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Intensification of landbased aquaculture production in single pass and reuse systems

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Abstract:

Over the last 20 years, the productivity in hatcheries and farms producing fry and smolt of trout and salmon has increased substantially. These land-based farms are mainly situated along the coast and discharge effluent water directly to the sea. Such production is the basis of the recruitment of marine salmon and trout cage farms in Chile, Scotland, Norway and some other temperate countries with a coastline. Similarly, productivity and use of recirculation systems for the production of both seawater and freshwater fish has increased throughout the world. In many cases, the use of recirculation systems has ecological advantages over other technologies, especially those relying on flow through operations. The Norwegian authorities required a minimum flow supply of 1.5 m3 per 100,000 salmon smolt produced annually since the mid-80's. Without oxygenation of the water, the specific flow rate fluctuated between 0.5 and 2.5 L kg-1 min-1 throughout the year. Addition of pure oxygen then significantly reduced the flow requirements, now typically in the range 0.3 – 0.5 L kg-1 min-1. According to another regulation for licensing of hatcheries, the lowest allowable flow in single flow-through systems was 0.3 L kg-1 min-1. Water quality parameters have however been introduced recently as criterion instead of water flow requirements (concentrations of oxygen, carbon dioxide and ammonia). Mainly due to the usage of oxygenation technology, the water consumption at most smolt farms is at present 100 – 200 m3 kg-1 produced fish compared to 1,000 – 1,700 m3 kg-1 some 20 years ago. When the water flow is reduced, there is a build-up of both carbon dioxide and total ammonia, whilst pH is reduced. Both carbon dioxide and pH may become limiting factors when the water flow is decreased due to oxygen injection. There is however a lack of information regarding safe levels of carbon dioxide concentrations for Atlantic salmon smolts. Increased ventilation frequency and reduced growth have been observed in smolts exposed to reduced water flow. Effects observed during long-term experiments with rainbow trout and Atlantic salmon exposed to elevated carbon dioxide in fresh water include reduced growth and feed utilisation and nephrocalcinosis.

Recirculation systems allow in the same time to reduce the make up water needs, to control the recirculated water quality and facilitates the treatment of the effluents (lower flow rate and higher concentration). They were developed at commercial scale in several countries and for various marine or freshwater fish species. In this article, some recirculation systems adapted to different fish life stages (from breeders to commercial size fish) and environments (Europe and USA) will be described.

Improved feed quality, better feeding control and other factors have strongly reduced the waste production from farms. Since the mid-80's, the mean feed conversion ratio (FCR) in the Norwegian smolt industry as in other developed countries has decreased from 1.5 – 1.8 to less than 1.0 (kg feed kg-1 produced fish) which indicates a halved effluent load of organics and nutrients per kg produced fish. Additionally, many farms have introduced end-of-pipe treatment for solid removal before release to recipient.

1. Introduction

Water supply is a major limiting factor in landbased aquaculture production. Therefore pure oxygen is often added to the inlet water or directly to fish tanks. If water flow to a production system is reduced due to the introduction of pure oxygen, there can be a build-up of both carbon dioxide and total ammonia, and a reduction in pH. The drop in pH is directly related to the buffer capacity (alkalinity) of the water and therefore both carbon dioxide and pH may become limiting factors when water flow is decreased and oxygen is added. In low alkalinity water, pH tends to be the first limiting factor reached [1] and the reduction in pH from the inlet water to the discharge can be so great that the water is not suitable for fish farming. When pH is reduced aluminium becomes toxic as it accumulates on the gills of fish impairing osmoregulation and oxygen up-take [2]. When alkalinity is high, carbon dioxide is an important water quality limiting factor in single pass oxygenated landbased systems and also in recirculation systems. There is, however, a lack of information regarding safe levels for carbon dioxide for Atlantic salmon smolts. Effects observed during long-term experiments with rainbow trout and Atlantic salmon exposed to carbon dioxide in fresh water, include reduced growth, reduced food conversion efficiency and nephrocalcinosis.

Norwegian authorities have required a minimum flow supply of 1.5 m^3 min^{-1} per 100,000 smolt produced annually since the mid-80'ies. Without oxygenation of the water, the specific flow rate fluctuated between 0.5 and 2.5 L kg^{-1} min^{-1} throughout the year. Addition of pure oxygen then significantly reduced the flow requirements, now typically in the range 0.3 – 0.5 L kg^{-1} min^{-1}. According to a next regulation for licensing of hatcheries, the lowest allowable flow in single use flow-through systems was 0.3 L kg^{-1} min^{-1}. Water quality parameters are now used instead of water flow requirement (oxygen, carbon dioxide and ammonia).

Many reports indicate that water use and effluent loading in landbased farming can be significantly reduced by intensification practices, such as more aeration, recirculation of water including waste removal by methods such as the temporary storage of drainage water in sedimentation ponds before entering the recipient water body [3, 4].

Single pass systems

The main water quality parameters in single pass systems are oxygen, pH, carbon dioxide, alkalinity and metals (as aluminium). These parameters are related to the water flow in the systems. In single pass fish farming systems oxygen is considered to be the first limiting factor for the water flow requirement [5, 6]. The freshwater supply is one of the most important production limiting factors in Norwegian smolt production facilities. Quantitatively the water flow requirement may be expressed as [7]:

$$q_0 = \frac{M}{DO_{in} - DO_{out}} \qquad (1)$$

where q_0 is the specific water flow requirement (L kg^{-1} min^{-1}), M is the oxygen consumption rate (mg kg^{-1} min^{-1}) and DO_{in} and DO_{out} is the oxygen concentration (mg L^{-1}) in the inlet water and at the discharge, respectively.

This equation may also be written as :

$$q_0 = \frac{M}{d} \qquad (2)$$

where d is the difference between DO_{in} and DO_{out}. When the concentration of oxygen is increased in the inlet water the d value is increased at a given value for DO_{out} and the specific water flow is reduced for a given metabolic rate (Fig.1.).

FIG. 1.

The basic connection between ambient dissolved oxygen (DO) and growth rate is described by Jobling [8]. When DO is low, feed intake may be suppressed probably due to the fact that reduced oxygen availability would be unable to support the high energy demands of well-fed fish. At low DO, the reduced feed intake would obviously have consequences for growth. Therefore, it is very important to determine the critical level of DO at which feed intake and growth become affected in farmed fish species.

The concentration of DO has to be kept at a stable, high level, especially in culture systems rearing cold-water species, such as salmonids (Figure 2). Even at low temperature below 10°C, long-term DO levels at 70% of saturation will reduce the appetite and growth of Atlantic salmon. Lower DO concentrations in salmon cages or tanks will cause total performance collapse. Similar performance drop at decreased DO concentration has been shown in rainbow trout at its optimum temperature, 15°C [9].

FIG. 2.

Waterflow, carbon dioxide and pH.

Recently Atlantic salmon (*Salmo salar* L.) smolts (out-of-season), average weight: 42-77 g were exposed during 40 days to three water flow rates: 0.55-0.71 L kg^{-1} min^{-1} (High), 0.25-0.31 L kg^{-1} min^{-1} (Medium) and 0.15-0.20 L kg^{-1} min^{-1} (Low) at two different salinity levels (Table 1). There were two replicate tanks in each group. Oxygen was added to the inlet water to maintain discharge water oxygen concentration higher than 7.5 mg L^{-1} at 8-9 ^{o}C. pH was 6.1-6.4 and 6.3-6.7 in the tanks supplied with low and high salinity water, respectively. Concentrations of carbon dioxide were 14 mg L^{-1} at Low flow, 10 mg L^{-1} at Medium flow and 7 mg L^{-1} at High flow. After six weeks, all groups were transferred from the brackish water to normal seawater. In this experiment no significant differences in growth rate was observed either in freshwater or in seawater [2] even though the water flow was as low as 0.15 L kg^{-1} min^{-1}.

Table 1.

Fig. 3a and 3b show that pH is reduced as a function of the carbon dioxide concentration. However, at the highest salinity level pH is above 6.2 in all groups.

Fig. 3a.

