and effect in recirculating aquaculture. The general aim of this thesis is to analyze the fragile aquaculture system and show how causes and effects will impact the system in many ways. The following research questions are put forth to be able to achieve these aims.

1 What are the key variables of a recirculating aquaculture system and how are these variables connected to each other through the cause and effect?

2 What are the success, problematic and control variables for a recirculating aquaculture system?

1.1.1 Scope and assumptions

This thesis was built on the previous work of Björnsdóttir (2015) and Vilbergsson (2016) and focuses on the rearing tank in the system, where fish are in the final stage before being harvested. Some of Björnsdóttir (2015) and Vilbergsson (2016) functions are out of the scope of this thesis and thus not included. These functions are:

- Providing light: Providing light wasn't included since the effects haven't been studied enough.

- Phosphorus buildup: It wasn't necessary to look into to the phosphorus build up since the main focus of this thesis is the rearing tank. Phosphorus will pollute when it is released into the environment.

- Metal concentration: Metal concentration is not included in this thesis.

- The process of effluent water and solid waste: This all happens outside of the rearing tank and is thus not a concern in this thesis.

- Emission control: Emission also happens outside of the rearing tank and is thus not a concern in this thesis.

Almost every variable can be controlled by water exchange in some way. Water inflow and outflow are not included in the CLD. The only reason for that is to make the CLD simpler. This thesis only intends to create an overview of causal relation between key variables.

2 Methodology

2.1 Literature used

This thesis was based on a literature review and the previous work of Björnsdóttir (2015) and Vilbergsson (2016). Two books about aquaculture were used in the beginning to get a good overview of aquaculture and also help with creating a causal relation between key variables in the system: Recirculating Aquaculture by (Timmons et al., 2007) and Aquaculture Engineering (Lekang, 2007). Those two books were read partially to get the main idea about the relationship between variables in an aquaculture system.

Over 200 hundred articles from Björnsdóttir (2015) and Vilbergsson (2016) were gathered and relevant articles were used to figure out the relationship between key variables and to construct the causal loop diagram between these variables.

2.2 Flowchart

Flowcharts were constructed of the key variables in a recirculating aquaculture system to get a holistic overview of how the system operates and to assist with construction of such a complex CLD. A flowchart is a good tool to understand the logic of complex problems and to get a holistic overview of the problem. Shneiderman, Mayer, McKay, and Heller (1977) state that flow charts are an essential tool for problem solving. It is a formalized graphical representation of the sequence of all operations in a process or a step-by-step solution of a problem. A flowchart illustrates the flow of the system and how things are currently working, how they could be improved, and assists in finding the key variables of a process. A different symbol is used to represent each step in the process and these symbols are connected with arrows showing the process flow direction (Chapin, 1970). Figure 3 is good flow chart example in aquaculture. It shows how food is added into the water and flows out with fish eating.

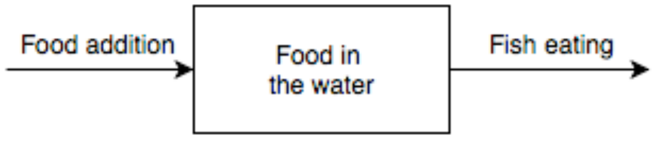


Figure 3: A flow chart example in aquaculture.

2.3 System analysis

A systematic approach was used to evaluate the recirculating aquaculture system key variables and what impacts them. It provides a holistic understanding of the relationship between different aspects in the RAS system, and offers the tools to clarify the complexity of a RAS system. Sterman (2001) describes system analysis or system thinking as the ability to see the world as a whole complex system in which we understand that we can not change one thing since everything is connected in some way. It is a method to enhance learning in a complex system.

Feedback loops, non-linearites and delays of cause and effect are what characterize a complex system. That is why system analysis is an ideal tool to analyze land-based aquaculture. It has a lot of feedback loops for example when dealing with the concentration of oxygen in the water, which affects the health and growth rate of fish. When the fish consumes oxygen it will enhance fish growth and reduce the oxygen concentration in the tank and when the oxygen concentration is low it will affect the health and growth of the fish. This example shows that the aquaculture managers needs to know how different factors interact with each other and how they can keep them within optimal values. Non-linear effects in aquaculture are also common, for a example how temperature affects fish growth. If the temperature is within optimal boundaries then the growth rate can be as close to the maximum growth rate as possible. If the temperature is outside these optimal boundaries it will reduce the growth rate drastically. That is why a small change in one part of the system can have a large impact on another part of the system. Delays of cause and effect in a land-based aquaculture can be seen in many forms. For example the accumulation of solid waste will in the long run affect the environment and generate toxic chemicals such as ammonia. Some effects are more direct than others, such as low oxygen concentration which will kill your fish quickly but other effects will have more impact in the long run, such as accumulation of solid waste (Sterman, 2001).

In system analysis, causal loop diagrams (CLDs) are used since they give a good overview of the whole system and they increase understanding regarding the structure of a underlying problem (Homer & Oliva, 2001). There are two types of arrows to represent causal relationship between variables, a positive arrow and a negative arrow as can be seen in figure 4. Positive arrows indicate that the variables are changing in the same direction and negative arrows indicate that the variables are changing in a different direction. These arrows then construct feedback loops that can be either positive (reinforcing) or negative (balancing). Positive loops cause continuous growth or amplify whatever is happening in the system. Negative loops do the opposite, they cause equilibrium or balance the system (Binder, Vox, Belyazid, Haraldsson, & Svensson, 2004; Sterman, 2001). Figure 4 is a good CLD example for aquaculture. Feed is added into the water, the more feed that is inserted the more the fish are going to eat, just as the plus sign indicates. The minus sign from fish eating to food in the water indicates that the more the fish eat, the less feed there is going to be in the water. These two arrows form a balancing loop, indicated as B in figure 4. The second loop in the figure has two plus signs, making it a reinforcing loop indicated with R in the figure. The R loop would continue to grow if it was allowed to but it is controlled by the other balancing loop.

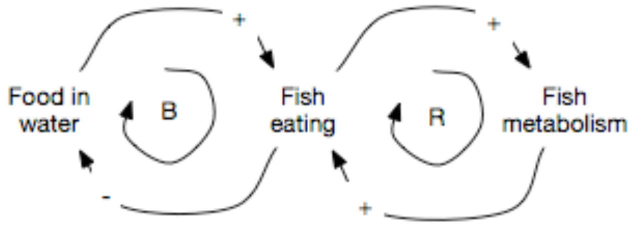


Figure 4: A CLD example from aquaculture.

System analysis is a great tool to inspect and test the behavior of a dynamic system. It can be used to generate different scenarios to see what will happen. For example to see what will happen to the system if the solid waste is not removed from the system or see if the fish will be able to reach the most profitable size if it does not get enough oxygen.

2.4 This research

Keeping in mind the variables emphasized in the research of Björnsdóttir (2015) and Vilbergsson (2016), when going to the literature, focus was kept on the basic functions: controlling solids, controlling nitrogen (N) compounds, controlling dissolved oxygen and CO_2 and controlling organic matter. The next step was to gather detailed information from literature regarding the functionality of a recirculating aquaculture system. This was essential to be able to construct flowcharts of the main functions and to construct the CLDs based on the flow charts. The following chapters will describe these functions.

3 Systematic view on recirculating aquaculture

To be able to manage such a complicated system and ensure that the condition of the culture environment is optimal, it is important to constantly monitor and control crucial variables of the system such as dissolved oxygen, ammonia, nitrite and pH value. Alkalinity, salinity, CO_2 concentration and solid waste are also important to monitor and control to maximize the performance of the system. If that is neglected, it is impossible to know how the system is preforming and whether the water quality is up to standards to maximize fish growth and ensure sufficient fish quality. All of these variables are important on their own but it is their interrelationship that can cause problems in the system. The most important variables to manage will be described in the following sections.

3.1 RAS overview

Recirculating aquaculture systems (RAS) are rather expensive to build and operate compared to other aquaculture systems but they have major advantages. The system can control the water quality, the water temperature, it is not dependent on the weather and it has low water and land requirements. The key to a functional RAS is the use of a water treatment system (Ebeling et al., 1995). These treatment units depend on the degree of water reuse and water quality requirements, which are based on the species grown in the rearing tank. In general, the treatment functions of a RAS system are a combination of solid waste removal, gas control to add oxygen and strip the system of CO_2, and a nitrification process to transform ammonia to less harmful nitrite (d'Orbcastel, Blancheton, & Belaud, 2009). Figure 5 illustrates a common setup of a RAS system where all these treatment functions are present.

A recirculating aquaculture system can be designed in various ways but it mostly consists of tanks, back-up tanks, pumps and filters. One of the advantages of a RAS system is that the environment and water quality variables can be controlled to gain optimal fish health and growth. Also the system does not use as many chemicals to fight diseases and parasites and does not discharge as much waste. This will allow farmers to stock their fish intensively and meet strict environmental standards since the whole environment is controlled. A RAS system can utilize 90-99 percent less water than a typical fish farm and can constantly produce fish all year round. Fresh water is often introduced at the side of the tank to make a circular water flow in the tanks to support natural behavior of the fish. The aerial environment is controlled and the fish is raised in highly monitored and secure tanks where the water flows from the fish tank through a treatment process so it can be reused. This will reduce the amount of water and space required to grow fish and minimize all environmental impact from the operation. To be able to reuse the water it is important to monitor and control variables in the system such as these critical variables: temperature, pH value, ammonia, nitrite, solid waste and dissolved oxygen. The other variables that are not as crucial to monitor but still need attention are alkalinity, salinity and CO_2. To be able to grow the fish it is essential that all of these variables are within their optimal boundaries but it is the interrelationship between these variables that affects the health and growth of the aquatic animal. It only takes one failure in any part of the system to cause catastrophic loss (Colt, Watten, & Rust, 2009; Nazar, Jayakumar, & Tamilmani, 2013). The fish are not the only living creatures that make up the population in a RAS system, bacteria thrives in the system and needs to be taken into account when managing a functioning RAS system. These bacteria are vital since they metabolize chemicals but in that process they consume oxygen and produce waste. The importance of these bacteria is often overlooked in a RAS system and that is one of the leading causes of failure (Badiola et al., 2012).

To be able to grow fish in such a complicated system there has to be some action taken to prevent failure. Steps that have to be taken in a common RAS system are; removing solids, converting ammonia to less harmful nitrite/nitrate, removing CO_2 and adding O_2 as can be seen Figure 5 which illustrates a common setup of a RAS. First, the effluent water from the rearing tank is passed through a filter with a small mesh size to remove the solid waste. The circular water flow will push the waste down to the bottom of the tank where it is easily removed. Smaller waste that does not settle can be removed by adding air bubbles. Waste will settle on these bubbles and will be removed from the surface. Water is then passed through the biofilter where bacteria grow on its surface, shown as controlling N compounds in figure 5. The biofilter consists of material such as plastic, sand or gravel and the bacteria transform ammonia-nitrogen to the less harmful nitrate-nitrogen. The final step to close the circulation process is to add O_2 and remove CO_2 from the water to maintain sufficient concentration of dissolved oxygen in the system (Losordo, Masser, & Rakocy, 1999; Timmons et al., 2007). These processes will be covered in detail in the upcoming chapters.

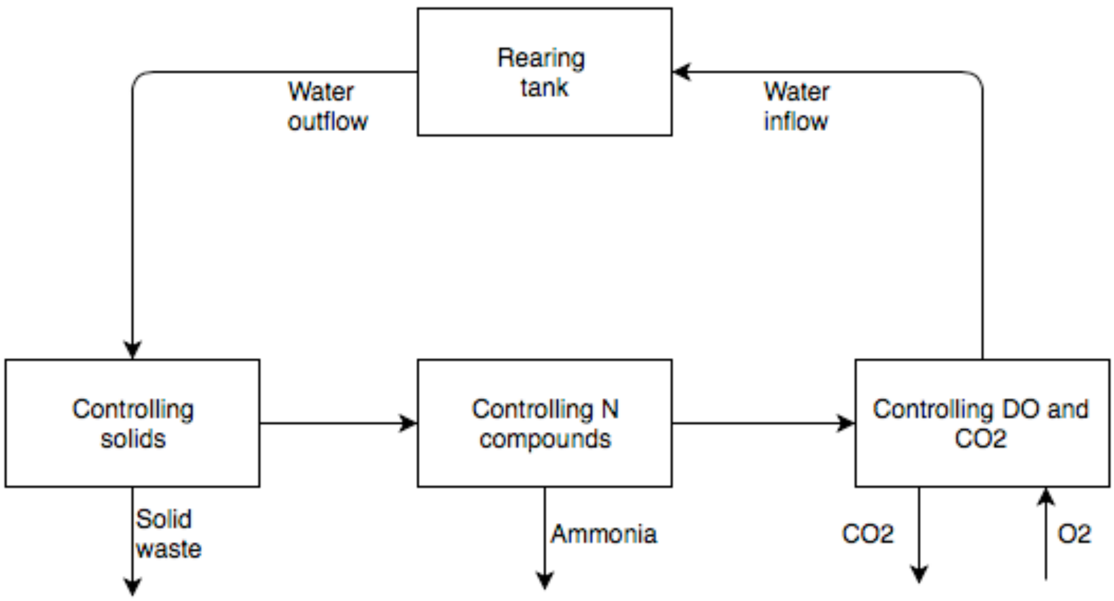


Figure 5: Flow chart of a common setup for water circulation in a RAS system.

3.2 Water source

Water is essential for fish to live in and it is better to have more available water than less if required to flush out the system or expand it. One of the objectives of a RAS system is to minimize water usage and the most common water sources are pumped groundwater and municipal water. Groundwater has a major benefit of constant water temperature all year round but it contains little or no dissolved oxygen and is rich in nitrogen gas and carbon dioxide. It is important that the water source is of high quality for the fish to live in and thus oxygen has to be added to the inflow water and excess gases have to be removed.

The other common water source, municipal water, is designed for human consumption so some chemicals have been added to the water to make it safe for humans to consume. When using municipal water for a recirculating aquaculture system these chemicals have to be removed. Most RAS systems utilize their water up to 90 -95 % per day. Only 5-10% of new water is introduced into the system every day. Water outflow will remove waste, toxic chemicals, CO_2 and any other dissolved chemicals from the water. Water inflow will add chemicals that are dissolved in the water source but mainly add oxygen and regulate water temperature (Timmons et al., 2007). Water exchange is used to treat the system and should be enough for small facilities. Water exchange lowers the odds of harmful chemicals building up in the system (Good et al., 2009). When another production cycle begins and new fish is introduced to the system it is very important to flush out the old water and start again with fresh water (Losordo et al., 1999).

