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FRESHWATER CULTURE OF SALMONIDS IN RECIRCULATING AQUACULTURE SYSTEMS (RAS) WITH EMPHASIS ON THE MONITORING AND CONTROL OF KEY ENVIRONMENTAL PARAMETERS

Technical Report

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1. INTRODUCTION

This report is intended as a briefing paper on Recirculating Aquaculture Systems with emphasis on the monitoring of water quality parameters relating to the freshwater culture of the Arctic charr *Salvelinus alpinus.*

1.1 Salmonids

The term salmonid is derived from the family name *Salmonidae* and is most frequently used in reference to species found in the genera *Oncorhychus, Salmo* and *Salvelinus* commonly referred to, respectively, as the trout, salmon and charr (Pennell, 1996). The family also includes the freshwater whitefish (subfamily *Coregoninae*) and graylings (subfamily *Thymallinae*) (Behnke, 2002). Salmonids are the only extant members of order *Salmoniformes*.

Species of both grayling and freshwater whitefish are fished and cultured commercially in Europe and North America, but on a massively reduced scale when compared to trout, salmon and charr (Carlstein, 1997; FAO, 2012). They are also targeted by recreational, sport fisherman, although are again far less popular than more well known salmonids.

Salmonids are easily identifiable as they are relatively primitive in appearance when compared to other teleost (bony) fish (McDowell, 1998). They are ray-finned, but with a distinctive, fleshy, dorsal adipose fin located between the main dorsal and caudal (tail) fins. One of the most significant features of salmonids as a group is that they exhibit an anadromous life cycle (Anon, 2004). Aside from the first 1 to 2 years post hatching where the fry remain in rivers and streams, they spend their entire life in the marine environment only returning to freshwater when fully grown to spawn, after which some species (e.g. the Pacific salmon) die (Anon, 2004). There are exceptions to this rule, however, discrete, relict, nonanadromous (resident freshwater) populations have been discovered of Atlantic salmon (*Salmo salar*), sockeye salmon (*Oncorhynchus nerka*), brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) (Foote & Larkin, 1988; Kalish, 1990). One of the most interesting cases of nonanadromy is that of landlocked populations of Arctic charr, *Salvelinus alpinus*.

In its anadromous form the Arctic charr is circumpolar, native to Arctic, sub-Arctic and northern coastal waters as well as lakes and flowing inland waters throughout Europe and N. America (freshwater only) (Marsh, 2006). *S. alpinus* is the most northerly occurring fish species, in freshwater, in the world and have been found above the 80th parallel. Their range extends through northern Russia, Alaska, Canada, Greenland, Scandinavia, Ireland and Scotland (Maitland and Lyle 1991). There exist three distinct subspecies of *S. alpinus* in North America; *S. alpinus erythrinus*, *S. alpinus oquassa* and *S. alpinus taranetzi*. Many wild, relict populations of Arctic charr are present throughout their range, these are nonanadromous and typically the result of geographic isolation as a consequence of ice ages and land upheaval events. Isolated relict populations exist in New England, Switzerland, and Great Britain (Scotland).

A useful characteristic of Arctic charr is that they do not die after spawning and often spawn several times throughout their lives, typically every second or third year. Young charr emerge from the gravel in spring and remain in freshwater rivers and streams until about 6 to 8 inches in length (5 to 7 years).

1.2 History of Salmonid Aquaculture

The history of fish farming is a long and extremely broad ranging subject; consequently, this section will briefly cover the history of salmonid aquaculture followed by that of Arctic charr in greater detail.