Fig. 3b.

Combined effects of pH, carbon dioxide and aluminium.

Recently, we found that accumulation of water carbon dioxide in freshwater tanks, reduction in pH and changes in aluminium chemistry may be detrimental to Atlantic salmon parr and smolts, even at low water aluminium concentrations. Fig. 4 is calculated from a theoretical model and shows pH as a function of the carbon dioxide concentration at a bicarbonate alkalinity of 0.08 mM. The graph also shows the relationship between pH, carbon dioxide and aluminium toxicity. Above pH 6.8 aluminium is toxic since $Al(OH)_4^-$ is formed. According to Jensen and Leivestad [14] aluminium is toxic to Atlantic salmon smolts even at low concentrations when pH is below 6.2. At high Al concentrations, pH should be kept in the range 6.5-6.8 to avoid toxic effects. The fish farmers avoid negative effects of aluminium by stabilizing pH by adding bicarbonate to the water (adding sea water or limestone) or by complexing aluminium with sodium silicate.

Fig. 4.

The safe levels for Atlantic salmon smolts are now given in the Norwegian guidelines for operating instructions for Aquaculture (Table 2),

Table 2.

2. Water quality requirements

As is the case in flow through systems, water quality requirements for recirculation systems depend on the biological requirements of the species and life stage being cultured. The parameters described above (temperature, dissolved oxygen, pH, carbon dioxide, and ammonia) as being potential limiting factors in flow through systems are also potential limiting factors in recirculation systems. Metals, such as aluminium, can also be of concern in recirculation systems. Some water quality parameters, such as nitrite, nitrate, alkalinity, etc., may be of concern in recirculation systems as these compounds may be produced or consumed in nitrification water treatment operations. There is an additional category of compounds that may be of concern in recirculation systems with very low rates of make up water: the accumulation of compounds that may enter the system in trace concentrations with the feed or in other ways, or that may be produced in the system by the fish or in the water treatment operations [18]. Compounds in this last group include some metals, pheromones, and chemicals that may cause off-flavour [18,19].

Changes in some water quality parameters, such as pH, can impact not only the health of the fish produced, but also the performance of water treatment operations. Although the importance of carbon dioxide to the health of culture fish, especially in recirculation systems, is widely recognized, there is a dearth of information on many aspects related to it. This lack of information spans from issues related to practical methods for measuring CO_2 concentration in aquaculture waters, to studies on the physiological impacts of slightly elevated CO_2 concentrations and on the determination of recommended values for culture. Recently, a research network has been formed to increase awareness, disseminate information, and foster research in this area [20].

Carbonate System

Given the importance of pH and carbon dioxide in recirculation systems, it is especially important to consider the alkalinity-pH-carbon dioxide relationship. The carbonate system is responsible for determining the pH of most natural waters. It consists of the dissolved forms of carbon dioxide: carbon dioxide ($CO_2(aq)$), carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}). Only a small fraction of CO_2 (aq) is hydrated to H_2CO_3, and it is usually unnecessary to differentiate between the two forms, hence a hypothetical compound $H_2CO_3^*$ is defined as:

$$[H_2CO_3^*] = [CO_2(aq)] + [H_2CO_3] \qquad (3)$$

The concentration of $H_2CO_3^*$ is normally referred to as free CO_2 or as total dissolved CO_2. Given the definition of this new term, the equilibrium reactions and the corresponding constants for the carbonate system can be written as:

$$CO_2\,(g) + H_2O \rightleftarrows H_2CO_3^* \qquad K_H = \frac{[CO_2(g)]}{[H_2CO_3\,*]} \tag{4}$$

$$H_2CO_3^* \rightleftarrows H^+ + HCO_3^- \qquad K_{a,1} = \frac{[H^+][HCO_3^-]}{[H_2CO_3\,*]} \tag{5}$$

$$HCO_3^- \rightleftarrows H^+ + CO_3^{2-} \qquad K_{a,2} = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} \tag{6}$$

Where K_H is Henry's Law constant and it and the two equilibrium constants (K values) are functions of temperature and salinity [21-25]. The square brackets in the equations above indicate molar concentrations (mole L^{-1}).

Alkalinity, the capacity of a water to neutralize acid to the carbonic acid endpoint, may be defined as [24, 25]:

$$\begin{aligned}\text{Alkalinity} = {} & [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [NH_3] + [SiO(OH)_3^-] + \\ & [HPO_4^{2-}] + 2[PO_4^{3-}] - [H_3PO_4] + [OH^-] - [H^+]\end{aligned} \tag{7}$$

In many situations and for most aquaculture-related calculations, the alkalinity expression is simplified to include only the carbonate, hydrogen, and hydroxyl terms:

$$\text{Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \tag{8}$$

In seawater applications and in some recirculation systems it may be necessary to include additional alkalinity terms to obtain accurate results in calculations related to alkalinity, pH, and carbon dioxide. The terms that would normally be included in such cases are:

$$\text{Alk}_{\text{extra}} = [B(OH)_4^-] + [NH_3] + [SiO(OH)_3^-] + [HPO_4^{2-}] + 2[PO_4^{3-}] - [H_3PO_4] \tag{9}$$

Alkalinity is easily measured by titration. In addition to providing useful information on the buffering capacity of the water, alkalinity is a useful term in calculations of carbon dioxide concentration, as it can be calculated from (Fig. 5):

$$[H_2CO_3^*] = \frac{\{H^+\}^2}{\{H^+\}K_{a,1} + 2K_{a,1}K_{a,2}}\left(\text{Alkalinity} - \text{Alk}_{\text{extra}} - [OH^-] + [H^+]\right) \tag{10}$$

Figure 5

In recirculation systems, alkalinity is consumed in the nitrification process at the stoichiometric ratio of two equivalents per mole of ammonia nitrified to nitrate. The reduction in alkalinity is accompanied by a drop in pH that can affect, not only the cultured fish, but also the nitrifying bacteria in the biofilter. As a result, many recirculation systems require the addition of an alkalinity source (sodium bicarbonate or sodium hydroxide are two examples). Denitrification, on the other hand, produces alkalinity and a recirculation system that includes nitrification and denitrification normally does not require the addition of alkalinity [26].

Other Water Quality Parameters

As indicated above, some water quality parameters that are normally of little concern in flow through systems, are potentially very important in recirculation systems. Nitrite is an intermediate product of nitrification that can accumulate during biofilter start up and in cases in which a biofilter is excessively loaded or operating at non-optimal conditions. The toxicity of nitrite to fish is highly variable and tends to be higher in freshwaters than in seawater due to the presence of chloride ions [18].

Nitrate, the end product of nitrification has typically been regarded as toxic to fish only at very high concentrations (over 1000 mg L^{-1} total nitrate nitrogen) [18]. However, recent work with sturgeon suggests that in some cases, nitrate may have an endocrine disruption effect, as it resulted in an increase in plasma sex steroids at concentrations as low as 57 mg L^{-1} nitrate nitrogen [27]. Although it is possible that other compounds with potential impact on the fishes' endocrine systems may accumulate in recirculation systems, there is little published information on this topic. The use of ozone, a common practice in recirculation systems, may be beneficial in this context due to its ability to oxidize organic compounds that are difficult to biodegrade [18].

In addition to metals, such as aluminium, that may enter a system dissolved in the make up water, there are others that may enter as the products of dissolution from system components, such as metal pipes, or as trace contaminants in feeds. Examples of these are copper and zinc. Their toxicity is highly dependent on water hardness and salinity [18]. Whereas these compounds typically do not pose a problem in recirculation systems, particular attention needs to be taken with construction materials and feed contaminants when very low water make up rates are used.