3.3 Fish stocking density

When designing a RAS system one of the first things that needs to be addressed is the mass of fish that can be stocked. The production of fish in such a complicated and expensive RAS system is only economically profitable if the stocking density is high. The total biomass that can be stocked into the system is determined by the oxygen consumption of the fish and the available water. If the density is too high it can cause stress to the fish that can lead to reduced growth rate, increase odds of disease, lower swimming activity and increase mortality rate (Thorarensen & Farrell, 2011; Zakęś & Demska-Zakęś, 2006).

The number of fish that can be stocked is also dependent on the species and their size, which will determine the feeding rates that nearly all components in the system are designed for. The size of the fish can vary in the culture unit but it is more likely that the cause of that is poor water quality and less then optimum feeding rather than stocking density. It is common in fish farming production that fish is moved between tanks depending on its stage of growth. All movement of fish will increase stress (Timmons et al., 2007).

Fish can survive at very high stocking density if it is only fed enough feed to meet its basic needs. Fish that is underfed produces less waste and consumes less oxygen. That is why fish density is determined by the amount of feed that the system can accommodate without compromising water quality and waste of feed (Nazar et al., 2013).

3.4 Water quality

Water quality management is a crucial process in seafood production since seafood is only as good as the water it lives in. Water quality in the rearing tank depends on two things, (1) the quality of the influent water and (2) changes in the water quality inside the rearing tank driven by feed input and biological activity. Figure 6 illustrates a good overview of the most important processes affecting the water quality in the rearing tank (Colt et al., 2009). Water quality has to be controlled and monitored since it affects fish growth, fish health, carrying capacity, the effectiveness of the biofilter and many other variables. The most important variables to monitor and to keep within acceptable range are dissolved oxygen, pH value, temperature, solid waste, ammonia, nitrite, alkalinity and CO_2 (Losordo et al., 1999; Nazar et al., 2013). Fish can survive and grow in water of suboptimal quality but that will reduce its ability to grow. Having optimal water quality will lower the odds of disease outbreak and will keep stress low. Water quality requirements are species and life stage dependent where fish in the early stage need higher water quality requirements than fish at the later stages (Lekang, 2007).

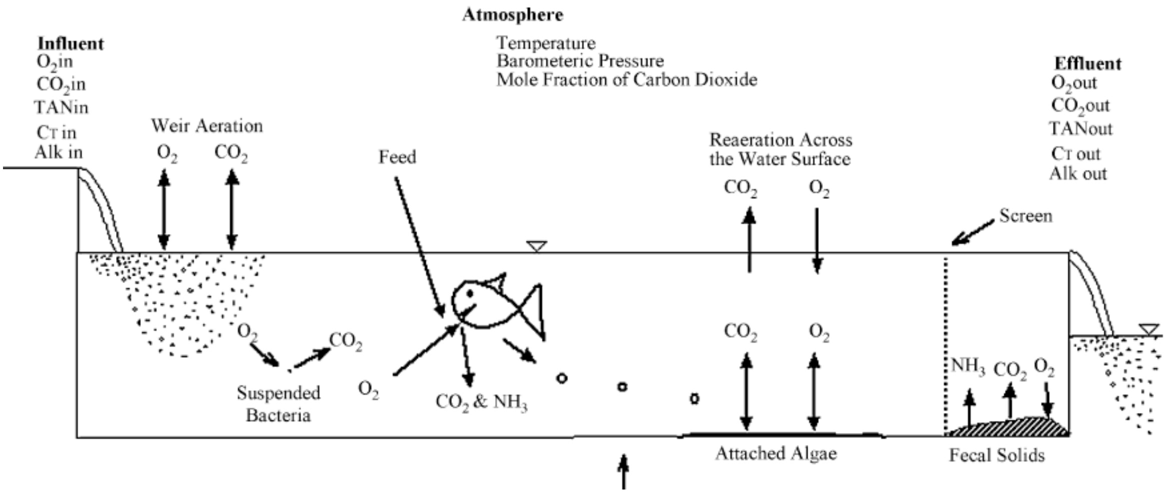


Figure 6: Processes that affect water quality in a recirculating aquaculture system (Colt et al., 2009).

Stress should always be kept at a minimum since it increases the risk of diseases. If the water quality is good, fish is not over or under fed and fish mishandling does not occur, then there should not be a problem with stress related diseases (Lekang, 2007). But if a disease outbreak occurs then there is no way to treat it without affecting the biofilter. If the fish is medicated then it will have a counter action that can destroy the biofilter, and without a functioning biofilter the fish will die. So the best way is to get rid of the fish and start over, for that way the biofilter will stay intact (Ebeling et al., 1995).

The water quality should always be monitored and fish behavior can indicate if there is too high or too low concentration of oxygen, CO_2, nitrite/nitrate, ammonia, alkalinity or any other important variable. If it is discovered that one or more variables are too high or low it is important that changes are made gradually. The reason for that is that you have two living systems, the fish and the biofilter. By changing gradually you give these species time to adapt to the new conditions. The Only exception is when dissolved oxygen is low, for it can be raised as quickly as possible (Colt, 2006; Ebeling et al., 1995).

3.5 Dissolved oxygen and carbon dioxide

Dissolved oxygen is one of the most critical variables out of all water quality variables since the fish needs oxygen to survive and grow (Mallya, 2007). Nitrifying bacteria in the biofilter also uses oxygen when transforming ammonia to nitrite and nitrate. It is important to constantly monitor and control the dissolved oxygen concentration since it will fluctuate due to the oxygen consumption of these two species. There are many factors that affect oxygen consumption in the system such as temperature, fish size, feed consumption and fish activity. The oxygen consumption will increase parallel to increased fish size and higher temperature. When the fish is metabolizing feed the oxygen consumption will increase drastically, dependent on the meal size and temperature. Fish will consume around 0,12 kg of oxygen for every kilo it eats. Fish activity is another factor that will increase fish oxygen consumption (Thorarensen & Farrell, 2011). Forsberg (1997) states that the major component regarding oxygen consumption is the digestion and transportation of feed. The Saturation for dissolved oxygen in water is dependent on salinity and temperature. The highest saturation concentration is at low temperature and low salinity (Lekang, 2007; Timmons et al., 2007).

Preferred levels for dissolved oxygen are around 5-6 mg/L for optimal fish growth in most warm water systems. However, a higher concentration of dissolved oxygen does not appear to benefit the fish in any way since the gills cannot carry more oxygen to the blood and too much oxygen can make the fish sluggish (Colt, 2006; Ebeling et al., 1995; Losordo et al., 1999; Timmons et al., 2007).

Some kind of aeration needs to be constantly running to meet the high demand of oxygen for both the fish and other microorganisms. Dissolved oxygen depression can occur shortly after feeding, dependent on how large the feed quantity is, where more feed leads to bigger variations. Fish respiration rate increases drastically when it digests food. This will cause dissolved oxygen concentration to plummet and thus it is important to divide the daily feed quantity into smaller portions over the day, rather than big portions a few times a day to keep the dissolved oxygen at preferred levels. Occasionally dissolved oxygen will fall below preferred concentration but it will cause no harm if it is for a short period of time. A sign of too little oxygen concentration in the water is when the fish is gathering at the surface or any other places where oxygen concentration is higher (Ebeling et al., 1995; Losordo et al., 1999).

CO_2 is released by respiration of the fish and other microorganisms and it will accumulate in the system if it is not removed as quickly as it is produced (Badiola et al., 2012; Nazar et al., 2013; Timmons et al., 2007). Colt (2006) states that fresh water fish can tolerate a CO_2 concentration greater than 100-200 mg/L but that a high CO_2 concentration will cause reduced growth rate and appears to be linearly related to CO_2 concentration. The concentration of CO_2 should be kept below 20 mg/L, or else it will increase stress and make the fish drowsy. Concentration of pH value is dependent on CO_2. If the CO_2 concentration increases then that will lead to increase of ionized ammonia because of low pH value. Just like temperature affects concentration of oxygen it also affects CO_2. If the temperature is low then the concentration of CO_2 is high (Colt, 2006; Thorarensen & Farrell, 2011; Timmons et al., 2007). CO_2 is a function of alkalinity and pH value. Fluctuation in pH value will cause CO_2 to act as a buffer, either releasing or consuming hydrogen ions which will shift the fraction between carbonic acid and bicarbonate (Leu, Libra, & Stenstrom, 2010).

3.6 Temperature

One of the major advantages of a RAS system is that it can control the temperature and is not affected by seasonal weather changes in nature. By controlling the temperature you can maximize fish growth rate since the seasonal fluctuations are no longer a factor. Temperature has to be maintained within optimum range for each species since the temperature has a direct effect on fish growth, efficiency of feeding, behavior and better resist diseases. The biofilter is also affected by variation in temperature, for if temperature is increased then it will increase the nitrification rate (Losordo et al., 1999; Thorarensen & Farrell, 2011). Fish are classified as cold blooded or poikilothermic meaning that their body temperature is the same as the temperature of environment that they are in. Fish are generally grouped into three groups based on their temperature preference: warm water (>20°C), cool water (15-20°C) and cold water (<15°C). Therefore, every species has an optimal limit to maximize its growth rate (Timmons et al., 2007).

The fish can not control its body temperature, which also varies with external temperature. If the environment temperature is changing it will affect the metabolic and oxygen consumption rates of the fish. When the temperature goes near its lowest tolerable temperature range these ranges will decrease. On the other hand, when the temperature is near its highest tolerable temperature, the fish will become more active, consume more oxygen and feed and in that process it will generate more CO_2, ammonia and other chemicals (Timmons et al., 2007). The temperature can be regulated with different heaters and coolers (Losordo et al., 1999).

3.7 Feed management

Feed management is one of the most important factors in aquaculture to maximize fish growth. Fish has to be fed the right amount of feed at a certain rate to maximize fish growth and preserve the water quality. The feeding rate then affects the waste generation, oxygen consumption and nitrogen compounds. If the fish is underfed it will not reach preferred size, if it is overfed this will lead to less water quality by more uneaten feed and excreted solids in the water. The feed is one of the major costs when operating aquaculture, so it is important to feed the right amount of feed to the fish every time to minimize cost, maximize growth and maintain water quality (Timmons et al., 2007).

It is difficult to estimate the right amount of feed to put in the tank, in order to maximize growth without wasting feed. Fish are usually fed based on their body size. Smaller fish will be fed frequently but in small portions and larger fish will be fed in bigger portions and with less frequency as table 1 illustrates. When fish metabolize feed they will consume more oxygen. They will on average consume 0,12 kg of oxygen per kilo of feed consumed. Feeding fish more frequently and in smaller portions will thus lead to less shortage of dissolved oxygen and will distribute less waste to the biofilter.

Table 1: Feed ratio depending on bodyweight.

Size of fish (grams)	*Percentage of bodyweight to feed*
20	6%
50	5%
100	4%
200	3%
300	2%
400	1,5%
500	1%

The feeding process can be a good indicator if there is something wrong with the fish. If the fish is not responding as it normally would when feed is introduced to the system then the manager needs to check all aspects of the system (Losordo et al., 1999).

To be able to minimize solid waste generation it is necessary to maximize the feed utilization. Solid waste enters the system in two ways when the fish is fed: it either consumes all or most of the feed and excretes it as feces, or the fish is fed too much and the excess amount of feed will settle at the bottom as waste. The problem is, therefore, how much feed is needed to maximize fish growth and minimize solid waste.

The formulation of the feed has to be adequate to maximize fish growth. Fish utilize protein, carbohydrate and lipid for energy and growth. The rest of the feed, such as phosphorus (P) and nitrogen compounds (N), is not utilized and is excreted as waste. That is why it is important that the right composition of feed is chosen to minimize these factors (Cho & Bureau, 2001; Cripps & Bergheim, 2000).

Most producers use feeding charts that are provided by the feed manufacturer. Aqua culturists must be careful when using these feed charts since they do not account for the various fish species, water temperature and other important factors (Cho & Bureau, 2001).

3.8 Solid waste

Solid waste in the rearing tank mostly consists of feces and uneaten feed and it has to be removed as quickly as possible. It is estimated that 60 % of feed fed to the fish will end up as solid waste (Badiola et al., 2012). Badiola et al. (2012) and Losordo et al. (1999) state that removing waste solids is one of the most difficult jobs to manage in a RAS system and is one of the leading causes of failure. That is why the treatment function of removing solid waste is one of the most important steps of a RAS system, because solids accumulation affects the efficiency of other component functions which will worsen water quality (Summerfelt, 1996; Timmons et al., 2007). When solid waste removal is not sufficient it will lead to more oxygen consumption since bacteria uses oxygen to break waste down. When waste is broken down it will produce more ammonia in the water which is toxic to the fish (Losordo et al., 1999; Nazar et al., 2013).

It is important to know which form the waste takes to be able to remove it from the system, whether dissolved or particulate, since virtually all of the waste generated inside the RAS system is originates in feed (Lekang, 2007).

As stated earlier, fish feed mainly consists of protein, fat, carbohydrate, vitamins and minerals, and the breakdown of these chemicals is the main cause of impurities in the water. As can be seen in figure 7 the fish produces different waste when metabolizing feed to grow. In that process the fish requires oxygen to turn the food nutrients into energy. Fish muscles are mainly composed of protein and when the fish digests protein to grow muscles and gain energy it excretes nitrogen compounds. When protein is metabolized the end products are inorganic nitrogen and CO_2. Inorganic nitrogen will be released as un-ionized ammonia (NH_3), mainly from the gills, and a minor part from urine. The protein in the feed is not all digestible and that is why the fish has to return it to the water as waste. If the fish could digest all of it then the fish wouldn't excrete this protein containing waste. Since the amount of protein in feed has a great effect on cost and is the reason for ammonia waste it is of the upmost importance to reduce indigestible protein in feed as much as possible (Colt et al., 2009; Lekang, 2007).

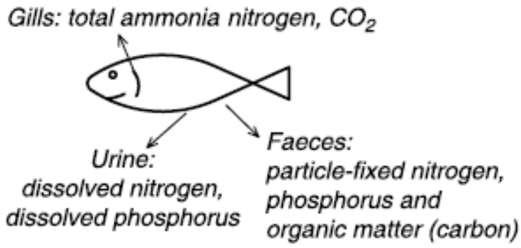


Figure 7: Released end products of a growing fish from metabolization (Lekang, 2007).