The first recorded mention of salmonid aquaculture can be found in the *Historia Naturalis*, created by Pliny the Elder in the 1st century AD; it also contains the first written use of the name *Salmo* (Pennell & Williams, 1996). Many experiments and attempts were made to hatch and raise salmon and trout over succeeding centuries, however, the true founder of salmonid culture is regarded to be John Shaw (Pennell & Williams, 1996). Shaw, was Scottish scientist, whose work in the mid-19th century definitively proved that naturally spawned eggs could be artificially fertilised and grown on to 2 year old smoults in fresh water (Shaw, 1836; 1840). In the latter half of the 19th century salmonid hatcheries became established in Europe and North America, in recognition of the decline in natural stocks and the desire to export salmon and trout to other countries (Pennell & Williams, 1996). By the end of the century there were eighteen salmon hatcheries operating in Scotland alone, with the first seawater raised fish being housed in ponds at the mouth of the river Spey in the early 1900's. Salmonid culture in North America during this period kept pace with European advancements, with the first salmon hatchery constructed on a Lake Ontario tributary in 1866 (Pennell & Williams, 1996). However, these early hatcheries were intended to raise smoults for reintroduction into the wild and it was not until the early portion of the 20th century that salmonid farmers began to raise adult fish for human consumption in any significant number. This was pioneered in northern Europe, particular by the Danes and Scandinavians; however, despite many trials it was not until the 1950's that the Norwegians began a dedicated program to raise salmon and trout in seawater pens in order to solve the problem of winter culturing (Pennell & Williams, 1996). It was this program that paved the way for modern salmonid farming, with the industry exhibiting exponential growth since 1970 in order to meet consumer demand. This growth is demonstrated by Norwegian production figures for Atlantic salmon which increased from 4,153 tonnes in 1980 to 208,000 tonnes in 1994, an expansion mirrored in the Scottish industry (Pennell & Williams, 1996). By 1990, the tonnage of Atlantic salmon produced through aquaculture methods by countries bordering the north Atlantic outweighed by fifty fold that produced by wild capture fisheries.

By comparison the Arctic charr is a relative newcomer to the salmonid aquaculture sector, with research into its sustainability as a culture species beginning in the late 1970's. The species' incorporation into commercial farming has been slow in comparison with the expansion of salmon and trout culture. That said, its low optimum temperature requirements, decent growth rates in cold waters and familiarity with living in high densities have made it an increasingly popular choice for North American, Norwegian and Icelandic farmers (Marsh, 2006). Its popularity with both farmers and consumers has also been boosted by its classification in 2006, as an environmentally sustainable "Best Choice" for consumers by the Monterey Bay Aquarium Seafood Watch program (Marsh, 2006). The species is has also been listed as a 'best choice' by the SeaChoice and FishWise programs. Arctic charr is regarded as an ideal aquaculture species not only for its ease of culture and cold water growth attributes but also from an environmental stand point. Due to the way the species is farmed (primarily in Recirculating Aquaculture Systems (RAS) described in following section) the risk of escape and the subsequent transmission of diseases, genetic material and parasites to wild stocks is minimal.

charr are fished commercially, although the industry is now highly regulated due to previous overexploitation and as with salmon and trout aquaculture production has far overtaken that of wild capture fisheries. In 2000, the global farmed production of Arctic charr was only 3,195 metric tons, by 2010, Icelandic production (the world leader in farmed Arctic charr) had reached 3,500 metric tons (Rogers & Davidson, 2001; Icelandic Ministry of Fisheries and Agriculture, 2013). This compared to the FAO figure for total wild capture landings in 2009 of only 77 metric tons (FAO, 2012). Arctic charr is also a popular sport fish in both Europe and North America, with subsistence fisheries accounting for landings of approximately 500 metric tons (Maitland, 1995).

1.3 Culture Methods

Several methods can and are utilised in the culturing of salmonid species; employing varying levels of infrastructure and manpower. These range from pond and raceway culture methods to recirculation systems and the most common; the open water net/cage farm.

Pond and flow through (raceway or tank) systems typically require intermediate levels of infrastructure and staffing. Both are long standing methods, harking back to the hatcheries and farms of the 19th century and are typically located in close proximity to a natural water source, either freshwater or marine. Pond farms are more enclosed than flow through systems, the latter relying on diverted water from a waterway, such as a stream, river or well. The water is diverted through manmade channels (earthen or concrete) containing the fish before typically being treated and returned to the source. Flow through systems are utilised by fish farmers in the United States to raise rainbow trout but are heavily regulated and monitored by the government with regard to water quality and pollution (Monterey Bay Aquarium Seafood Watch Programme, 2013). Pond systems, which also utilising natural water sources, typically use less and are better suited to containing and treating the waste water produced. Typically, pond/raceway facilities are employed as hatcheries in the culture of anadromous salmonids; utilised to produce smolts from fertilised eggs as opposed to raising fish to marketable size (Anon, 1980). In the case of Atlantic salmon juvenile fish are regarded as smolts when they have undergone a physiological transformation which includes the development of a silvery colouration. This usually takes place in the spring, typically when 12 - 18 months old.