3. Recirculation systems

Background and principles:

All over the world, environmental and regulatory constraints are pushing more and more fish farmers to move towards Recirculation Aquaculture Systems (RAS). In this type of system fish are reared at high stocking densities and the make up water needs are divided by 10 to 100 compared to flow through systems. Consequently, wastewater flow rates are proportionally decreased and waste concentration proportionally increased, which facilitates their treatment. The degree of closure of RAS depends on the fish species, on the degree of sophistication of the treatment loop and of the efficiency of its components. After passing through the rearing tanks, water is depleted in oxygen and loaded with suspended solids, total ammonia and urea nitrogen, phosphorus and carbon dioxide. The components of the treatment loop are chosen and designed to restore the water quality before reuse in the rearing tank. They consist of physico-chemical (mechanical filtration, liquid - gas exchange, temperature and pH control, and disinfection) and biological (aerobic and anaerobic biofiltration) processes. Make up water quality has to be carefully controlled and most of the time, the wastes are treated in a specific additional side loop.

In Europe, during the two last decades, RAS have mainly been developed in northern countries for ongrowing fresh water species (eels and African catfish) and in southern countries for marine species (bass, bream and turbot) fingerling production. In North America, RAS have been used primarily for freshwater species, with less frequent use in marine hatcheries. The use of RAS is becoming more widespread for fish ongrowing at all salinities, and the current size of the farms allows the production of several tons to hundreds of tons of fish annually.

As indicated above, a recirculation system includes a number of treatment unit operations that recondition the water and make it suitable for the continued culture of the target crop. Not all systems include all unit operations mentioned, as the need for a particular unit operation depends on factors such as the degree of water reuse (e.g. m^3 kg^{-1} of feed) and the water quality requirements of the target crop. There are also regional differences in the preference, partly related to economics, for certain types of technologies. Some sample configurations are presented below.

Current recirculation systems:

Recirculation systems for larval rearing and broodstock:

Recirculation systems provide a rearing medium that is constant and adjustable, with only slight and slow variations. At the same time, they allow significant savings in heating energy needs [28]. The association of this production system with significant improvements in larvae feeding procedures and feed formulation was the key to developing a reliable production of low price fingerlings and was achieved at the beginning of the nineties in most European hatcheries [29, 30].

Ensuring the biosecurity of the production system, by blocking the spread of disease to or from a farm and within a farm, is necessary to produce high quality fingerlings. This is the key to profitability for hatcheries and the following rearing phases. This concept needs a combination of: (1) sanitary control of the breeders through the early detection of pathogens; (2) optimal control of water quality using recirculation with a controlled bacterial population, and (3) treatment of the water inlets and outlets, in order to secure a high inlet water quality and limit the impact on the environment [31, 32].

Recirculation systems for fish pregrowing and on-growing:

During the last twenty years, fish on-growing systems with water recirculation were developed in Europe, notably for freshwater fish at a commercial scale [33-35] and for marine fish with a production capacity around 100 tons per year [30, 35]. Today, the technology is mature and commercial applications have proven their stability [36]. For instance, in 2003 roughly 90 farms were operating in the Netherlands and producing around 10000 MT annually.

Pilot scale systems (several tons per year) were set up with other species such as the red drum (*Sciaenops ocellatus*) or the silurid (*Silurus glanis*) in France or the sole (*Solea solea*) and the pike perch (*Stizostedion lucioperca*) in the Netherlands. In North America, RAS have been used primarily for freshwater species, such as tilapia (*Oreochromis sp.*), striped bass (*Morone saxatilis*), and various sturgeons (*Acipenser sp.*), with less frequent use in hatcheries for marine species. Whatever the concept is, the water treatment systems and the rearing tanks have to be adapted to fish requirements, which vary with the fish species. All recirculation systems follow the same basic design described by several authors [28, 30, 35, 37-39]. The recirculating flow of the fish tanks is first directed to a solids removal system, which may be a mechanical filter with a mesh size of 40 - 100 µm. Thereafter the water is transported to a biofilter where ammonia is oxidised by the nitrification process, which may take place either in a trickling or in a submerged filter (sometimes both). Nitrification rates in a biofilter play a key role in biofilter design and have been subject of several studies on laboratory and commercial scales. Biofiltration is typically followed by gas transfer equipment to remove excess carbon dioxide and add oxygen. Efficient stripping of carbon dioxide produced by the fish is carried out in a specific ventilated packed column or in a ventilated trickling biofilter, which may also be used for water cooling when necessary [40]. The oxygen, which is necessary for fish respiration, may be injected directly into the water entering the tanks by a pressure system (generally a cone).

Recirculation systems for freshwater fish ongrowing:

Fresh water fish such as African catfish are not very demanding in terms of water quality, which results in a small recirculation flow and enables the use of a lamella sedimentation unit or a tube settler for the removal of suspended solids. In eel farms large flows and screen filters are used for the removal of suspended solids (Fig.6).

Fig. 6.

After the sedimentation unit or screen-filter, the water is collected in a sump where it is heated and treated with UV light. The next treatment unit is a ventilated trickling biofilter, which oxidises ammonia, removes carbon dioxide and may be used as water cooling system during summertime. In many eel farm designs, part of the recirculating water flow is also directed over a submerged biofilter in a separate loop for the removal of fine suspended solids, which are not removed by a drum or disc filter. In recirculation systems without a denitrification reactor, the accumulation of nitrate in the system limits water recycling and make up water has to be added to keep the nitrate level below the threshold value for the cultured species [39].

Although fish waste, soluble COD (Chemical Oxygen Demand) and ammonia, are partially removed by the biofilter, a large part of the COD and Kjeldahl-Nitrogen (organic-N and ammonia-N) is removed with the suspended solids. If this part is not retained and treated, the levy for waste discharge may be considerable [41-44]. To reduce the cost for waste discharge many eel and catfish farms apply septic tanks as end of the pipe treatment. Septic tanks remove N and retain P efficiently, when a proper hydraulic retention time and hydraulic surface load is applied but do not reduce water consumption.

In many eel farms, a denitrification unit is installed to reduce water consumption. Denitrification can be carried out using large tanks filled with floating beads moved by a propeller and methanol as additional carbon source.

The effluent from the denitrification reactor is returned to the system through a drum filter. In the newest designs a flocculation (dephosphatation) unit in combination with a ‘belt-filter’ is installed to remove the solid waste from the farm-effluent. The remaining liquid fraction is discharged into a sewer. Little solid material remains after treatment. As a bonus, much of the phosphorus is precipitated in the sludge [45].

Recirculation systems for the culture of tilapia (*Oreochromis niloticus*) in the Netherlands, differ from eel farms. These systems with a production capacity of 300 and 600 MT per year, apply an air stirred moving bed reactor as biofilter and control nitrate by single sludge denitrification. Since 2004 single sludge denitrification reactors, using completely mixed sludge, and fecal carbon only are designed for and applied in commercial tilapia (*Oreochromis niloticus*) systems. These systems are operated at make-up water supply rates of 25-50L/kg feed/day and maintain nitrate levels below approximately 150 mg NO_3-N L^{-1}. It shows that in commercial farms C/N ratio in combination with a certain sludge retention time allow nitrate concentration control at relative low water exchange rates.

For denitrification, an upflow sludge blanket reactor (USB reactor, single sludge denitrification) and fecal carbon as the only carbon source can be used also [46].

Recirculation systems for seawater fish ongrowing:

Marine fish seem to be much more sensitive to accumulating dissolved organic substances than fresh water fish. These substances are produced from the bacterial break down of organic particulate matter, which is not removed from the recirculated water by mechanical filtration [47]. The role of bacteria in marine farms seems to be very important, mainly for the early stages, but has never been clearly identified. It is well known that a stable bacterial population avoids the outbreak of monospecific bacterial species, which can be a threat to the farmed animals. The treatment systems for marine fish species (Fig.7.) comprise a UV disinfection unit, that controls the concentration of bacteria population in the rearing system and inactivates pathogenic bacteria that could be produced in the rearing tank or introduced with infected fish [48].

Fig. 7.

In an intensive fish farming system functioning on a routine basis, the oxygen consumption of the bacterial population is of the same order of magnitude as fish oxygen consumption. Roughly half of the bacterial consumption is due to heterotrophic bacteria, which use the small particles that are not removed by mechanical filtration [49]. This heterotrophic activity competes with autotrophic bacteria for oxygen consumption and contributes to a reduced total ammonia nitrogen (TAN) removal rate [50] and to the creation of unfavourable conditions, such as low pH or soluble degradation products (humic-like substances). The biofilter shown in Fig. 7 is of the submerged type, in which the biofilm carrier material is submerged in the water as opposed to a trickling filter in which the biofilm is exposed to both water and air.