Solid waste needs to be removed from the system as quickly as possible to preserve the water quality. Waste is grouped into three categories, settleable-, suspended- and dissolved solids based on their particle size. In a RAS system the primary concern are the settleable and suspended solids because of their size. If they are not removed they will decompose to smaller particles which are harder to remove. Floatable or dissolved solids can also be a problem if the water exchange is not sufficient. All these solids are referred to as total suspended solids (Ebeling et al., 1995; Lekang, 2007; Timmons et al., 2007). All sizes of solid waste must be addressed and managed by the appropriate treatment method e.g., sedimentation and screening which are preferred for larger particles and foam fraction or flotation for smaller particles (Timmons et al., 2007; Vilbergsson, 2016).

Solids that settle in the water within an hour are called settleable solids. Those are easiest to deal with and should be dealt with as soon as possible. The solids can settle at the bottom of the culture tank or in a settling tank under still conditions (Ebeling et al., 1995). Settleable solids are defined by the size and the size can vary from centimeters (cm) to microns (μm) (Timmons et al., 2007).

The difference between settleable solids and suspended solids is that the suspended solids will not settle within an hour under still conditions and are not removed by conventional settling (Ebeling et al., 1995). The presence of suspended solids in the system is the main water quality issue (Badiola et al., 2012). Suspended solids have a serious effect on general fish health by causing irritation to the fish by smothering its gills and by that compromising oxygen transfer (Timmons et al., 2007). The most common way of treating suspended solids is by mechanical filtration, and the most common filters are screen filters and granular media filters (Ebeling et al., 1995; Vilbergsson, 2016).

Dissolved solids are less than 30 μm and they cause similar problems as suspended solids, as they cause gill irritation and increase oxygen demand. Flotation or foam fraction is one way of removing floatable and dissolved solids, since mechanical filtration and sedimentation will not remove these solids efficiently (Cripps & Bergheim, 2000; Ebeling et al., 1995).

3.9 Ammonia-nitrogen

Since the RAS system is a closed cycle there are many variables that need to be monitored and controlled. Ammonia, nitrite and nitrate need to be monitored since they will accumulate in the system and at a certain concentration they are toxic to the fish. Fish excrete un-ionized ammonia (NH_3) from their gills when they digest protein rich feed (Timmons et al., 2007) and bacteria use oxygen to decompose organic waste in the system to produce ammonia-nitrogen compounds. That is the reason why waste and uneaten feed should be removed as quickly as possible from the culture tank. Feeding the right amount and the right composition of feed to the fish can control the concentration of ammonia, and fish should not be fed more than the biofilter can remove of ammonia. It is estimated that for every 100 pounds of feed that is fed to the fish, it produces on average 2.2 pounds of ammonia waste (Blancheton, Attramadal, Michaud, d'Orbcastel, & Vadstein, 2013).

Ammonia comes in two forms in the water, ionized ammonia (NH_4^+) and un-ionized ammonia (NH_3) and the sum of these two are referred to as total ammonia-nitrogen (TAN) (Crab, Avnimelech, Defoirdt, Bossier, & Verstraete, 2007; Ebeling et al., 1995; Losordo et al., 1999). Un-ionized ammonia is more toxic to the fish than ionized ammonia. Even a small concentration of un-ionized ammonia will increase stress on the fish since it affects the nervous system and will lead to reduced growth rate and tissue damage. The concentration of the two forms of ammonia are in equilibrium and are dependent on water pH value and temperature (Körner, Das, Veenstra, & Vermaat, 2001). Increase in water pH value or temperature will shift the concentration to un-ionized ammonia form. But if the pH value is low then the concentration of ammonia will be shifted towards ionized form (Gendel & Lahav, 2013; Thorarensen & Farrell, 2011).

Lekang (2007) put forth figure 8 that shows that the relation between un-ionized and ionized ammonia is pH value dependent.

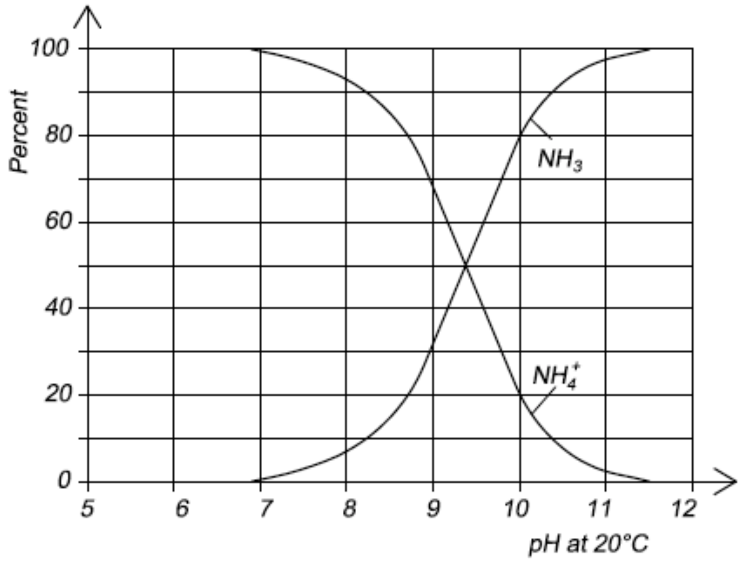


Figure 8: The relation between ionized and un-ionized ammonia is dependent on pH value (Lekang, 2007).

Concentration of pH value above 9,5 in figure 8 is a hostile environment for the fish but concentration below 9,5 would have less effect. Indicating that pH value is a critical component to keep the toxic ammonia level low.

Ammonia should be constantly monitored and controlled. If ammonia concentration starts to increase it is an indicator that the biofilter is not working. Badiola et al. (2012) states that biofiltration is one of the hardest things to manage in a RAS system and is one of the leading causes of failure. Nitrifying bacteria grow in the basin of the biofilter in the recirculating system, utilizing the un-ionized ammonia and oxygen as an energy source, and in that process the bacteria produce nitrite (NO_2^-). Nitrite is not as toxic as ammonia but it has to be removed from the system since it can be harmful to the fish at high concentration (Dalsgaard, Larsen, & Pedersen, 2015; Ebeling et al., 1995)

When constructing a biofilter the main purpose is to create a surface for optimal growth for bacteria. A certain amount of startup time is needed for the biofilter to grow enough bacteria for the nitrification process. The bacteria in the biofilter, that oxidize ammonia, carry out the nitrification process. These bacteria grow on the filter. Nitrification is a two-step process where ammonia is oxidized to nitrite and then nitrite is oxidized to nitrate. The bacteria require oxygen to grow and to transform ammonia to nitrite and nitrate, which is why it is important that there is enough oxygen in the nitrification process. Bacterial activity takes place at 0-30 °C and the bacterial growth and nitrification rate is dependent on temperature with the optimal value around 30 °C. When the temperature is increased the growth rate will increase. If the temperature goes below 5° C it will drastically slow down all bacterial activity. The nitrification process is also dependent on pH value and CO_2 concentration. If the pH value is increased the nitrification process will be greater. But a too high pH value will reduce the efficiency. Lekang (2007) states that the optimal pH value is 8-9 for optimal nitrification and if CO_2 concentration is increased the nitrification rate will decrease. There are many factors that play together when it comes to biofiltration, which is why it is hard to give precise recommendation on how to operate it (Lekang, 2007).

3.10 Nitrite and nitrate

Bacteria in the biofilter are used to remove ammonia and in that process they produce nitrite and nitrate. New bacteria begins to grow in the biofilter when ammonia concentration starts to build up in the system. These new bacteria will convert nitrite to less harmful nitrate. Nitrite is toxic since it prevents the fish from utilizing the oxygen. It can lead to a lower growth rate, inhibit swimming ability and high concentration of nitrate can lead to fish mortality (Ebeling et al., 1995; Lekang, 2007; Thorarensen & Farrell, 2011; Timmons et al., 2007).

Nitrate is not as toxic to the fish as nitrite but at very high concentrations it can be. If water exchange rate is sufficient in the system, the nitrate concentration will most likely not exceed harmful concentration. Another way to keep concentration of nitrate low in the system is to install a de-nitrification filter. The filter transforms nitrate to nitrogen gas and the gas can then be removed from the system with aeration (Kuhn, Drahos, Marsh, & Flick, 2010; Lekang, 2007).

3.11 pH value

The pH value indicates how acidic or basic the water is on the scale of 0-14. Values below 7 indicate that the water is acidic and values above 7 indicate that the water is basic, with the value 7 as the neutral point. Every one unit change in pH value represents a tenfold change in water acidity or basicity. A rapid change of 2 pH values or more can be harmful to the fish although it is within the optimal pH value range. Timmons et al. (2007) and Lekang (2007) state that the optimum pH value for growth and health of most aquatic animals is 6,5-9. The microorganisms living in the biofilter do not function as well within the optimal range of the fish, as the optimal pH value for the biofilter is between 8 and 9.

Exposing the fish to extreme values of pH will reduce the growth rate and have stressful or lethal effects on the fish but the main concern is how pH value affects other variables in the environment. The most important factor is the effect it has on the un-ionized and ionized ammonia and nitrite. If the pH value is high then the ammonia in the system will be in un-ionized (NH_3) form, which is very toxic to the fish. If the pH value is low then the ammonia will be in ionized form, which the fish can rather tolerate (Lekang, 2007; Timmons et al., 2007; Tyson, Simonne, Treadwell, White, & Simonne, 2008).

The biofiltration process that removes ammonia from the system, will reduce the pH value because the nitrification process reduces alkalinity when converting ammonia to nitrite. Summerfelt et al. (2015) states that when alkalinity decreases it will cause reduction in the pH value, which will lead to less efficiency in the nitrification process through a low pH value. H^+ ions are released into the water by converting un-ionized ammonia (NH_3) into nitrite (NO_2) which will reduce the pH value in the system (Timmons et al., 2007). Fish respiration and bacteria produce CO_2 and the pH value is also dependent on the CO_2 concentration. An increase in CO_2 will reduce the pH value in the system (Lekang, 2007; Losordo et al., 1999; Summerfelt et al., 2015). Alkaline buffers are added to the water to regulate the pH value, as the pH value will increase by increasing alkalinity in the water. The pH value needs to be constantly monitored and controlled to keep it at optimum levels in the rearing tank and the biofilter. If nothing is done the environment will eventually become toxic (Ebeling et al., 1995; Lekang, 2007; Losordo et al., 1999).

3.12 Alkalinity

Alkalinity is a variable that is dependent on pH value and the nitrification process. Alkalinity is important for the biofilter since the biofilter removes carbonates from the water to produce bacterial mass. In that process it uses energy that comes from nitrification. Therefore, if the amount of ammonia removed by the biofilter increases, the amount of alkalinity will decrease. If the alkalinity concentration is not maintained at the preferred level then the pH value will drop and the bacteria in the biofilter will stop functioning due to lack of carbonates. It is recommended that concentration of alkalinity should be above 40 mg/L $CaCO_3$ in order to keep the pH value at the preferred level and to protect the fish health. The most common way to raise the alkalinity level is to add carbon buffers such as baking soda (Ebeling et al., 1995; Lekang, 2007; Timmons et al., 2007). Summerfelt et al. (2015) estimated that when the nitrification process turns ammonia into nitrite it consumes 0,15 -0,19 kg of sodium bicarbonate for every kilo of feed consumed by the fish. Alkaline buffers need to be added into the water to compensate for this loss of alkalinity. An aquaculture system operated at low alkalinity is likely to encounter a high concentration of ammonia due to an efficiency drop in the nitrification process (Summerfelt et al., 2015).

3.13 Salinity

Salinity is defined as the amount of dissolved salts that are present in water. Usually it is reported as grams of salt per kilo. The dissolved salt is a combination of different ions, such as the chloride ion that serves the great purpose of blocking nitrite toxicity in the water. The salinity tolerance of fish is a measured on rather broad scale but the aquatic animal has an optimal range of salinity for growth and reproduction. Salinity up to 4-5 ppt (parts per thousand) is the range at which most fresh water fish grow and reproduce. When fish is exposed to salinity outside the optimal level it has to focus its energy on stabilizing its salinity and that will take energy from the growth process so that in extreme cases it dies (Timmons et al., 2007).

3.14 Summary

It should be clear now that a recirculating aquaculture is a complex dynamic system with many variables that need to be understood to manage successfully. A common setup of treatment functions in a RAS system consists of solid waste removal, oxygen addition, strip the system of CO_2 and a nitrification process to transform ammonia to less harmful nitrite. The RAS system reuses up to 90-95% of the water, so there has to be some water source to provide all the water. Water outflow will carry accumulated waste and any other chemicals dissolved in the water out of the system. On the other hand, water inflow can be rich of oxygen, alkalinity and other chemicals, dependent on the water source.

Recirculating aquaculture systems are an expensive facility so the fish has to be stocked as densely as possible for the system to be economically profitable. The total biomass that can be stocked is determined by the oxygen consumption of the fish.

Water quality is what defines recirculating aquaculture. The water has to be at the highest quality possible so that fish can be grown at such a high density and water quality in the rearing tank depends on two things: The quality of the influent water and changes in the water inside the rearing tank which is driven by feed input and biological activity.

One of the most crucial water quality variables is oxygen, since the fish and bacteria need oxygen to survive and oxygen consumption by these organisms will generate CO_2. Oxygen addition, one of the treatment functions, is thus needed to increase oxygen concentration and strip the water of CO_2. Oxygen draught can occur when fish metabolize feed, so feeding the fish the right amount of feed at the right frequency is important to maximize their growth and minimize oxygen draught and solid waste in the water.

Removing accumulated solid waste is a crucial treatment function in aquaculture. It is one of the most difficult jobs and is one of the leading causes of failure. Bacteria in the system will break down waste and produce ammonia if waste is not removed sufficiently. This ammonia comes in two forms, in un-ionized form that is very toxic to the fish and in ionized form that is not as toxic to the fish.

The third treatment function is to transforming toxic ammonia to less harmful nitrite and nitrate. The process is called nitrification and takes place in the biofilter. Bacteria in the biofilter consume oxygen as feed and oxidize ammonia into nitrite and finally into nitrate. The two forms of ammonia are in equilibrium in the water but will shift to either side depending on the pH value of the water. At low pH value the ammonia will be in less harmful ionized form, but at high pH value the ammonia will be un-ionized from which is very toxic to fish. Alkalinity and CO_2 regulate the pH value in the water. If the CO_2 concentration is high then the pH value is low, so the pH value can be controlled by stripping the water of CO_2. The bacteria in the biofilter reduce alkalinity to transform ammonia and at lower alkalinity the pH value will by lowered. Adding alkalinity buffers will increase alkalinity.