At this point in anadromous species the smolts are ready to move to the marine environment and are transferred to floating sea cages or net pens (Anon, 1980). These are typically located in sheltered coastal waters, e.g. Scottish sea lochs and Norwegian Fjords, can be square or circular and range considerably in volume with the largest housing up to 90,000 fish. In purely freshwater strains of salmonid, i.e. cultured non-anadromous Arctic charr, these pens/cages can be positioned in freshwater lakes. The fish are grown-on in these cage pens, being fed pelleted feed, until they reach a marketable size, typically a further 12 - 24 months. The length of this growth period is dependent on numerous factors including water temperature, stocking density (generally 8-18kg per m^3), parasite load and feed conversion rates (FAO, 2013).

Although cage rearing is the most widespread method, certainly of salmonid mariculture, it has a very low requirement (if any) for automated systems monitoring and therefore little relevance to this briefing document. This is due to the quality of the rearing environment being largely determined by its position in open water. The most significant rearing methods in relation to systems monitoring are those utilising recirculating aquaculture systems (RAS).

2. <u>RECIRCULATING AQUACULTURE SYSTEMS (RAS)</u>

Recirculating aquaculture systems (RAS) are the most modern incarnation of the fish farming production system. RAS are largely indoor systems that allow for very fine control over the culture environment and just as significant the provision for reliable year round production. As with all methods of commercial aquaculture there are benefits and drawbacks to the use of RAS. The principle drawback being the initial set-up and construction costs of such facilities, which typically run into the millions. From a running cost standpoint (i.e. feed, utilities and labour), the outlay required to produce fish in recirculating systems does not vary a great deal from that of other production methods. The pattern of cost may vary, i.e. pond culture systems generally require a great deal of electricity during the summer months, for the purposes of aeration (at least 1 kW/acre of pond) while the electrical demand in recirculating systems is evenly distributed over the entire year (Krause *et al*, 2006). While it may appear that recirculating systems have a higher staffing requirement than pond/cage farms (i.e. for systems maintenance), the difference is likely minimal if the long hours necessary for checking oxygen levels in ponds, positioning emergency aerators and harvesting are taken into account (Krause *et al*, 2006). Recirculating systems generally have a significant advantage over pond/cage systems in the area of feed cost. Tank based production typically results in far higher feed conversion ratios than either pond or cage systems. This results from the fact that the producer can monitor the fish population and its feed consumption more accurately in a tank system. Automated time release feeders can be utilised and fine-tuned to deliver the correct amount of feed to maximise growth rate while minimising the amount of wasted feed.

However, the question remains, if RAS facilities cost significantly more to construct and largely the same to operate as an equivalent pond/cage system, why are they becoming an increasingly viable option for commercial fish farmers? There is the obvious benefit of guaranteed year round production; however, a more significant factor may be the increased public awareness of the pollution and environmental degradation issues associated with pond and cage farming methods (Kaiser and Stead, 2002; Fraser and Beeson, 2003; Mazur, 2004). Unlike traditional pond and cage farming methods, RAS are self-contained with, in theory, all water being treated and recycled. This therefore negates much of the environmental argument against intensive aquaculture, such as the transference of diseases/genetic material/parasites to wild stocks, the eutrophication of associated water bodies and the oversubscription/contamination of ground water supplies. A further factor is that recirculation systems allow for higher stocking densities than either pond or flow through systems, which allows RAS facilities to be positioned over a wider range of locations and return a much higher yield per hectare (Krause *et al*, 2006). Water requirement is also a major factor in the establishment of aquaculture facilities. Both pond and flow through systems have very high requirements for water (typically groundwater). In areas where water is less abundant such facilities are often not viable as higher priority is given to agricultural and domestic use. By comparison facilities employing RAS require relatively little water (less than 10% of the total system volume per day) as they treat and recirculate as much as possible (Krause *et al*, 2006). Consequently, recirculating systems can be employed and be commercially viable in locations previously denied to other methods of aquaculture.