System for cold, fresh water fish:

Systems for the culture of arctic char (*Salvelinus alpinus*) and rainbow trout (*Oncorhynchus mykiss*) have been developed using double drain tanks and fluidized sand filters [51, 52]. The systems include a swirl separator to remove settleable solids, followed by a drum filter, a fluidized sand bed biofilter and a degassification and oxygen injection column (Fig 8).

Fig. 8.

The use of double drain tanks helps in removing suspended solids from the culture water and in making it possible to reduce the size of some treatment units relative to what would be needed if double drain tanks were not used. Fluidized sand filters have the advantage of using relatively inexpensive filter media (sand), but may require higher pumping energy than other biofilters.

System for warm, fresh water fish:

Systems based on the use of floating bead filters, which provide solids removal and biofiltration [53, 54] have been used especially for warm water fish. By adjusting the frequency and aggressiveness of the backwash process it is possible to improve the performance of the bead filter for one application (whether solids removal or biofiltration) over the other. Depending on water quality requirements of the species cultured, the bead filters may be followed by a second biofilter, such as a fluidized sand bed, a trickling filter, or a microbead filter [55].

Comparison of the systems:

The systems described differ in at least two major aspects, both linked to the biofilter which is the core of the treatment system:

- Nitrification and transformation of dissolved and particulate carbon is carried out in all types of biofilters. Trickling bio filters and air-stirred moving beds combine aeration of the treated water, degassing (carbon dioxide removal) and cooling when needed in one single unit. The systems with submerged filters require a separate ventilated column designed for CO_2 degassing, aeration and cooling.
- Trickling filters are self cleaning and the water treatment processes work continuously, without water quality fluctuations due to back flushing, so the associated labour is reduced

accordingly. A submerged biofilter is characterised by a reduced volume (around 10 times) but may need to be backwashed depending on the particular type of submerged biofilter. For example, static bed submerged biofilters typically need to be backwashed between 2 and 4 times per month on average, while a submerged moving bed biofilter may not need to be backwashed.

In spite of these differences, it is important to note that whatever the system (marine or freshwater), the results in terms of energy needs or tons produced per worker are similar. (Table 3).

Table 3

Description and evaluation of a new application of water reuse systems.

An improvement goal for all types of RAS is decreasing the energy needed per kg fish produced. An attempt at achieving this goal was made by using the 'Danish system' at a French trout farm. Semi-closed systems for trout ongrowing were developed in Denmark a few years ago, as the Danish water legislation enforces strict measures on water consumption and waste discharge. Fish producer representatives and government regulators worked together to define trout production systems meeting the regulatory constraints. Some "model farms" operated in recirculation system were tested, with the aim of producing at low cost. Today, more than 10 % of the Danish trout production is produced in those farms.

The general concept is based on reducing energy consumption through minimisation of the head loss. The principle utilises a fast water circulation in Foster-Lucas type tanks, corresponding to 5 to 10 tank volumes per hour compared with the 1 to 2 in regular systems (Fig. 9). One part of the tank is devoted to fish rearing and trapping of the waste particles through cones equipped with stoppers and permitting a daily draining of the sludge. The other part is devoted to water treatment. The water treatment system is composed of a complementary suspended solid removal system, a submerged biofilter and an airlift for water circulation and gas exchange (O_2 addition and CO_2 degassing). Mechanical filtration with a mesh filter (drum or belt) may be installed to remove part of the particles that are not trapped in the settling systems. The biofilter, which is backwashed weekly, is either a moving bed of plastic media or a static bed made of high porosity media, or a combination of both.

Figure 9

With this kind of system, the make up water needs (around 10 m^3 kg^{-1} feed) are around 10 times lower compared to flow through farms.

Wetlands (unused old earth tanks at the farm) are used to treat the wastewater before release in the river. Diseases that are usually observed in Danish farms (red mouth disease, viral hemorrhagic septicaemia and proliferative kidney disease) have not been observed in the French model farm using clean underground water. Other types of pathologies, such as white spot disease, gill disease and bacterial kidney disease are kept under control.

Some projects and developments related to RAS effluents

Effluent treatment and use is considered to be one of the key issues associated with RAS, which will lead to the use of part of the knowledge acquired in the field of integrated systems.

Research and development is being carried out to define the best way to process and reuse the waste particles. In the Netherlands, a project called "Blue Label" has been developed. In "Blue label" recirculation systems one of the goals is to install water treatment processes that prevent fluctuations in water quality, while minimising all wastes and natural resources needs. An EU project (INCO framework) called ZAFIRA (Zero nutrient discharge Aquaculture by Farming in Integrated Recirculation systems in Asia) aims at improving the nutrient retention in the production system by integrating processes [56]. High rate algal ponds proved to be suitable for the treatment of wastewater [57] in order to reuse it in recirculation systems [58].

4. Conclusion

Recirculation aquaculture systems are today operating commercially on a medium scale. A satisfactory optimisation will only be obtained by working in parallel on technical improvements and on enlarging our knowledge of the farmed species. The quality of the rearing medium provided by the recirculation system relative to the cultured fish requirements is a key element in defining a suitable design of an economically efficient farm. Once the economic efficiency of the production recirculating loop is secured, a step by step addition of waste treatment and tools to make best use of the waste will progressively contribute to a decrease in the impact of the production activity on the environment. A close collaboration with teams developing integrated production systems would be very beneficial in this respect.

Environmental consequences

The water use in aquaculture is closely linked to the system applied and the intensification of the production (Bergheim, this volume). In a recent report, Verdegem et al. [59] also include the water consumed for production of the grains in the formulated feed in order to estimate the ultimate water use in aquaculture. As a global average, 1.17 m^3 of water is needed to produce 1 kg of grain. The food-associated water consumption, as a percentage of the total, increases with increasing intensification of the production (Table 4). In recirculation systems and high-producing ponds, the water consumption for production of the cereals incorporated in the fish feed normally exceeds the consumption within the fish farm. The water use in extensive ponds per produced weight of fish is some 100 times the use in intensive recirculation systems.

Table 4.

In coldwater systems producing salmonids, the water use in traditional single-pass tanks and raceways in the 1970 – 80'ies was very high, up to 500 m^3 kg^{-1} produced, while introduction of full recirculation (> 90 – 95 % recirculation rate) in the 1990'ies reduced the consumption to 3 – 5 m^3 per kg produced fish [60]. However, the lowest water use reported is achieved in a warm water, highly intensive recirculation system (recirculation rate > 99 %) which produced 1 kg catfish only using about 0.1 m^3 of water [61].

Increased solid concentration of the effluent from fish tanks due to reduced water flow generally increases the solid removal efficiency of mechanical treatment attempts, i.e. microsieves [62]. Solid removal combined with improved physical properties of effluent solids [63] has reduced the effluent load from landbased coldwater farms to 1/3 – 1/4 of the level two-three decades ago. The methods of collecting, thickening/stabilizing and disposal of sludge are also improved [60].

Both water use and effluent loading in pond based farming can be significantly reduced by practical/technical attempts, such as more aeration, moderate recirculation and temporary storage of drainage water in sedimentation ponds before entering the recipient (Figure 10) [4]. The documented improvements at Arroya Aquaculture Association Farm actually reduced the water use by 93% and the solid load by 95% without diminishing the shrimp production [4].

Figure 10.

5. References

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Tables

Table 1. Water flow, salinity and other water quality parameters in the tanks during the freshwater stage, EWOS Innovation research station Dirdal, November – December 2000. Tanks stocked with Atlantic salmon smolt. Start: 11 November, End: 20 December (40 days). Transfer to seawater: 21 December. Average temperature: 8.6 °C, max – min: 9.0 – 7.9 °C . Mean carbon dioxide concentration in the inlet water was 4.7 mg/L (range 3.2 -5.9 mg/L; n = 8). Reprinted from [6].