In the following chapters key variables and their influencing variables will be chosen based on literature review. Flow charts will be constructed based on fish production and the three treatment functions of waste removal, adding oxygen to the system and the transformation of ammonia. These flow charts will then be the foundation of the causal loop diagrams (CLDs). Variable behavior will be introduced to clarify how the CLD functions. Finally, variables in the CLD will be marked by different colors to indicate whether they are control-, problematic-, or success variables.

4 Identifying causality of aquaculture variables

Identifying causality relation between variables in aquaculture systems is the focus of this chapter. The relation will be based on the articles read and on the previous chapters. Relation between variables in aquaculture are nearly endless so the scope will be based on the main treatment funcitons identified by Vilbergsson (2016) and Björnsdóttir (2015) which are: controlling solids, controlling nitrogen (N) compounds, controlling dissolved oxygen and CO_2. The relation will be presented visually through CLDs and flowcharts.

4.1 Key variables in aquaculture

Key variables are chosen through intense literature review and are based on the basic functions of the RAS system, controlling oxygen, ammonia, feed input and removal of solid waste, just as figure 5 shows. The key variables and their influencing variables are selected based on what Colt et al. (2009), Summerfelt (1996) and (Timmons et al., 2007) pointed out to be major variables in RAS systems. The key variables selected are: *Feed management, solid waste, total ammonia-nitrogen, dissolved oxygen* and *CO_2.*

Dissolved oxygen and *CO_2* were chosen as key variables for obvious reasons, as fish *consume oxygen* to survive and grow and in that process they generate *CO_2* (Nazar et al., 2013). *O_2 addition* and *atmospheric absorption* are the decisive influencing functions since they regulate the *dissolved oxygen* concentration in the water. *CO_2* has to be *removed* from the system or else it will accumulate and reduce fish growth. Low *temperature* and *water exchange* will reduce the *CO_2* and *O_2* concentration in the water. These variables were selected since they have a major effect on dissolved oxygen concentration and *CO_2* in a closed system (Colt, 2006).

Virtually all of the waste generated inside the RAS system is originated from *food addition* (Lekang, 2007). The decisive influencing variables chosen for food addition are the *number of fish in tank*, *food addition frequency* and *food portion size per fish* (Losordo et al., 1999).

Bottom sludge is known to cause one of the biggest problems in aquaculture and one of the main purposes of a RAS system is to remove this waste and its by-products (Badiola et al., 2012). Sludge can accumulate in two ways, from *food sedimentation* or *feces sedimentation.* The sludge has to be *removed* as quickly as possible so *bacteria decomposition* will not pollute the water. The final decisive influencing variables are *water exchange* and the fact that some fish *eat the bottom sludge.*

The final key variable chosen was total ammonia-nitrogen. It is the combination of *un-ionized ammonia* and *ionized ammonia.* These two forms are regulated by the *pH value.*

Un-ionized ammonia is generated through *fish metabolism* and *bacteria decomposing waste.* High *Temperature* will increase the concentration of *un-ionized ammonia* and decrease the concentration of *ionized ammonia.* The *nitrification* process in the biofilter converts *un-ionized ammonia* into nitrite and *water exchange* removes both from of *ammonia* (Timmons et al., 2007).

Table 2 summarizes the key variables and their decisive influencing variables in recirculating aquaculture, which is described above. The causal relationships between these variables will be shown visually through CLDs in the next chapters.

Table 2 Key variables listed with their decisive influencing variables of a RAS system.

Key variables	Decisive influencing variables
Dissolved oxygen	O_2 addition Oxygen consumption Atmospheric absorption Temperature Water exchange
CO_2	Oxygen consumption CO_2 removal Temperature Water exchange
Food addition	Food addition frequency Food portion size per fish Number of fish in tank
Bottom sludge	Food sedimentation Feces sedimentation Sludge removal Eating of bottom sludge Bacterial decomposition Water exchange
Un-ionized ammonia	Bacterial decomposition of waste Fish metabolism pH value Nitrification Temperature Water exchange
Ionized ammonia	Bacterial decomposition of waste pH value Temperature Water exchange

4.2 Mass flow and causal relation between key variables

In the following chapters flow charts and CLDs will be utilized to illustrate the functionality of the system. Flow charts are a good tool to get a holistic overview of a certain process, in this case of a recirculating aquaculture. Flow charts of the most important parts were constructed to help with the CLD making process. See chapter 2.3 for further information regarding flow charts.

Causal loop relations were examined between key variables and their decisive influencing variables. As mentioned in previous chapters causal loop diagrams consist of two arrows. A positive arrow indicates that the relation between the variables is changing in the same direction and a negative arrow indicates the opposite. See chapter 2.2 for further information regarding CLD.

As stated earlier, water exchange will be left out of the CLD figures since they affect nearly every variable in the system. This is done so the CLD's will be clearer and more readable.

Temperature also affects nearly every aspect of the system and thus it was not included in the CLD's. Instead, a temperature CLD was constructed since it is one of the main operating variables to control. The same was done to the stress factor for the fish. A CLD was constructed based on stress since a small change in nearly any variable will affect stress in some way.

In the following chapters a CLD will be presented. First the small CLDs are described in detail, and then they will be combined into a big CLD of the whole system. Finally the most important variables in the big CLD will be highlighted by different colors based on whether they are a success indicator, problem maker or whether they can be controlled.

4.3 Fish production

The focus of this thesis is on the rearing tank in the aquaculture process, and therfore the growth of fingerlings is out of the scope of this thesis. The main objective of aquaculture is to grow the fish as fast as possible to marketable size.

4.3.1 Mass flow in fish production

The fish can only enter the system in one way as can bee seen in figure 9. When fingerlings have reached a certain size they are put in to the last stage, the rearing tank, where they will grow to marketable size. The only way for the fish to leave the rearing tank is when they are harvested or if they die.

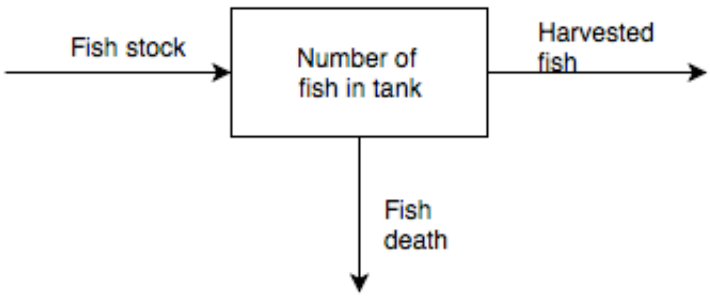


Figure 9: Flow chart of fish production in a RAS system.

4.3.2 Causality in fish production

Figure 10 illustrates the first causal loop diagram (CLD), how fish are introduced into the system, how they grow into marketable size and how the can leave the tank, as was mentioned in the previous chapter.

There are many factors that play together when it comes to optimizing fish growth. Fish is initially introduced into the system. The fastest way for the fish to grow is to be fed the right amount of nutritious feed, have enough concentration of oxygen and as little as possible of CO_2 in the water, as can be seen in figure 10. Most fish do not grow forever, and at some point they will reach growth saturation. Another limiting factor is fish density in the rearing tank. The fish are raised in a closed tank that has a certain capacity. When the fish get bigger density will increase, which will reduce fish activity and can cause stress symptoms. Fish utilize oxygen to grow through respiration and in that process they generate CO_2. If CO_2 concentration is high it cause reduce fish growth. By introducing more fish into the system it will get denser and they will consume more oxygen and generate more CO_2. Fish oxygen consumption is dependent on many variables, as bigger fish and increased activity of the fish will cause increased oxygen consumptions and the process of metabolizing feed increases oxygen consumption as well. This is all illustrated in figure 10.

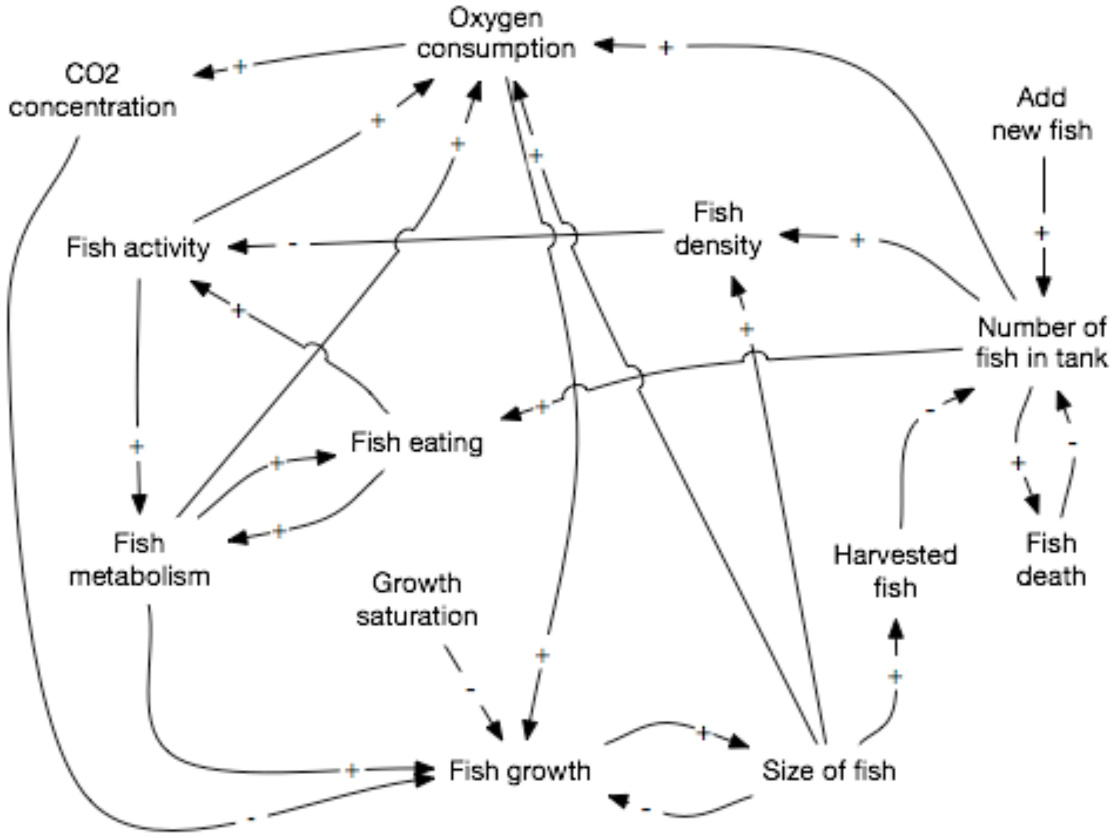


Figure 10: CLD of fish production in a RAS system.

One of the biggest tasks in aquaculture is to feed the fish the right amount of feed to minimize oxygen consumption, since fish will consume more oxygen when they metabolize feed, as will be described in more detail in the next chapter.

4.4 Dissolved oxygen and carbon dioxide

The availability of dissolved oxygen is crucial for increased water quality. Dissolved oxygen and carbon dioxide are one of the most vital variables that need to be monitored and controlled since the fish need oxygen to survive and grow.

4.4.1 Mass flow of dissolved oxygen and carbon dioxide

As can be seen in the flow chart in figure 11 here below, the oxygen can enter and leave the system in various ways. There are three different ways for the oxygen to enter the water. It will enter the system by water inflow where new oxygen-rich water is introduced into the existing water. Another way to increase the oxygen concentration in the water is to add oxygen into the system. There are many treatment functions to chose from to add oxygen. Aeration is the most common way to control the oxygen concentration and remove CO_2 from the water. The third way that oxygen enters the water is by atmospheric absorption by the surface of the water.

There are four ways for the oxygen to leave the water. Just as oxygen is added to the water through water inflow, the oxygen can also leave the system via water outflow. The main way for oxygen to leave the system is by respiration of living organisms, which will transform O_2 into CO_2 in the water and the biggest factor is fish respiration and then bacteria. Bacteria consume oxygen when they decompose accumulated waste in the water. A different kind of bacteria is grown in the biofilter which also need oxygen to convert ammonia to less harmful nitrite and nitrate, referred to as nitrification in figure 11. Finally, the CO_2 has to be removed from the system. There are different treatment functions to add oxygen and remove carbon dioxide.

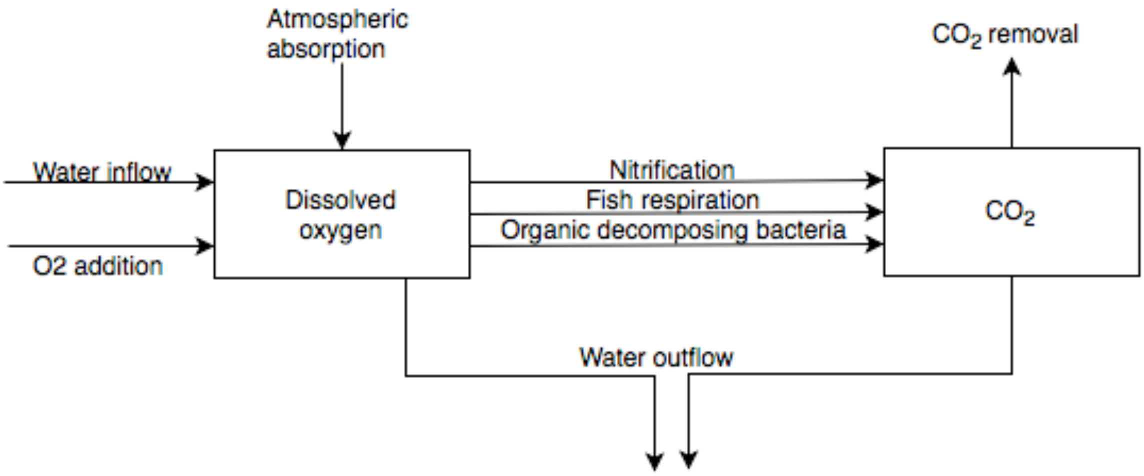


Figure 11: Flow chart of dissolved oxygen in a RAS system.

4.4.2 Causality of dissolved oxygen and carbon dioxide

Oxygen concentration has to be constantly monitored and controlled since it is one of the most crucial variables for fish survival and growth. As can be seen in the dissolved oxygen and CO_2 CLD in figure 12, there are many factors that affect the dissolved oxygen concentration. Fish need feed and oxygen to grow and when the fish gets bigger it will consume more oxygen. There are two variables that play the biggest role in decreasing the dissolved oxygen concentration, the amount of fish in the tank and fish metabolism. It is obvious if there's a lot of fish in the tank that they will consume more feed and oxygen, and in that process they will generate more CO_2. But a less obvious factor is that in the process of metabolizing feed they consume more oxygen. It is thus recommended to feed the fish frequently and in small portions rather than in large portions once or twice per day to prevent shortage of dissolved oxygen. Causality of food addition will be described in detail in the next chapter. If the fish is exposed to very low or high concentration of oxygen the fish will become less active and in that process it will reduce its oxygen consumption and metabolism.