The design and layout of a typical RAS varies little between marine and freshwater facilities. As with all aquaculture the maintenance of good water quality within RAS is of primary importance. Consequently, the most important consideration when designing any recirculating system is the incorporation of efficient water treatment processes to remove the by-products of fish and bacterial metabolism (Losordo *et al*, 1999). Therefore, recirculating production systems must be designed with several fundamental waste treatment processes embedded. These processes, generally referred to as "unit processes" (Figure 1.) include the removal of solid waste (faeces and uneaten feed), the breakdown (oxidisation) of ammonia (NH_3) and nitrite (NO_2 - a less toxic form of dissolved nitrogen), the addition of dissolved oxygen (DO) and the removal of carbon dioxide from the water (Krause *et al*, 2006). In the case of all but the most hardy species, and dependent upon the level of water exchange employed, a process to remove fine, suspended and dissolved solids, as well as a process to control bacterial load (population) is also required (Krause *et al*, 2006).

If not removed in a timely fashion, these wastes will decompose, a bacterial process that utilises a significant quantity of dissolved oxygen and produces large quantities of ammonia. Settle-able solids are the easiest to remove typically through the employment of drains positioned in the bottom of the tanks. Although numerous methods are employed the most common involve using a gentle circular water flow and/or sloping tank floors to encourage waste material to flow toward the central drain (Losordo *et al*, 1999).

With regard to suspended solids, the most effective method of removal is mechanical, either via screen filtration (typically stainless steel or polyester mesh) or the use of expandable, granular media filtration (Losordo et al, 1999). The latter functions by passing culture water through a bed of granular media (usually sand or small plastic beads) and allowing the suspended solids to adhere to the medium or become trapped between the granules. Both methods require regular maintenance in the form of cleaning. Fine suspended particles and dissolved organic material are removed via a process known as foam fractionation; also referred to as air-stripping or protein skimming (Losordo et al, 1999). Foam fractionation is a general term for a process by which air introduced into the bottom of a closed column of water creates foam at the surface. It functions by removing dissolved organic compounds (DOC) from the water column by physically adsorbing DOC on the rising air bubbles, while fine particulate solids are trapped within the foam at the top of the column. The foam can then be collected and disposed of.