Flow – salinity*	Tank No.	Flow, L/kg/min		Salinity, ppt.	
		Mean	Max-min	Mean	Max-min
LF - HS	1	0.17	0.20-0.15	4.6	5.2-3.5
	2	0.18	0.20-0.15	“	“
LF - LS	11	0.18	0.22-0.16	1.6	1.8-1.5
	12	0.19	0.20-0.17	“	“
MF - HS	3	0.28	0.31-0.28	4.5	5.4-3.6
	4	0.28	0.30-0.25	“	“
MF - LS	9	0.29	0.30-0.27	1.6	1.8-1.5
	10	0.29	0.31-0.28	“	“
HF – HS	5	0.63	0.68-0.55	4.4	5.3-3.4
	6	0.66	0.70-0.59	“	“
HF - LS	7	0.64	0.68-0.56	1.6	1.8-1.5
	8	0.64	0.71-0.57	“	“

*: Combinations of flow – salinity, see Table 2 **: Average and max-min of 2 tanks (total of 4 samplings)

Table 2. Safe water quality criteria for Atlantic salmon (Akvakulturdriftsforskriften, 2004; From the Norwegian guidelines for operating instructions in Aquaculture and our own research).

Environmental Factor	**Safe levels for salmon**	**References**
Oxygen (low total gas pressure)	85 – 100 percent saturation	[10]
Carbon dioxide	< 15 mg/L	[11-13]
pH alone	6- 8	[14, 14b]
Un-ionized ammonia Nitrogen	10 µg/L	[16]
Nitrite nitrogen	< 0.1 mg/L	[17]
Labile aluminium	< 5 µg/L	[17]
Gill aluminium	< 20 µg/gram	[17]

Table 3. General characteristics of commercial recirculation systems with annual production of 100 T for European eel, Sea bass and Turbot.

Characteristics	European eel	Sea bass	Turbot
	0.25 – 150 g	10 – 350 g	10 – 1000 g
Productivity (kg/m^2/yr)	200 – 300	200	70
Average standing stock (kg/m^2)	114	100	50
Oxygen use (kg/kgfeed)	0.74	1.5	1.2
Water exchange (m^3/kgfeed)	0.09 –0.1	0.5 – 0.9	1 – 4
Energy use (kWh/kgfeed)	7	6.5	6.7
Labour (Tonnes/yr/head)	70	95	50

Table 4. Water use in aquaculture systems from extensive ponds to intensive recirculation systems (Verdegem *et al.* [60]).

Production system	Total water use, m^3 water/kg fresh weight produced	% food-associated water consumption*
Ponds:		
Extensive	45.0	0
Pellet-fed	11.5	20
Nighttime aeration:		
10 t/ha x year	7.8	30
20 t/ha x year	4.7	49
Flushing (20% exchange, 30 t/ha x year)	30.1	8
Intensively mixed ponds (100 t/ha x year)	2.7	85
Super-intensive recirculation systems:		
African catfish	0.5	80
Eel	0.7	86
Turbot	1.4	37

*: assuming 1.17 m^3 water use/kg produced grains in the feed

Intensification attempts such as improved feed quality, introduction of high-energy feed, better feeding systems and optimisation of the rearing equipment (e.g. self-cleaning tanks, oxygenation) have significantly reduced the waste quantity per unit produced fish (Brinker, this volume).

Figures

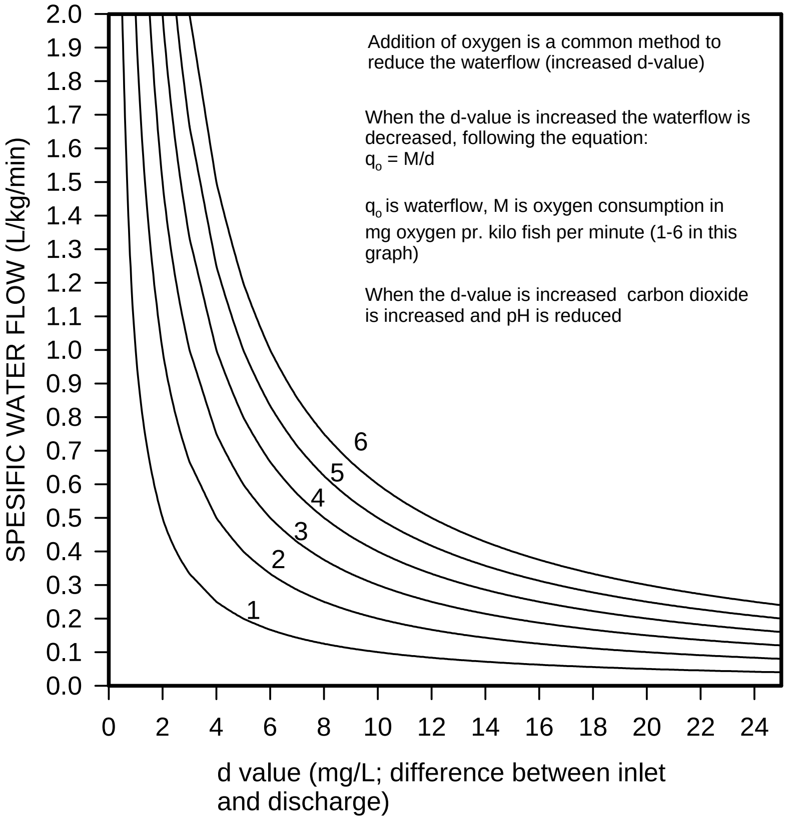

Figure 1. Relationship between the specific water use (L/kg/min) and the difference between influent and effluent dissolved oxygen concentration (d value, mg/L) for various oxygen consumption rates (mg/kg/min). Reprinted from Fivelstad 1988 [7].

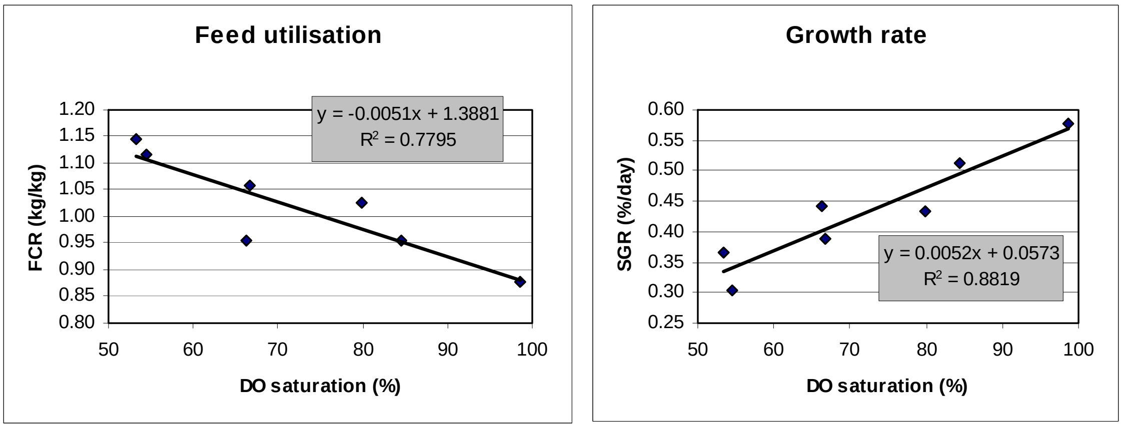

Figure 2. Feed utilisation (FCR) and growth (g) in post-smolt Atlantic salmon exposed to four levels of DO concentrations at low temperature (8 – 9 °C). Test period: 24 April – 17 June 2002. EWOS Innovation Dirdal [10]