The fish is not the only living organism that uses oxygen in the system. The bacteria are often overlooked when it comes to oxygen consumption. There are two types of bacteria that use oxygen to decompose waste. Bacteria decompose organic waste and turn it into an ammonia-nitrogen compound and the bacteria in the biofilter that converts ammonia to nitrite and nitrate is referred to as nitrification 1 and 2 in figure 12.

Accumulation of solid waste in the water can inhibit oxygen consumption. Small particles of solid waste can cause irritation to the fish by smothering its gills and in that process it will reduce the gill efficiency. Oxygen has to be added into the system and there are many ways to chose from to increase oxygen. Oxygen can also enter via atmospheric absorption. High concentration of CO_2 can lead to reduced fish growth and will also reduce the pH value so it is important to remove CO_2 from the system. Reduced pH value will lead to less nitrification efficiency.

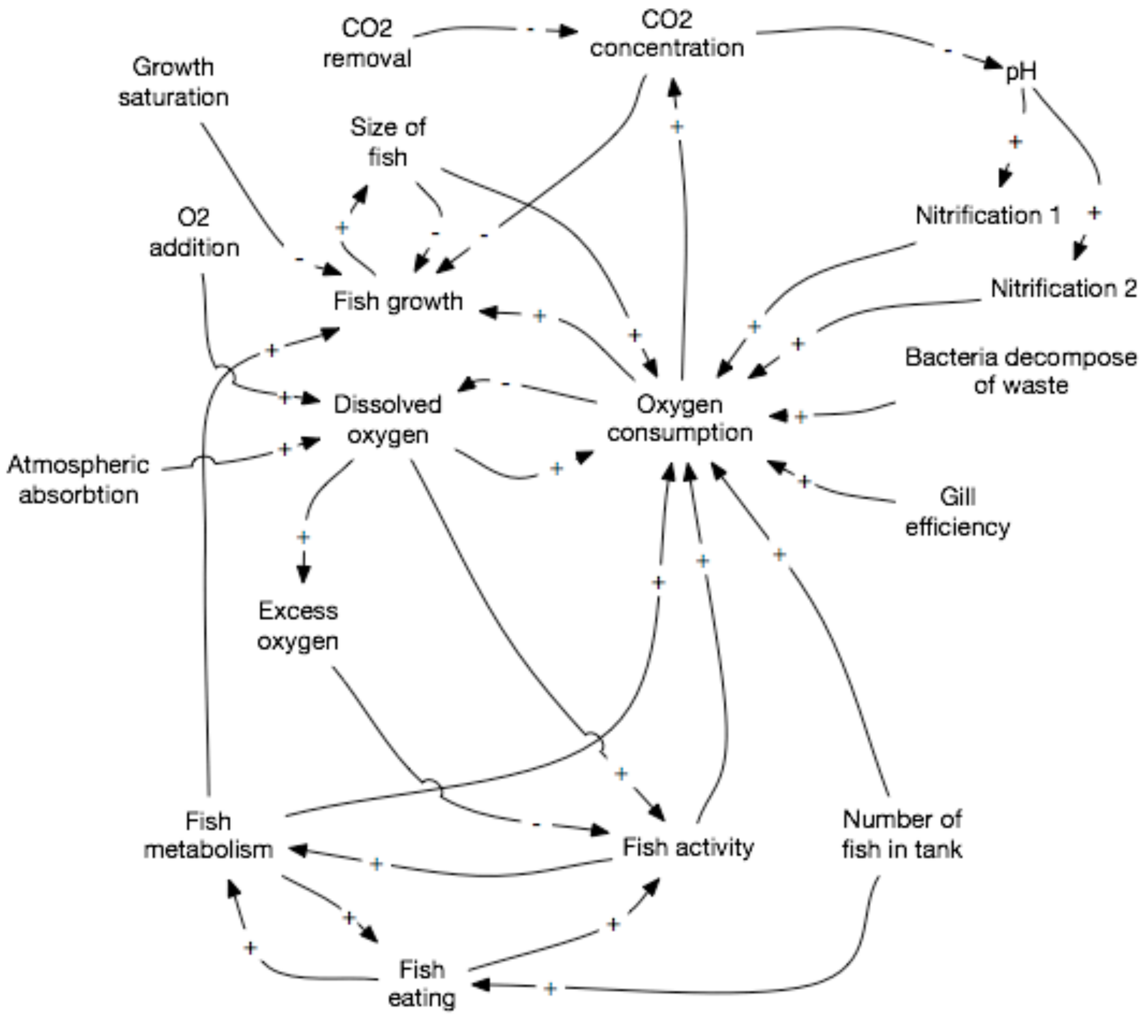


Figure 12: CLD of dissolved oxygen in a RAS system.

4.5 Feed and waste in the water

The purpose of aquaculture is to grow the fish to the preferred market size and to do so the fish must be bred in the best conditions possible. The fish needs nutrition to grow but it can be complicated to know how much feed to put in the water since feed will pollute the water.

4.5.1 Mass flow of feed and waste in the water

As can be seen in figure 13 the feed can only enter the water in one way. That is by manually feeding the fish its right amount of feed. There are four ways for the feed to leave the tank. Obviously the feed leaves the water when the fish eat the feed, which will eventually lead to excreted feed and account for feces in the water. The feces will settle at the bottom and form bottom sludge. If the fish is fed too much then the feed will slowly settle at the bottom of the tank and become sludge. In some cases the water will dissolve the feed into small particles that the fish is not able to consume. Finally, the feed, feces and dissolved solids can leave the water by water outflow.

The bottom sludge and dissolved solids have to be removed from the tank or else it will be broken down by bacteria that will reduce the water quality. There are many treatment functions to chose from to remove waste from the system. There are some fish species that will eat the bottom sludge.

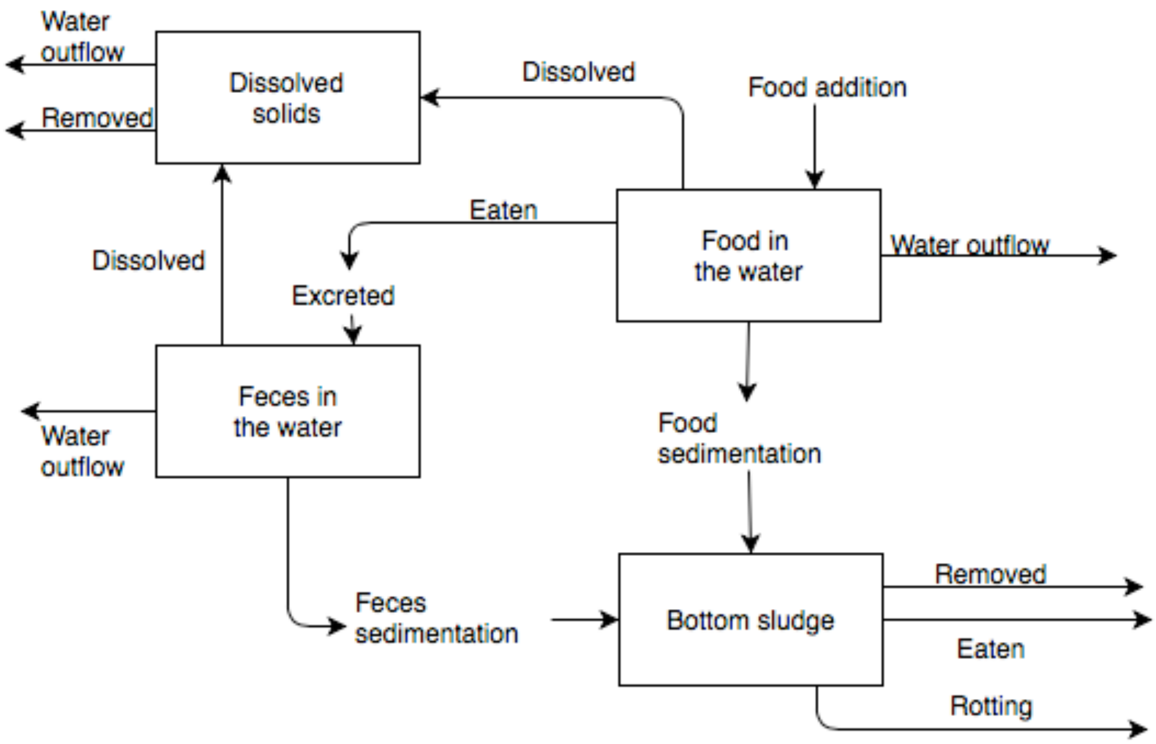


Figure 13: Flow chart of food and waste in the water in a RAS system.

4.5.2 Causality of feed and waste in the water

Virtually all of the waste generated inside the RAS system is originated from feed and one of the main treatment functions of a RAS system is to remove this waste and its by-products. To preserve good water quality the fish has to be fed the right amount of nutritious feed at a certain rate or else the excess amount of feed will end up as waste on the bottom.

The feed quantity and frequency is determined by the size and the amount of fish. Small fish are fed in smaller portions and at a higher frequency and large fish are fed in larger portions and at lower frequency as figure 14 clearly illustrates. Fish will eat more by introducing more feed into the water, but feed will eventually settle at the bottom if it is too much. Fish consume more oxygen when they metabolize feed and overfeeding the fish will lead to oxygen shortage, so it is important that the fish is fed accurately. Fish activity increases oxygen consumption and fish metabolism. With increased metabolism fish will excrete more waste that will eventually settle at the bottom, as can be seen in the waste and feed CLD in figure 14. This bottom sludge must be removed from the rearing tank as soon as it accumulates since feed and feces will eventually dissolve into smaller particles in the water which are referred to as dissolved solids in figure 14. Dissolved solids in the water will cause the fish gill irritation and by that it will reduce gill efficiency, making it harder for fish to uptake oxygen. Since dissolved solids will not settle like suspended solids, they will have to be removed by a different treatment function.

Sludge accumulation is a major problem. If sludge is not removed rapidly then bacteria in the system will break down the uneaten feed and feces. In that process it will generate un-ionized ammonia and ionized ammonia that is toxic to the fish. The fish will also release un-ionized ammonia through their gills when it metabolizes feed so it is of the utmost importance to optimize feed input.

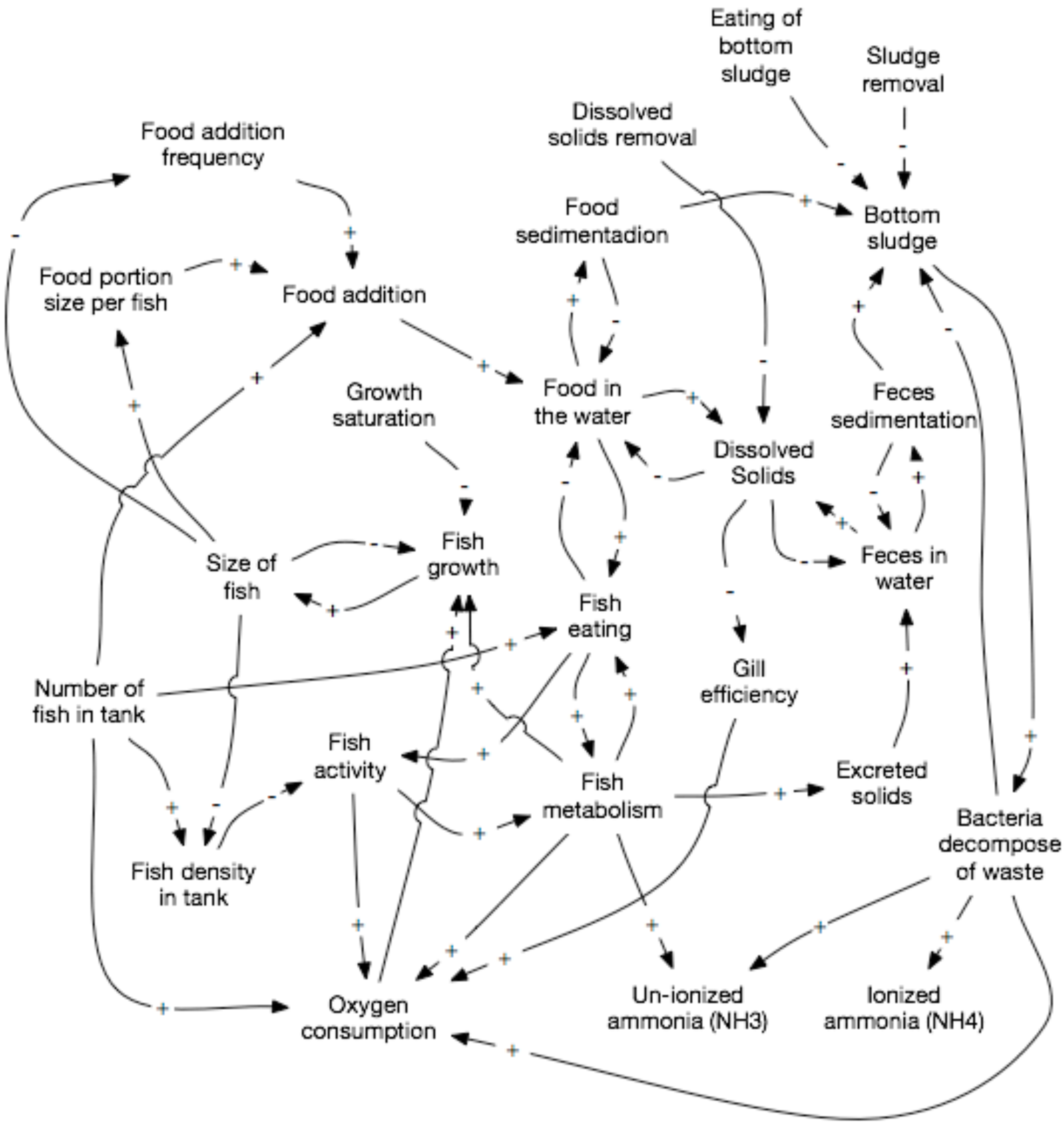


Figure 14: CLD of feed and waste in the water in a RAS system.

4.6 Total ammonia nitrogen

Ammonia buildup is one of the biggest problems in aquaculture. Ammonia must be removed as soon as possible or else it will contaminate the water and even kill the aquatic animals.