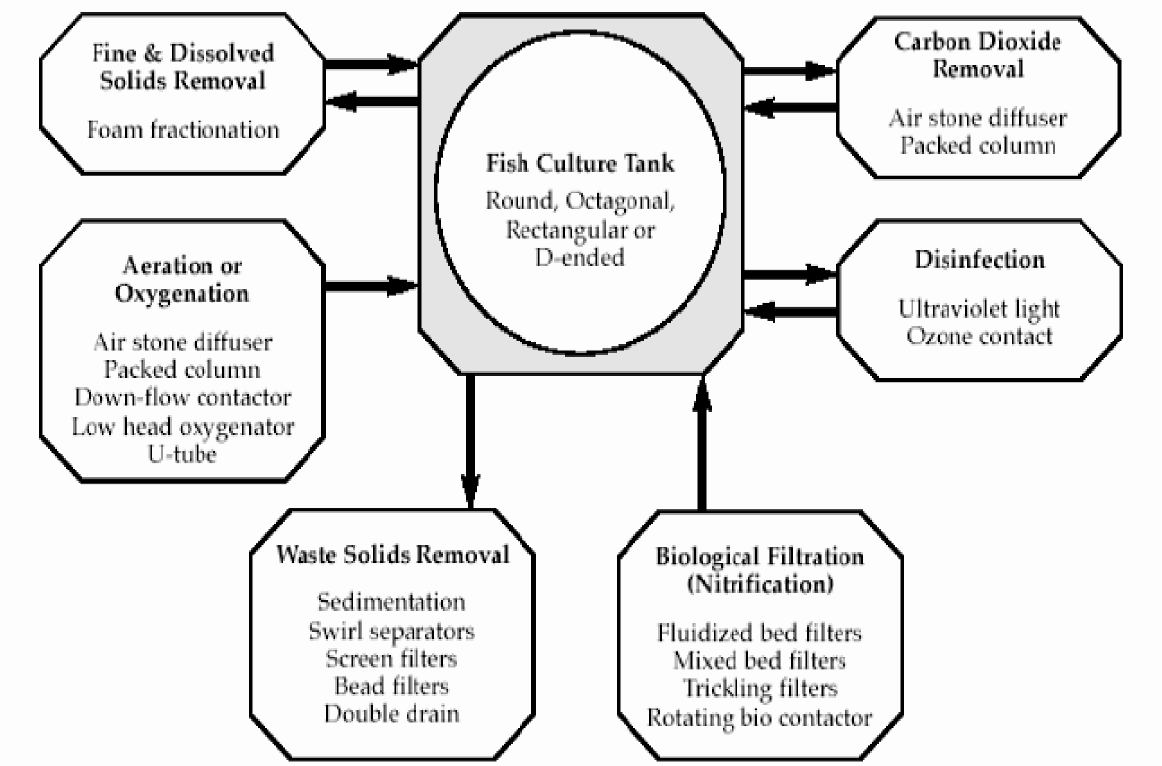

Figure 1. Required unit processes and typical components used in recirculating aquaculture production systems (Losordo, *et al*., 1998).

The control of ammonia and nitrite levels is a critical factor in the design of recirculating systems and is often the factor which determines the recirculating water flow rate. Both of these nitrogen based compound are toxic to fish (more so ammonia) and if the levels present in the culture water become too high, mass stock mortality will result. There are a number of methods utilised for removing ammonia, including air stripping, ion exchange, and biological filtration (Losordo *et al*, 1999). However, biological filtration, or biofiltration, is the most cost-effective and thereby the most widely employed of these. Biofilters are composed of a vessel containing a high surface area per unit volume substrate (e.g. gravel, sand, or plastic beads, rings or plates) on which nitrifying bacteria can attach and multiply. These bacteria oxidised ammonia and nitrite; *Nitrosomonas* spp. convert ammonia to nitrite, while *Nitrobacter* spp. convert nitrite to non-toxic nitrate. There are several different designs of biofilter employed commercially; including rotating biological contactors, trickle filters, expandable media filters, fluidised bed filters and mixed bed reactors.

In order to maintain adequate levels of dissolved oxygen in culture water (6 mg/L) and keep carbon dioxide (CO_2) concentrations at acceptable levels (less than 25 mg/L) aeration is required (Losordo *et al*, 1999). Aeration is the process by which atmospheric oxygen enters solution (in this case culture water). Various mechanisms of aeration have been utilised in aquaculture including, diffused aeration, packed column aeration and oxygenation. Oxygenation involves the dissolution of pure oxygen into water as opposed to air and can be performed using Down-flow bubble contactors, U-tube diffusers, low head oxygenation systems and Pressurised packed columns (Losordo *et al*, 1999). Regarding the removal of excess dissolved CO_2, this usually occurs as a secondary action of the aeration process, e.g. through use of a packed column aerator.

As mentioned previously, it is also often necessary to control the numbers of bacteria (usually referred to as the bacterial load) within a RAS. These bacteria if left unchecked can have a serious impact on the culture environment and stock. The bacterial population within a system may pose a direct health risk to the stock (i.e. pathogenic) or an indirect risk via a reduction in water quality through the breakdown of feed and faeces. Two methods may be employed to control bacterial load these are ultraviolet irradiation and ozonation. UV sterilisation is generally performed by passing culture water through tubes containing a UV source (a waterproof, elongated UV lamp). In the case of ozonation, ozone gas (O_3) a strong oxidising agent, is diffused through the culture water within an external contact basin or loop. Dissolved ozone is toxic to fish and shellfish and is highly toxic to humans in its gaseous form, therefore proper monitoring and maintenance of any ozonation equipment is essential.