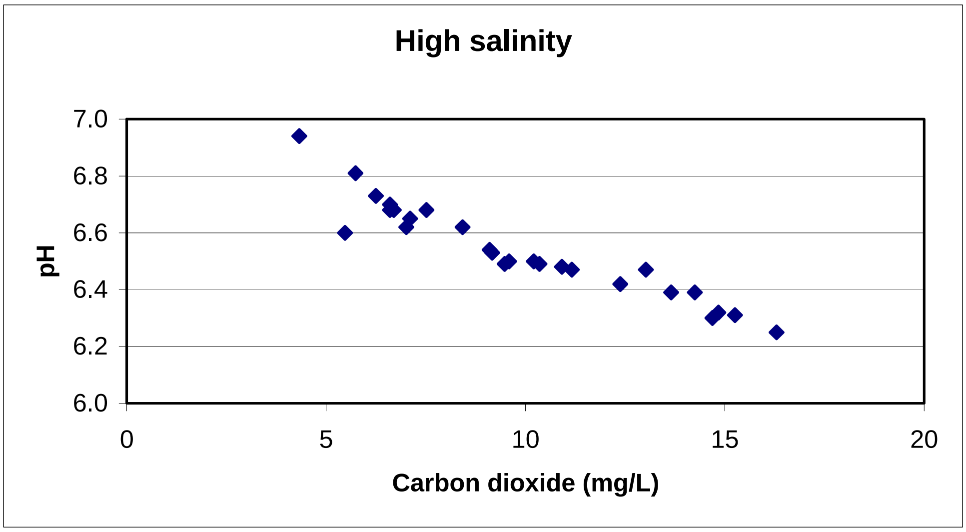

Fig. 3a. Relationship between carbon dioxide and water pH.

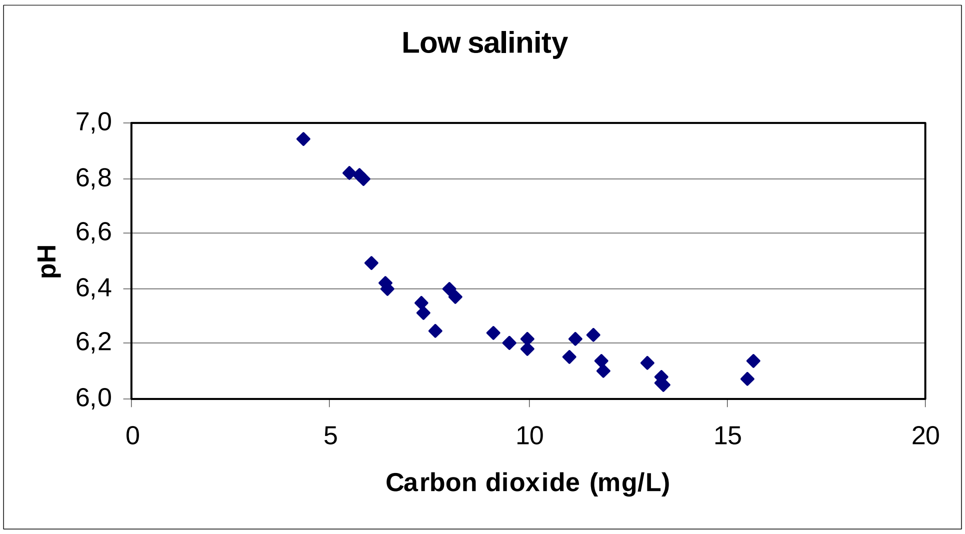

Fig. 3b. Relationship between carbon dioxide and water pH. Reprinted from [6].

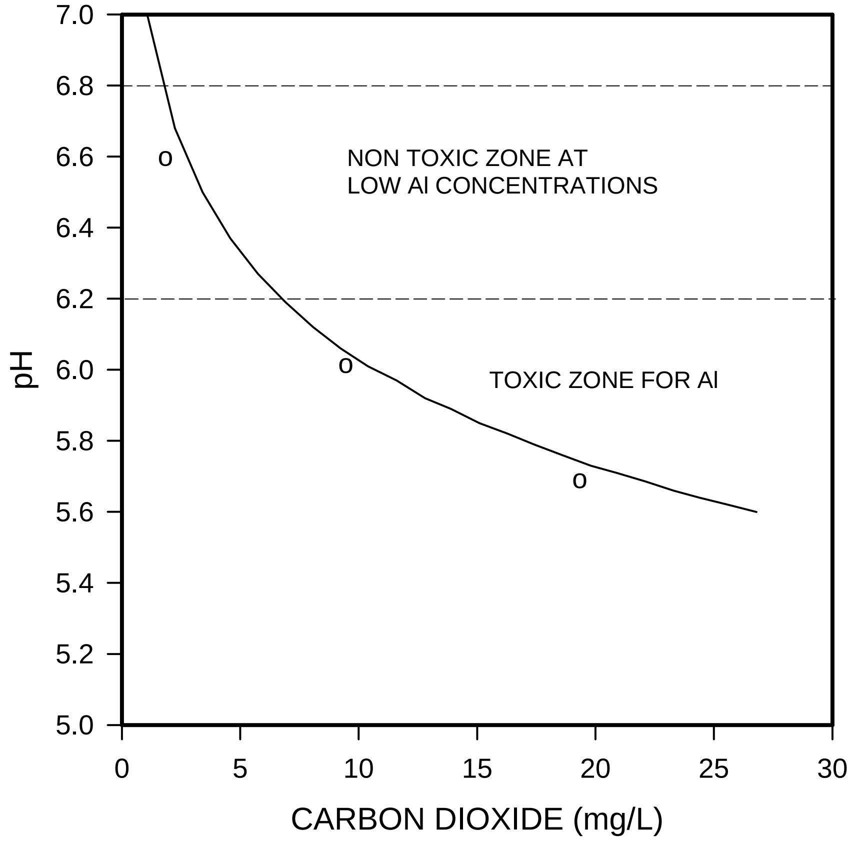

Fig. 4. The theoretical relationship between carbon dioxide concentration and pH level in the discharge of a fish tank when pH in the inlet water is 7.0, temperature is 8 °C and carbonate alkalinity is 0.08 mmol/L. The figure is based on the model of Colt and Orwicz [1]. The dashed lines indicate safe levels for pH at low levels of Al as presented by Jensen and Leivestad [14]. Observed values are shown (o). Reprinted from [12] (Copyright Elsevier Science and S. Fivelstad).