4.6.1 Mass flow of total ammonia nitrogen

Ammonia can build up in two ways in the system as can be seen in figure 15. It builds up when the fish metabolize the feed and when the bacteria break down waste. The total ammonia nitrogen consists of two types of ammonia, un-ionized and ionized ammonia. The un-ionized ammonia is more toxic to the fish than ionized ammonia and it is dependent on pH value. This will be described in more detail with the CLD in the following chapter. Since the ammonia is toxic to the fish it has to be removed from the system as soon as possible. There are two ways for it to leave the system. Some of the ammonia will leave with water outflow but the most common way is that of converting the toxic ammonia into less toxic nitrite by nitrification in the biofilter. Bacteria in the biofilter transform ammonia into nitrite, but a high concentration of nitrite can also be toxic to the fish. Water outflow will remove some part of the nitrite but different kinds of bacteria in the biofilter, which take longer time to grow, convert this nitrite into nitrate. Nitrate is only harmful to the fish at very high concentrations and if water exchange is sufficient it should not be a problem. Nitrate can also be removed be a de-nitrification filter which turns nitrate into nitrogen gas. Nitrogen gas will then be removed at the surface of the water by atmospheric desorption or with aeration.

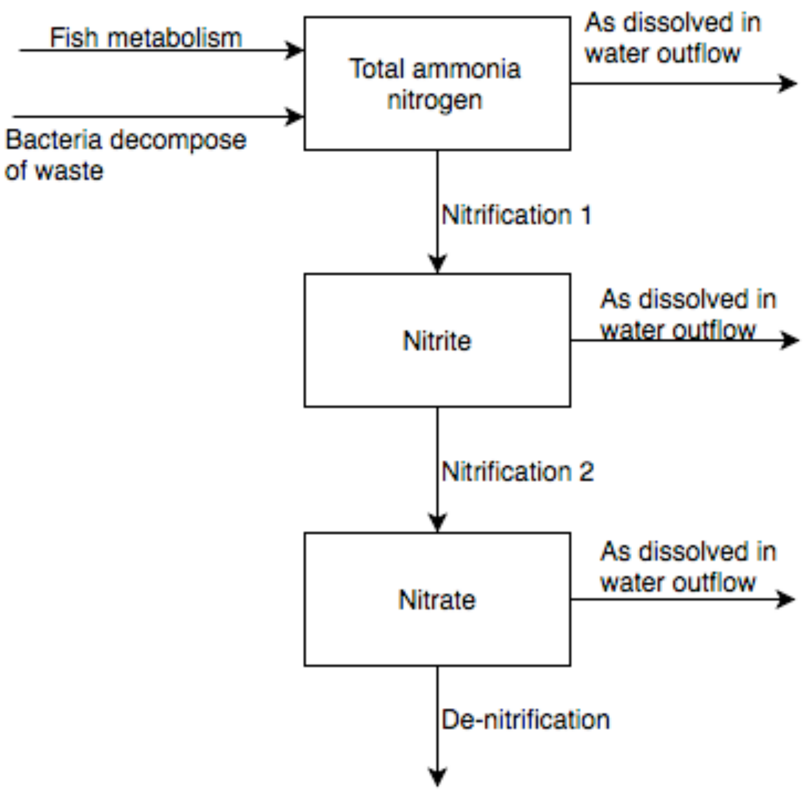


Figure 15: Flow chart of total ammonia-nitrogen in a RAS system.

4.6.2 Causality of total ammonia nitrogen

Ammonia starts to build up as soon as feed is put into the tanks and it comes in two forms, ionized and un-ionized ammonia. As mentioned earlier, ammonia is released from fish gills as un-ionized ammonia when they digest feed. Bacteria then break down the uneaten feed and waste to generate ionized and un-ionized ammonia, as can be seen in total ammonia nitrogen CLD in figure 16. Un-ionized ammonia and ionized ammonia are in equilibrium in water. Un-ionized ammonia is more toxic than ionized ammonia and the pH value controls the concentration of each. If the pH value is high, the concentration of un-ionized ammonia will be greater, but if the pH value is low, the concentration of ionized ammonia will be greater. It is thus important to control the pH value constantly.

Alkalinity is one of the main ways to control the pH value in the water. Alkalinity can be increased by addition of alkalinity buffers. If the alkalinity is increased the pH value will also increase. The CO_2 concentration also affects the pH value, for if the CO_2 level in the water is high then the pH value will be low. Aeration is a useful mechanism to remove CO_2 from the water.

In order to be able to keep the fish alive and his environment toxic free it is important to get rid of the ammonia in the system, or at least keep it in ionized rather than un-ionized form. The nitrification process removes this ammonia from the system. Bacteria in the biofilter utilize oxygen to transform ammonia into nitrite and a different bacteria in the biofilter transforms nitrite into nitrate as can be seen in figure 16 as nitrification 1 and 2. The nitrification 1 process releases H^+ ions into the water, which will decrease the pH value. The nitrification process decreases the alkalinity concentration in the water, which will eventually affect the pH value. The nitrification process is also affected by pH value, as higher pH leads to more efficiency transforming ammonia and the optimal pH value for the nitrification process is around 8-9. Nitrification efficiency will decrease by increasing the pH value past the optimal value as can be seen as pH inhibition of bacteria in figure 16.

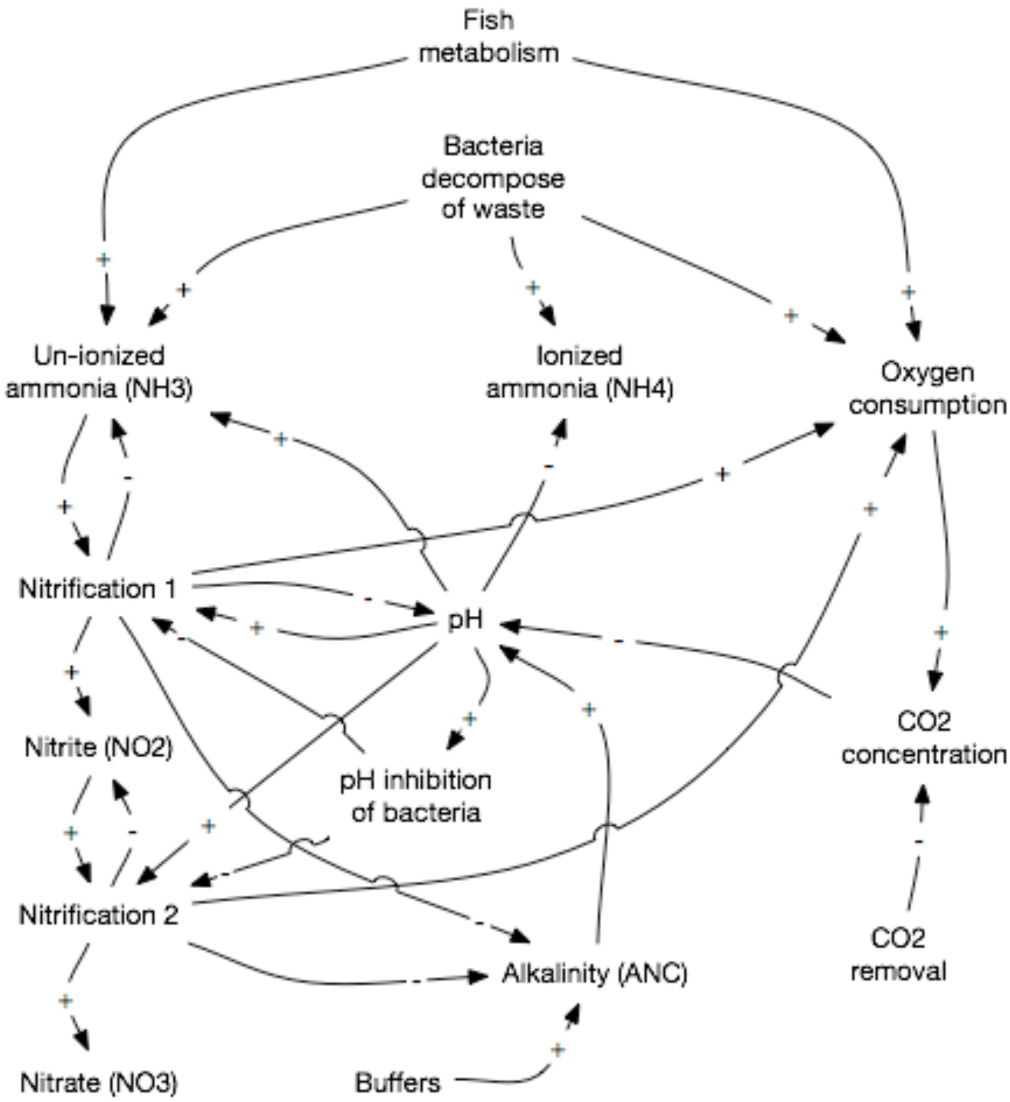


Figure 16: CLD of total ammonia-nitrogen in a RAS system.

4.7 Stress and temperature

The fish lives in a dynamic system where water quality is constantly changing. Water quality is one of the most important factors when growing fish in RAS systems. If the water quality is not up to standard the fish will not be up to standard for consumption. If water quality is not optimal it will cause stress on the fish and, as can be seen in the stress CLD in figure 17, there are many variables that affect stress. Each individual variable is important but it is the combination and interrelationship between those variables that affect the health and growth rate of the fish. Stress can be harmless to the fish but high levels of stress for a long period of time can create severe health problems that may increase mortality rate. It is impossible to eliminate all stress, but stress must be minimized to prevent many of the stress-related causes. Stress can have a negative effect on fish growth and will also lower the ability of the immune system, of the fish making it more prone to disease.

The fish has to live in optimal water quality to counteract stress. Chemical stress can have severe impact on stress levels, and chemical stress is the combination of un-ionized and ionized ammonia, nitrite, nitrate and fluctuation in pH value. These variables are constantly changing due to the dynamic environment the fish live in. Sudden change in concentration of un-ionized ammonia or pH value can cause catastrophe, killing all the fish or the bacteria in the biofilter. Ionized ammonia, nitrite and nitrate are not as lethal but can affect the growth rate through stress and at certain concentration they can lead to fish death.

An RAS system is only economically profitable if the fish are bred at high density but if the density is too high it will cause stress to the fish. More fish will also lead to higher concentration of CO_2, if it is not removed immediately. Wild fish live in water with nearly constant salinity, and the fish body needs to maintain the osmotic gradient between it and the water. So if the salinity concentration is fluctuating or is not near optimum the fish will have to work hard to maintain their osmotic gradient, which will cause stress. It goes without saying that oxygen concentration needs to be steady around the optimal value. If fish are exposed to low oxygen levels, this will increase stress levels and can cause fatality. Fish can become sluggish is exposed to too much oxygen. Most fish will not tolerate temperature fluctuation very well, or temperature outside of his optimum level, and thus controlling the temperature is one of the most important operating tools to control the temperature.

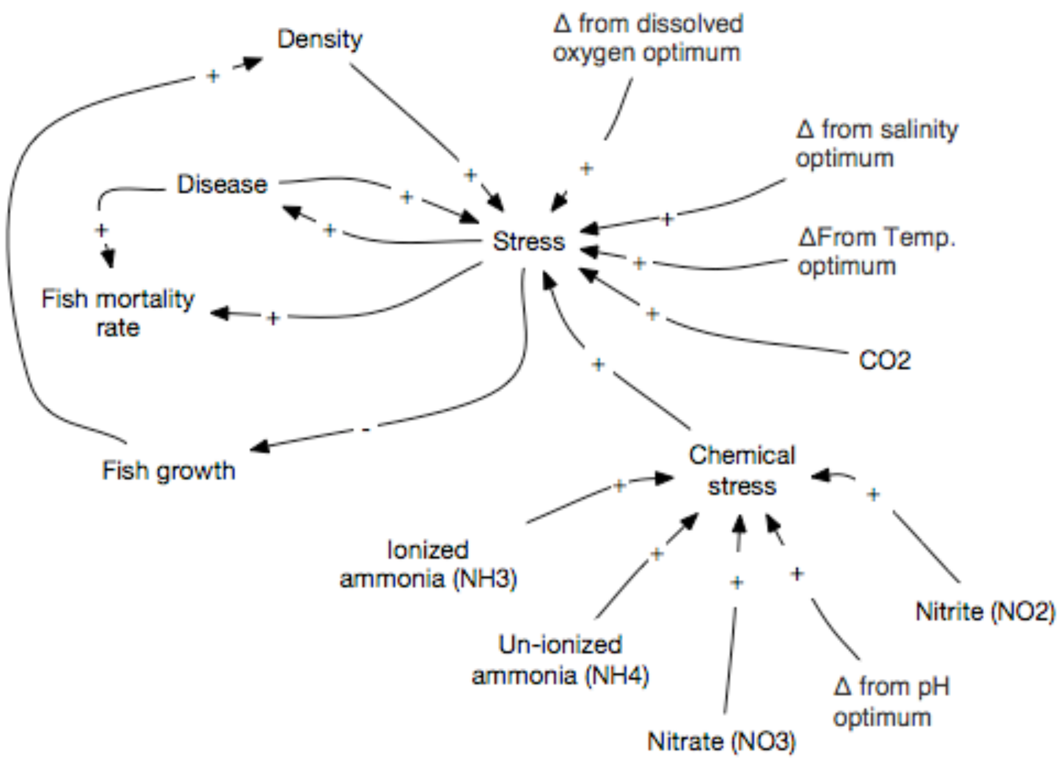


Figure 17: Stress in fish

Controlling temperature is extremely important since it affects nearly all other variables in the system, as can be seen on the temperature CLD in figure 18. Temperature is controlled via heaters or coolers depending on the optimal water temperature for the species grown. As stated earlier, optimal temperature has a positive effect on fish growth but the manufacturer needs to be aware that if heat gets too high or too low it will cause reduced fish growth or, in the worst case it, will cause death. Higher temperature will also change the behavior of the fish, which become more active, and eat more as its metabolism increases. The temperature also affects the concentration of dissolved oxygen and CO_2 concentration in the water, and increased heat will lead to less soluble gas in the water just as it will decrease water adsorption availability. The nitrification process is crucial for a successful aquaculture. Increased temperature will increase the nitrification process to convert ammonia into nitrite and nitrate, but too high or too low a temperature will decrease the nitrification rate. Increased heat will also encourage bacterial decomposition of waste which will generate more ammonia and with increased heat the ammonia will rather be in un-ionized form.