A typical commercial RAS will therefore contain the following general components; tanking (type will vary by culture species), some form of screen filtration for solid waste, a bacterial sterilisation unit (UV and/or ozonation treatment loops), a biofilter, an aeration unit, a protein skimmer and one or more sumps (Figure 2.).

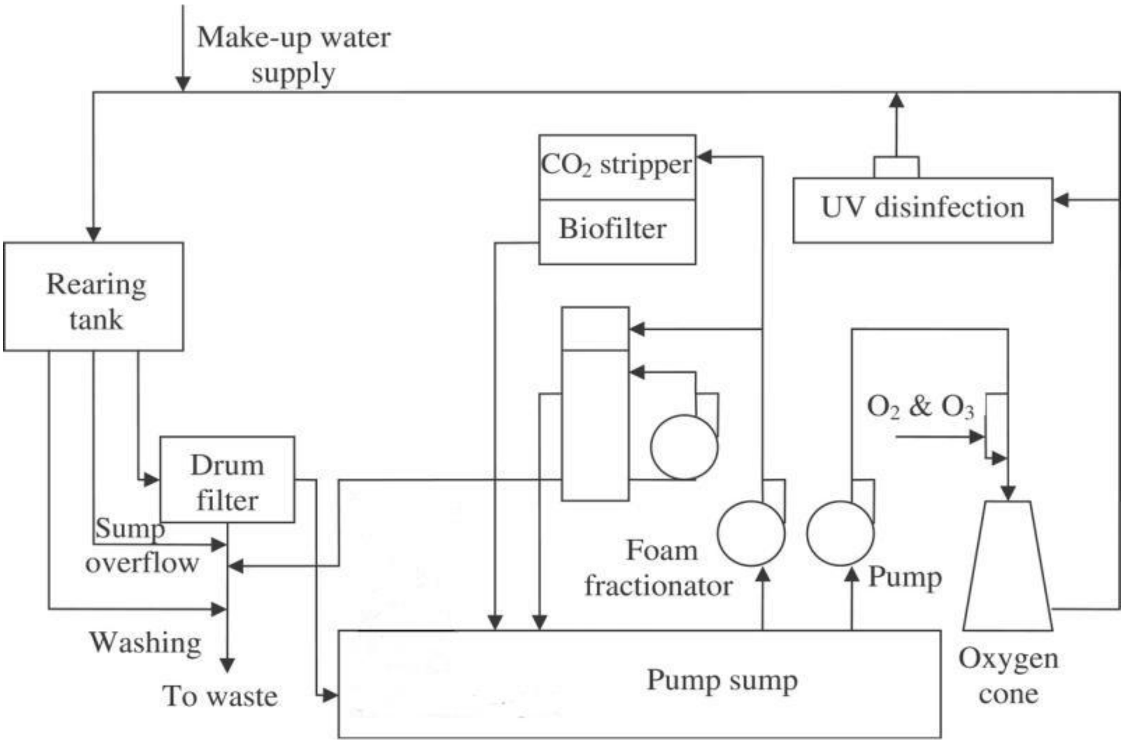

Figure 2. Basic layout of a generic Recirculating Aquaculture System (modified from Yang et al. 2006).

3. <u>REQUIREMENT FOR MONITORING & KEY PARMETERS</u>

Healthier stock suffers lower mortality and typically devotes a higher proportion of energy to growth and reproduction (rather than immune response). The resultant improved yields and product quality allows for maximisation of profit. A key component in ensuring the latter, particularly in RAS where stocking densities (biomass) are high, is the provision of adequate monitoring. Purely manual monitoring of environmental quality by staff may be possible, i.e. in small facilities operating at relatively low biomass, but this is neither practical nor cost effective for large commercial systems.

However, basic staff checks should be employed to supplement automation and provide a degree of redundancy in the case of a systems failure.