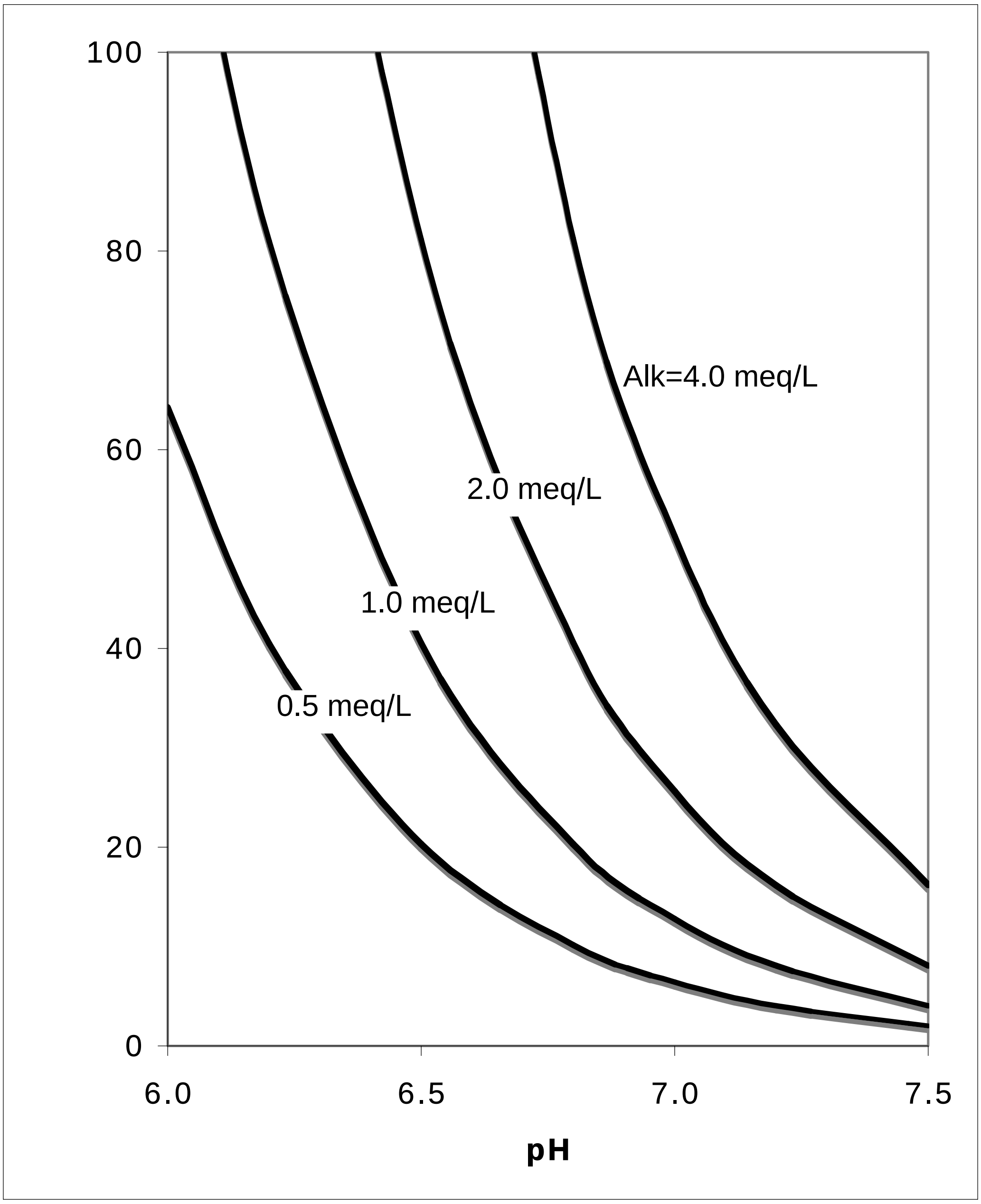

Figure 5. Relationship between carbon dioxide and pH for freshwater at 10°C and for alkalinities ranging from 0.5 to 4 meq/L.

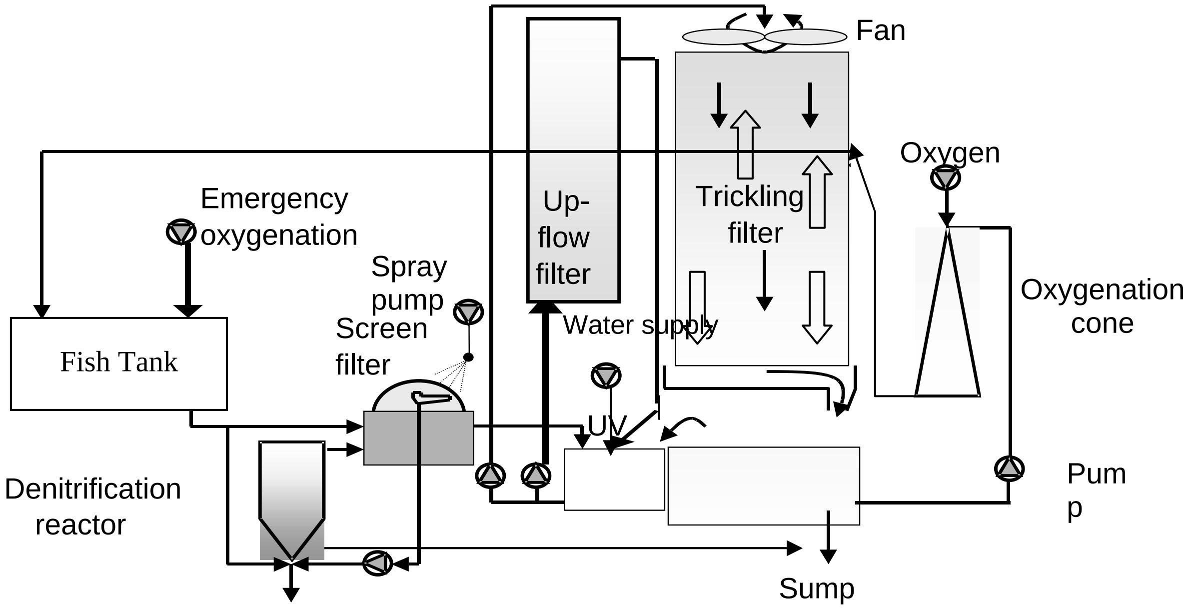

Fig.6: Fresh to seawater type recirculation system [35]