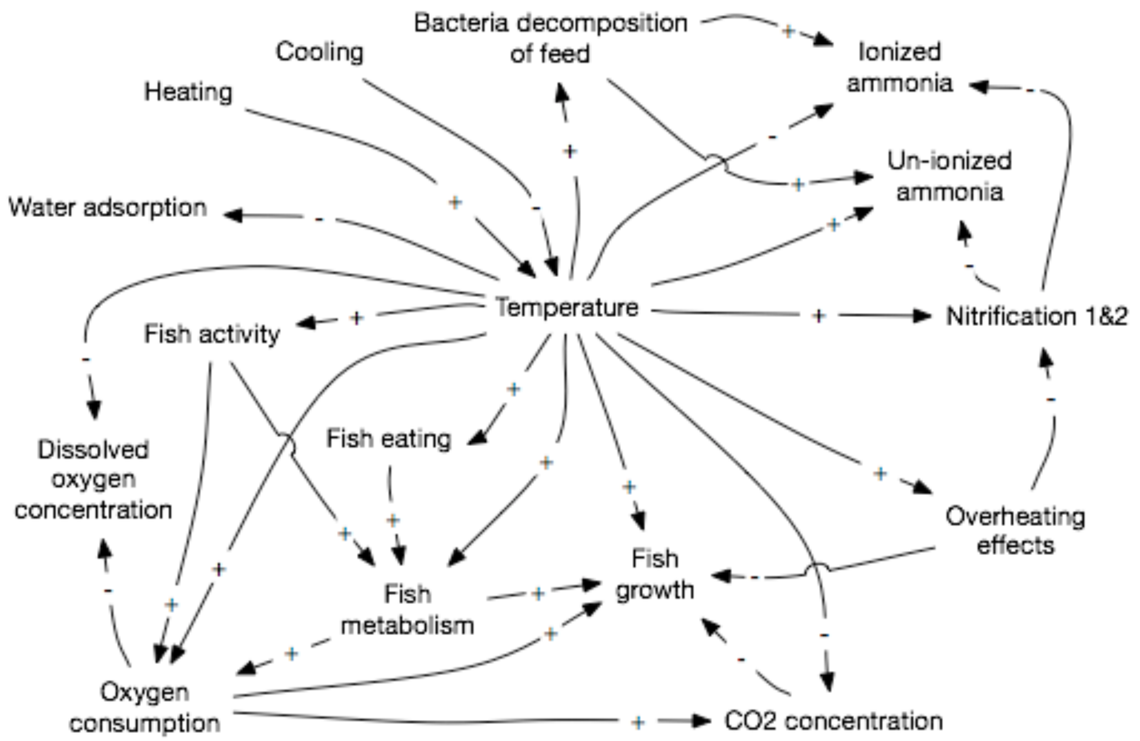


Figure 18: Temperature effect on the system.

So there are many variables that need to be taken into account when controlling temperature and stress. This is a dynamic system where changing one variable can lead to change in the whole system for the better or worse.

4.8 Causality overview

The CLD in figure 19 summarizes all off the CLDs discussed in the previous chapters and shows the relation between dissolved oxygen, feed, total ammonia nitrogen and solid waste removal.

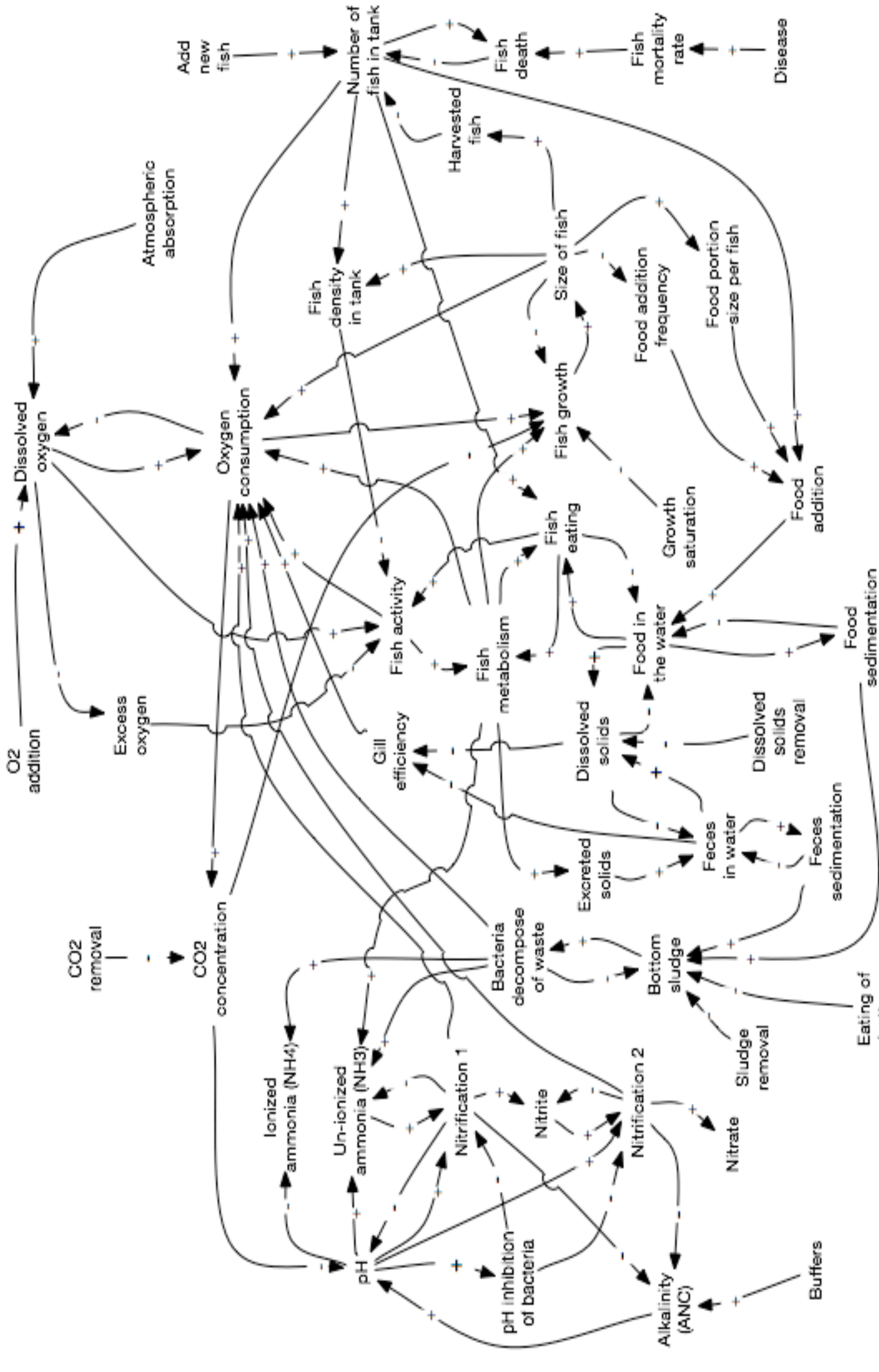


Figure 19: Overview CLD, showing the cause and effect of the whole system.

Figure 19 illustrates quite well how complicated recirculation aquaculture can be, although temperature and stress have been taken out of the picture to make it more readable. Overall the main treatment functions are controlling the dissolved oxygen and CO_2, removing waste and ammonia as can be seen in figure 5. The difficulty of managing an aquaculture system lies in the intensity involved in it. Increasing the number of fish stocked in the rearing tank will require more food addition, which in turn all problems in aquaculture can be traced back to. The fish consumes the feed and in that process oxygen consumption will rise drastically, more waste will be generated which will in the end produce more toxic ammonia. The treatment functions to control oxygen and CO_2 (increasing oxygen concentration), removal of sludge (preventing ammonia buildup) and ammonia (converting ammonia to nitrite and nitrate) are thus the foundation of a successful aquaculture.

Variables in the CLD behave differently, as they can have an optimal value, be decreasing or increasing. This will be described in the following chapter.

5 Analysis of causal relation between variables in aquaculture

In order to use such a complicated CLD it is important to analyze it. It is important to know how the major variables behave differently and which variables need to be controlled to prevent problems regarding the main goal, to maximize the harvest. The following chapters will explain different variable behavior and list up variables based on if they can be controlled, cause problems or indicate success.

5.1 Variable behavior

There are three ways that variables behave in the aquaculture system, as can be seen in the figures here below. First, they can be continuously decreasing or increasing or they can have a certain optimal value. The most important variables are listed to clarify their individual behavior.

Variables with decreasing behaviors:

Fish can not grow forever. The fish growth rate will be high in the early stages of the lifetime of the fish although it is dependent on water quality and other variables. In the later stages of the fish's lifetime the fish growth rate should have nearly stopped. Feed is manually inserted into the water and the amount of available feed in the water will decrease as the fish consume it and it settles at the bottom as sludge. At the early stages of the fish's lifetime it has to be fed more frequently and in smaller portions. When the fish grow it will be fed more frequently and in bigger portions.

Variables with increasing behaviors:

Initially small fish are introduced to the system and by optimal water quality and enough resources the fish will continue to grow until it has reached its maximum possible size.

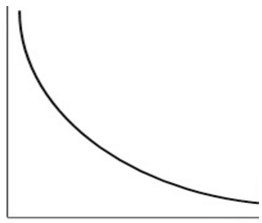
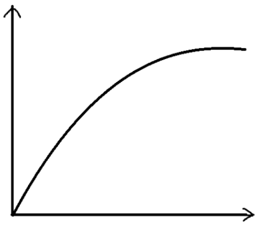
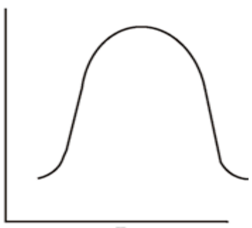
Fish growth will also limit the available space in the tank by increased density. Feed portion size will increase parallel to fish size. Solid waste will accumulate if it is not removed efficiently enough and if the sludge is not removed from the rearing tank it will generate toxic ammonia, which will continue to grow until the water is saturated. The ammonia has to be removed by nitrification and converted into nitrite and nitrate, and if water exchange is sufficient it should not accumulate in the system. Accumulation of CO_2 is a problem if it is not removed efficiently enough. Water quality has to be near its optimum to prevent additional stress buildup in the fish.

Variables with optimal behavior:

The optimal temperature differs with the species grown. The optimal temperature is crucial to maximize fish growth and other attributes. Oxygen concentration must be monitored and controlled constantly, for if the fish do not get enough oxygen it will reduce the fish growth and can lead to mortality. If the fish is exposed to a high concentration of oxygen it will get sluggish. Salinity must not fluctuate too much in the system or it will inflict stress on the fish through osmotic pressure between it and the water. The pH value has to be monitored closely since there is an optimum pH value for fish and bacteria in the biofilter. If the pH value is too high or to low it can have a catastrophic effect on the whole system.

Table 3 summarizes the selected variables based on their behavior.

Table 3: Variable behavior

Variable behavior	Variables
Decreasing behavior: 	• Fish growth rate • Feed in water • Feed frequency
Increasing behavior: 	• Size of fish • Ammonia • Nitrite and nitrate • Waste • CO_2 • Feed quantity • Stress • Density
Optimal behavior: 	• Temperature • Dissolved oxygen • Salinity • Water pH

Optimal behavior illustrated in the CLD's is for example the effect the pH value has on the nitrification rate. As can be seen on figure 20, the nitrification rate increases with a higher pH value. One might think that it would be beneficial to have the pH value as high as possible to convert un-ionized ammonia to nitrate more efficiently, but that is not the case. The bacteria in the biofilter, where the nitrification process takes place, have a certain optimal pH value. If the pH value is too high it will make the environment hostile for the bacteria and by that reduce the nitrification rate. Thus it is important to constantly monitor and control the pH value to have optimal water quality.

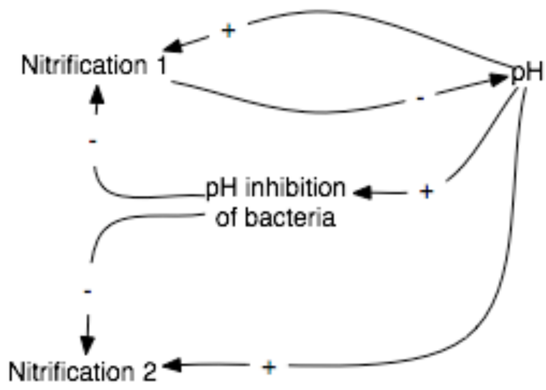


Figure 20: Optimal behavior of pH.

When controlling such a complicated system it is beneficial to know which variables are more important than others, which variables will cause the biggest trouble and which will indicate the biggest success for the whole system. In the following chapters these variables will be discussed and drawn in color into the overview CLD.

5.2 System indicators

It is important to understand all the mechanisms in the recirculation aquaculture system but it is crucial to know which ones to control, which ones will cause problems and which ones are the success indicators. Variables that indicate success, problems or that can be controlled in recirculating aquaculture will be listed in the following chapters based on an intense literature review.

5.2.1 Success indicators

Success indicators are those variables that will increase profit or generate success. Those are therefore the variables that managers should aim at maximizing. The success variables are *harvest* and *size of fish* since the main goal of aquaculture is to maximize fish growth and harvest size. The price is going to be higher for bigger fish and a greater amount of sold fish will generate more income. The quality of the fish will reduce the profit but that is outside of the scope of this thesis. Success indicators will be shown in the color green in the CLD in figures 21 and 22. There are a lot of different factors that affect the final outcome of the success indicator. These factors will be referred to as problematic indicators.

5.2.2 Problematic indicators

Managers need to know which variables need to be constantly monitored since they can have catastrophic effects on the system. The biggest concerns regarding recirculating aquaculture are concentration of *dissolved oxygen* and *un-ionized ammonia. Dissolved oxygen* is the most crucial variable in the system since fish need oxygen to survive and grow. If oxygen is not sufficient it will cause reduced growth rate and can lead to fish death in severe cases. *Un-ionized ammonia* is toxic to the fish and needs to be constantly monitored since it can kill the fish. Fish and other organisms produce CO_2 through respiration. CO_2 at high concentration can reduce growth rate by interfering with oxygen consumption by the fish and reducing the *pH* value in water. The *pH* value is another factor that has to be monitored since fish and bacteria have a certain optimum level which they can live in. High concentration of *nitrite* can also cause stress to the fish but if water exchange is sufficient it should not be a problem. *Temperature* needs to be constantly monitored and controlled since fish species have a certain optimal *temperature* range which they can survive in. Keeping the *temperature* at optimum levels will have positive effect on fish growth.

These variables will all affect the fish in some way but it is the interrelationship between the variables that affect the health and growth of the aquatic species. The manager will need to pay special attention to these variables so they will not affect the harvest size or worst case scenario, kill the stock. The problematic variables will be shown in the color red in the CLD in figure 21 and 22.

Managers will need to control these variables to be able to manage a successful aquaculture system. The Control of these variables will be defined in the following chapter.

5.2.3 Control variables

There are some variables that have to be controlled to reach the main goal of aquaculture, which is maximum harvest size. *Fish addition* can be controlled manually and it is dependent on treatment functions available and on capability of the system. *Water exchange* can be sufficient as a water treatment process for less intense aquaculture since it will flush accumulated chemicals out of the system and add fresh water into the system that is rich of oxygen. Temperature has to be regulated since it affects nearly every variable in the system. It is done with different *heaters* and *coolers*. Oxygen shortage is likely to occur in high intensity systems and thus it is crucial to regulate the *oxygen addition*. One way to control the oxygen concentration is by controlling the *food addition* since fish consume more oxygen when metabolizing feed. *Food addition* is determined by the size of the fish. Sludge will accumulate in the system eventually and it will cause problems if it is not *removed* from the system. *Buffers* can be added to increase the alkalinity in the system to counteract pH fluctuation.

These are the variables that the manager can interfere with. If all of these variables are controlled sufficiently then they should affect the system in a positive way, either by preventing cause on the problematic variables, or by counteracting the existing water quality state. The control variables will be shown in the color blue in the CLD in figure 21 and 22.

5.2.4 CLD with indicators

The indicators stated in the previous chapter will be illustrated in figures 21 and 22 with different colors. The colored causal loop diagram (CLD) can be utilized as a useful starting point to understand the underlying mechanism in such a complicated system. The CLD clearly shows which variables to monitor and which can be controlled to reach the goal of a successful harvest. It also shows the fragile and dynamic environment that fish live in.

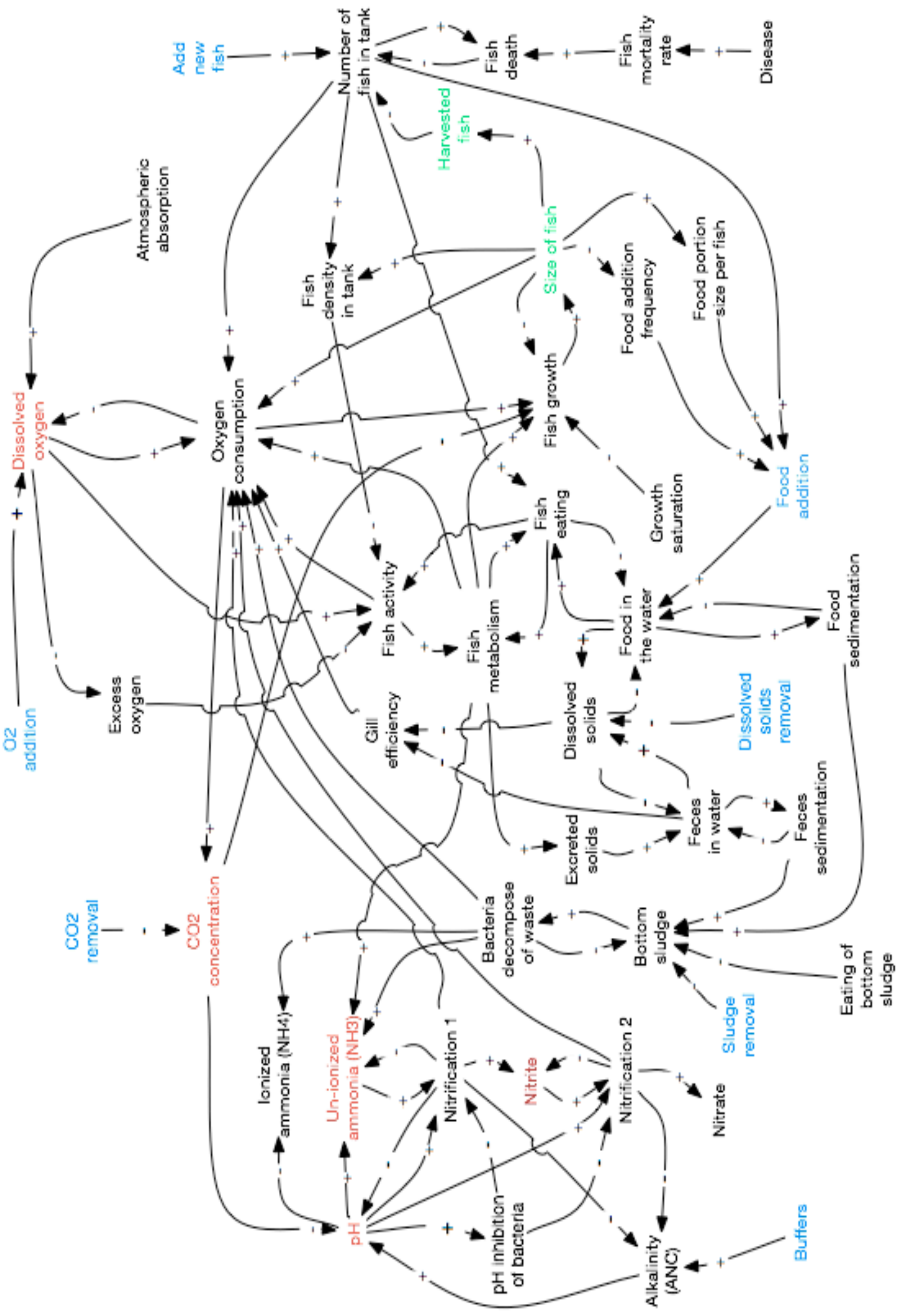


Figure 21: Overview CLD with success indicators colored as green, problematic indicators as red and control variables as blue.

Temperature can be a big problem if it is not monitored and controlled constantly. As can be seen in figure 22, the way to control the temperature is by different heaters and coolers depending on the optimum temperature range of the species grown. If the temperature is not managed properly it can have a catastrophic effect on the whole system since it has an effect on nearly all other variables in the system.

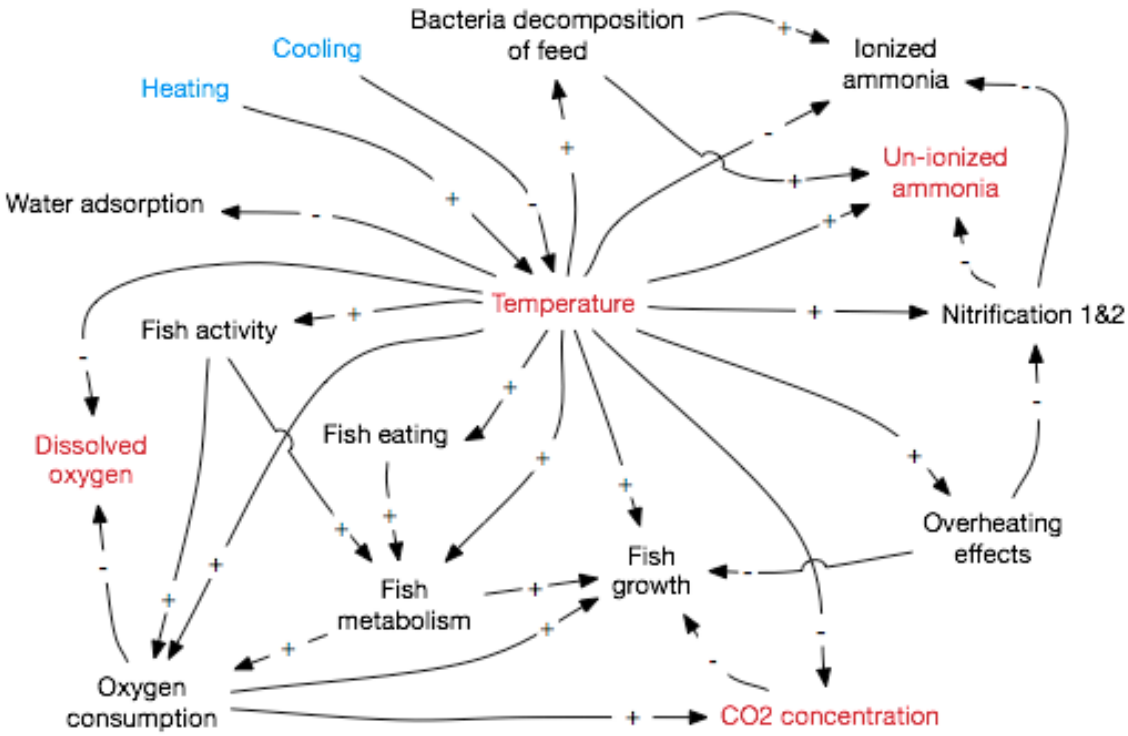


Figure 22: Temperature CLD with problematic indicators as red and control variables as blue.

6 Discussion

The CLDs and the relations between key variables introduced in this study are based on literature review and the previous work of Vilbergsson (2016) and Björnsdóttir (2015). The project was defined by Björgvinsdóttir's input-, output- and treatment functions and Vilbergson's specific treatment functions of controlling solids, ammonia, dissolved oxygen and CO_2. The CLDs presented provide an overview of known topics that are difficult to grasp and may not be fully complete since they are dependent on the articles selected.

The main focus for an aquaculture management is the full control of water quality variables and water treatment units to maximize their production and minimize their environmental impact. Since the scope of this project was only the rearing tank, then all environmental impact was excluded from this paper. Water quality does affect the health and quality of the cultured species inside the system. Numerous water quality variables were identified in this paper, but intentionally, not all were included since some variables have more effect on the system than others and there was not enough time to cover them all. Water quality problems can be traced back to the intensity of the system. Better use of treatment functions are required for breeding enormous quantity of fish only to be able to obtain optimal water quality for the species grown.

The CLD introduced should be a good tool to enhance understanding of aquaculture since they clarify the cause and effect relation between key variables in a RAS system. As this work progressed the author realized that the interrelations between variables in aquaculture are almost endless. The main treatment functions defined by Vilbergsson (2016) were thus used to define the project. The treatment functions (controlling dissolved oxygen, CO_2, solid waste and ammonia) on their own serve one purpose, for example that of controlling dissolved oxygen. But what the CLD made clear to the author was that treatment functions can affect the system in various ways that were not clear before. Aerating the water (oxygen control) will strip the water of CO_2. Reduced CO_2 concentration will increase the pH value in the system and high pH value will cause the ammonia to be in un-ionized toxic form in the system. The CLD is thus a powerful tool to enhance learning in such a complicated system.

In order to make the CLD's as simple as possible, temperature and stress were not included in the overview CLD. Temperature and stress CLD's were constructed separately since they will affect nearly every other variable in the system. A CLD for water exchange was initially on the drawing board since it affects nearly every variable in the system. As the work progressed the author realized that constructing a water exchange CLD is dependent on the current state of the water in the rearing tank and also dependent on water source. A water exchange CLD was not included but it was made clear that it is one of the biggest factors to regulate water quality.

Since the CLD can be confusing to the untrained eye it was decided to color the most important variables in the system based on whether they are a success, problematic or a control variable.

This thesis is only at the early stages of the theory building process and only scratches the surface when it comes to aquaculture. It is possible that some important connections are missing from the CLDs. Finishing the CLDs with all connections that aren't included needs to be done. There are countless variations of existing aquacultures so there will be some variables in the CLD which are unsuitable or some that are missing for specific aquacultures.

6.1 Further research

As stated earlier, this work is only in the process of theory building and the main focus was on the rearing tank so there is need for further research. First, it is needed to analyze the current CLD and identify important variables and connections that are missing, and to identify the weight of each connection between variables since that can vary. For example the question of which connection is stronger for pH value, the CO_2 concentration or the alkalinity. Since this research is only based on a literature review it will be beneficial to validate it and run it by professionals in the field. Data gathering will eventually have to be done for it to be possible to simulate. Different treatment functions can eventually be added into the simulation process to see how they affect the process in various ways. The work of Vilbergsson (2016) will be valuable for such a simulation.

The focus of this thesis is on the rearing tank. It would certainly be beneficial to look into the economy regarding recirculating aquaculture since it is an expensive process.

The quality of fish is something that can be looked into. There are a lot of supplements, hormones and antibiotics added into the rearing tank to enhance growth and to counteract diseases. The quality of the product is degraded by addition of supplements. The increased weight and size of the fish will increase profit but the degraded quality will reduce the income.

7 Conclusions

The object of this paper was to identify and map key variables and their relations in the rearing tank of a RAS system based on intense literature review. A CLD was constructed from these key variables and their decisive influencing variables to give a good visual overview of the system. This kind of approach is missing from the literature, as articles focus more on individual relations between certain variables than the whole system. This work aimed at finding the key variables in a recirculating aquaculture system and explaining how these variables are connected to each other through cause and effect. The key variables and their interrelations were found through an intense literature review and are all summarized in chapters 3 and 4. This chapter will answer the research questions:

1. What are the key variables of a recirculating aquaculture system and how are these variables connected to each other through the cause and effect?

   Key variables were chosen through an intense literature review and are based on the basic function of the RAS system, identified by (Vilbergsson, 2016), to control oxygen, ammonia, feed input and removal of solid waste. The key variables were presented in chapter 4.1 and the ones selected were: Dissolved oxygen, feed, solid waste and total ammonia-nitrogen.

   The connections between the key variables are accounted for in chapters 4.2 – 4.8. The connection can mainly be traced back to feed input. Feed input will increase the oxygen consumption of the fish and it will generate ammonia and solid waste through fish metabolism. Bacteria in the system will eventually decompose the accumulated waste to produce ammonia and in that process bacteria consume more oxygen. Increased production intensity will only amplify these causes, making the importance of efficient treatment functions indispensable.

2. What are the success, problematic and control variables for a recirculating aquaculture system?

   The indicators of the system were described in detail in chapters 4.10 and were chosen through a literature review. The indicators can be seen in different colors in figures 21 and 22.

   The success indicators were chosen based on what variables create the greatest success. The variables selected were the size of fish and harvest since these variables account for profit.

   The problematic indicators were chosen based on which variables cause the biggest problems in the aquaculture system and threaten overall success. The variables selected were un-ionized ammonia, dissolved oxygen, CO_2 concentration, temperature, pH value and nitrite.

The control indicators were chosen based on which variables can be controlled to prevent problems in the system. The control variables selected were water exchange rate, temperature, O_2 addition, buffers, introduction of new fish, sludge removal and food addition.

A first draft of a CLD was constructed in this thesis and hopefully this work will be a foundation for further research. The CLD overview of connections between key variables in a RAS system will enhance understanding for aquaculture operators and enable them to see the bigger picture.

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