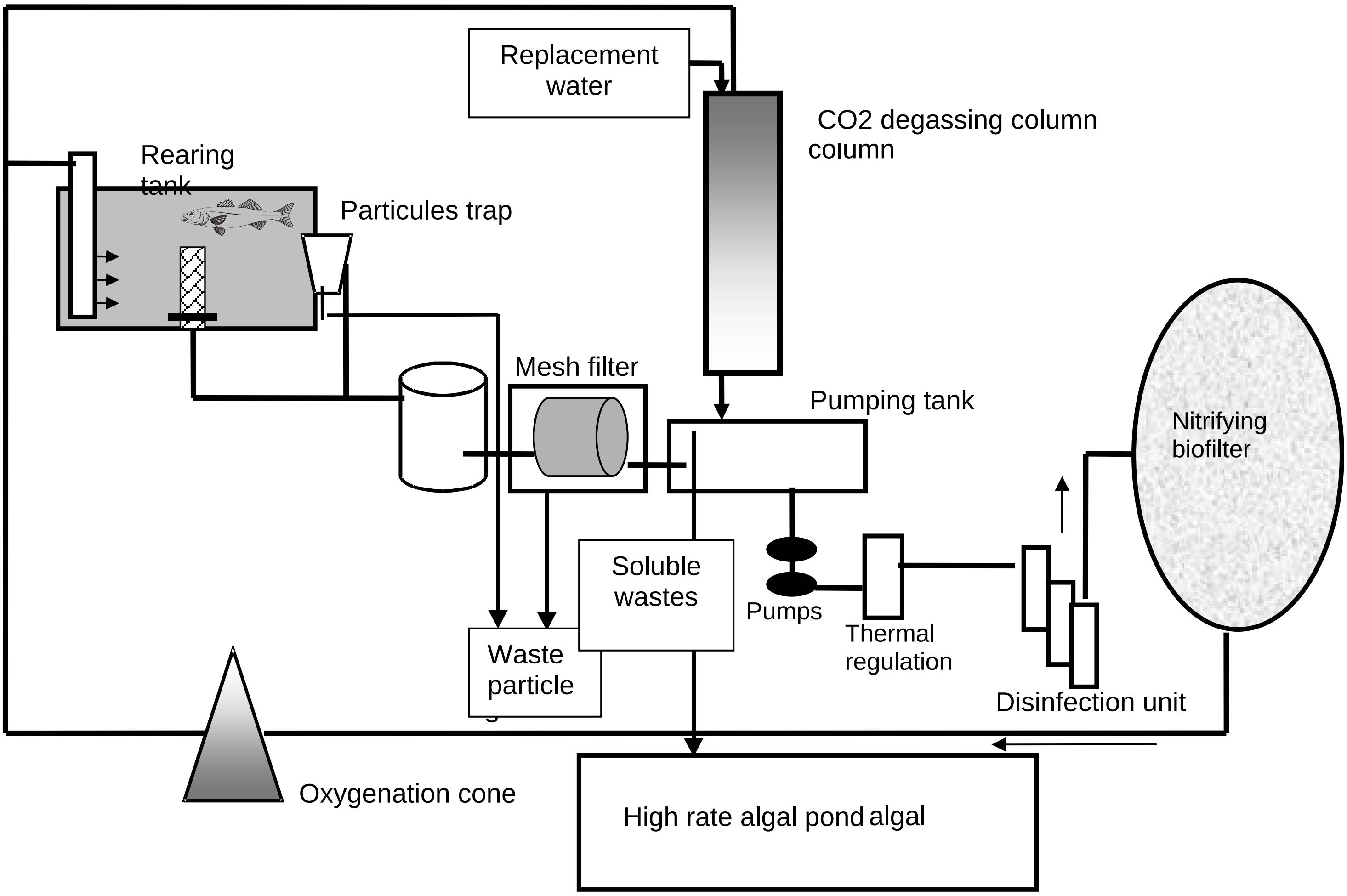

Fig.7: Sea to fresh-water type recirculation

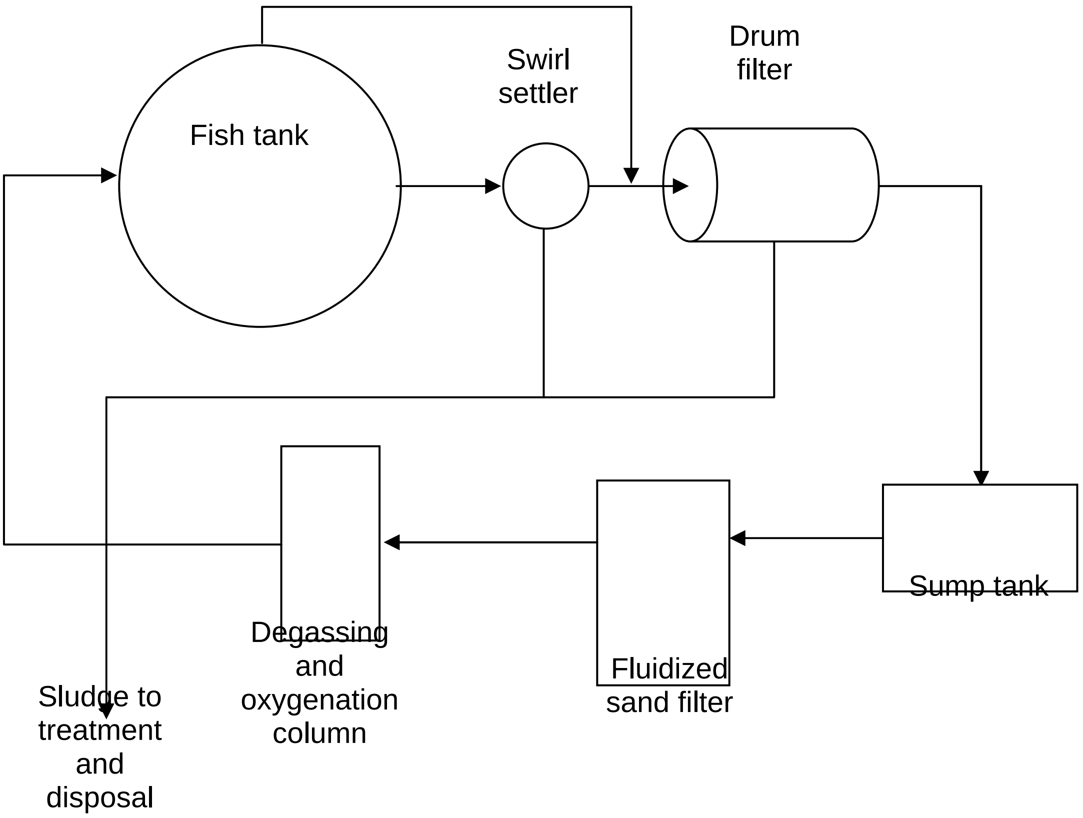

Figure 8. Schematic diagram of cold water RAS (after [3]).

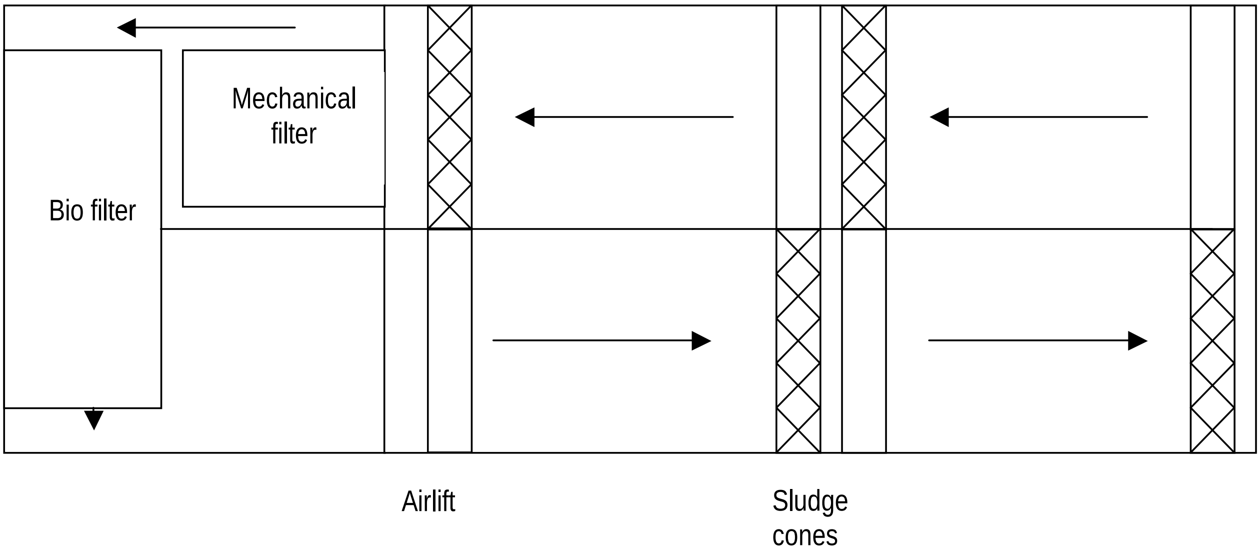

Figure 9. Danish type RAS for trout production

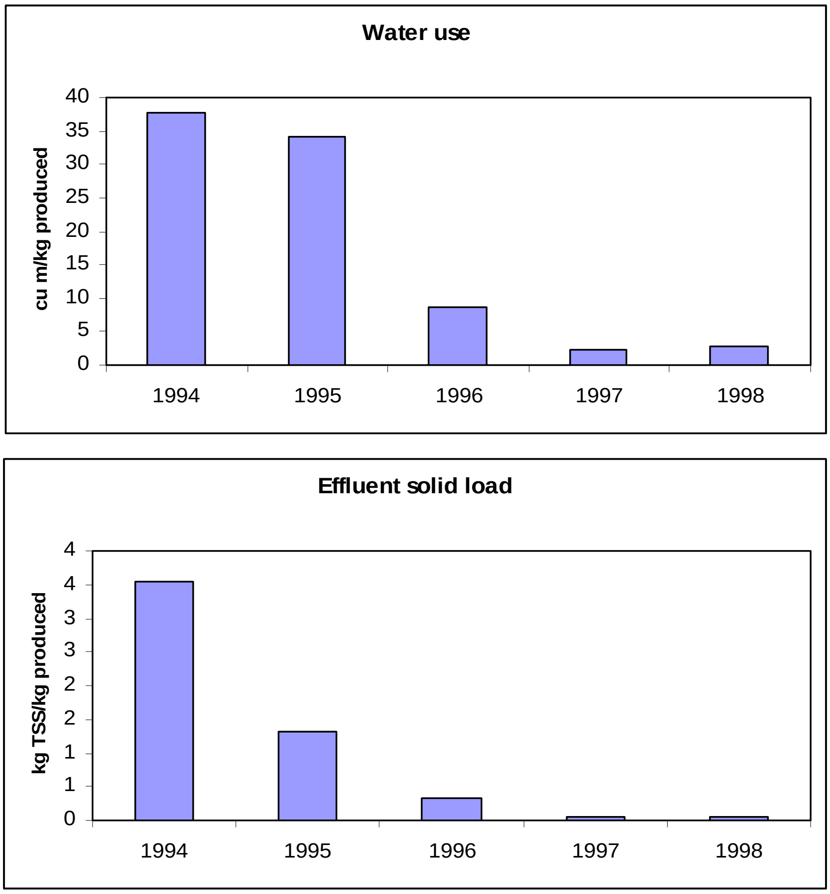

Figure 10. Intensifying modifications of shrimp ponds and consequences for water use and solid outlet at Arroya Aquaculture Association Farm, Texas, USA [4].