A stable RAS is a productive and profitable system; consequently any capital expended on automated monitoring should be regarded as money well spent. However, the type and level of monitoring can vary between systems and is primarily dependent on the species under cultivation, the size of the facility, stock density & value, location and operating budget (Ebeling). In the case of research systems several species may be cultivated, often in parallel; commercial production facilities however typically restrict themselves to a single species. Consequently, commercial facility monitoring systems generally do not require as high a level of adjustability with regard to culture parameters.

3.1 Key monitoring parameters

Key environmental parameters are those which must be closely monitored in all recirculating systems (as well as most other aquaculture facilities) and are displayed in Table 1. The frequency of monitoring is a dictate of the rapidity by which a given parameter may change, the more rapid a potential change the greater the frequency of monitoring required. A further factor is the importance of a given parameter, those vital to stock survival, as well as those capable of rapid alteration, will be linked to an alarm system. Such alarms may be auditory or message based (i.e. email and/or text) but most systems generally combine the two. Further to alerting staff, more sophisticated monitoring systems should be capable of instituting automatic responses in regard to detected changes in high priority parameters. For example activating emergency aeration measures in the event of a significant drop in dissolved oxygen, or shutting down ozonation equipment in the event of a leak.

PARAMETER	PRIORITY	MONITORING			
		METHOD	FREQUENCY	ALARM	RESPONSE PERIOD
Dissolved Oxygen (DO)	High	DO Meter	Continuous	Yes	Minutes
Tank water level	High	Mechnical/Electronic	Continuous	Yes	Minutes
Recirc. water flow rate	High	Mechnical/Electronic	Continuous	Yes	Minutes
Electrical power	High	Mechnical/Electronic	Continuous	Yes	Minutes
Ozone (O_3) leak (if fitted)	High	Mechnical/Electronic	Continuous	Yes	Minutes
Temperature	Medium	Thermocouple	Continuous	Yes	1-4 hours
Carbon Dioxide	Medium	Wet Chemistry/pH Meter	Daily	No	1-4 hours
Ammonia	Medium	Wet Chemistry	Daily	No	1-24 hours
Nitrite (NO_2)	Low	Wet Chemistry	Daily	No	24-48 hours
Nitrate (NO_3)	Low	Wet Chemistry	Weekly	No	24-48 hours
UV sterilisation (if fitted)	Low	Mechnical/Electronic	Daily	No	24-48 hours
pH	Low	pH Meter	Daily	No	24-48 hours
Alkalinity	Low	Wet Chemistry	Every 48 hours	No	24-48 hours

Table 1. Life support priorities and monitoring parameters utilised in a typical recirculating aquaculture system (modified from Ebeling, 1999 and Krause *et al*. 2006).

The parameters listed in Table 1 are regarded as the basic monitoring requirements for a RAS. Marine and brackish systems also require the addition of salinity monitoring via combined observation of temperature and water conductivity. Sophisticated systems may also monitor additional parameters such as turbidity (proportion of suspended particulate material within the culture water) via optical means, as well as the oxidizing or reducing potential of the water (ORP) and an estimate of the total dissolved solids (TDS) using analysis of water conductivity (ion content).

3.2 Arctic charr

As stated previously the vast majority of Arctic charr culture occurs in land-based, closed systems. In 2010, the largest producer, by far, of farmed charr was Iceland (approx. 3,500 mt), followed by Norway (421 mt) and the United States (>100 mt) (FAO Yearbook, 2009). Three types of recirculating system (utilising varying degrees of water recycling) are used in Arctic charr culture in North America; single-pass, partial-reuse and fully recirculated systems (Marsh, 2006). Salmonid species such as charr are more sensitive to water quality issues than other widely cultured types of fish such as catfish and tilapia. Despite this, Arctic charr are naturally well suited to culture in RAS as wild stocks often exhibit naturally high population densities (Marsh, 2006). Consequently, the high stocking densities required in recirculating systems have been demonstrated as having little if any impact on feed conversion rates (FCR) and growth rates in charr, while the majority of salmonids show decreases in both with increasing stocking density (Wallace *et al*. 1988; Baker & Ayles, 1990). This gives Arctic charr a distinct advantage over other salmonids species when selecting a variety for RAS culture.

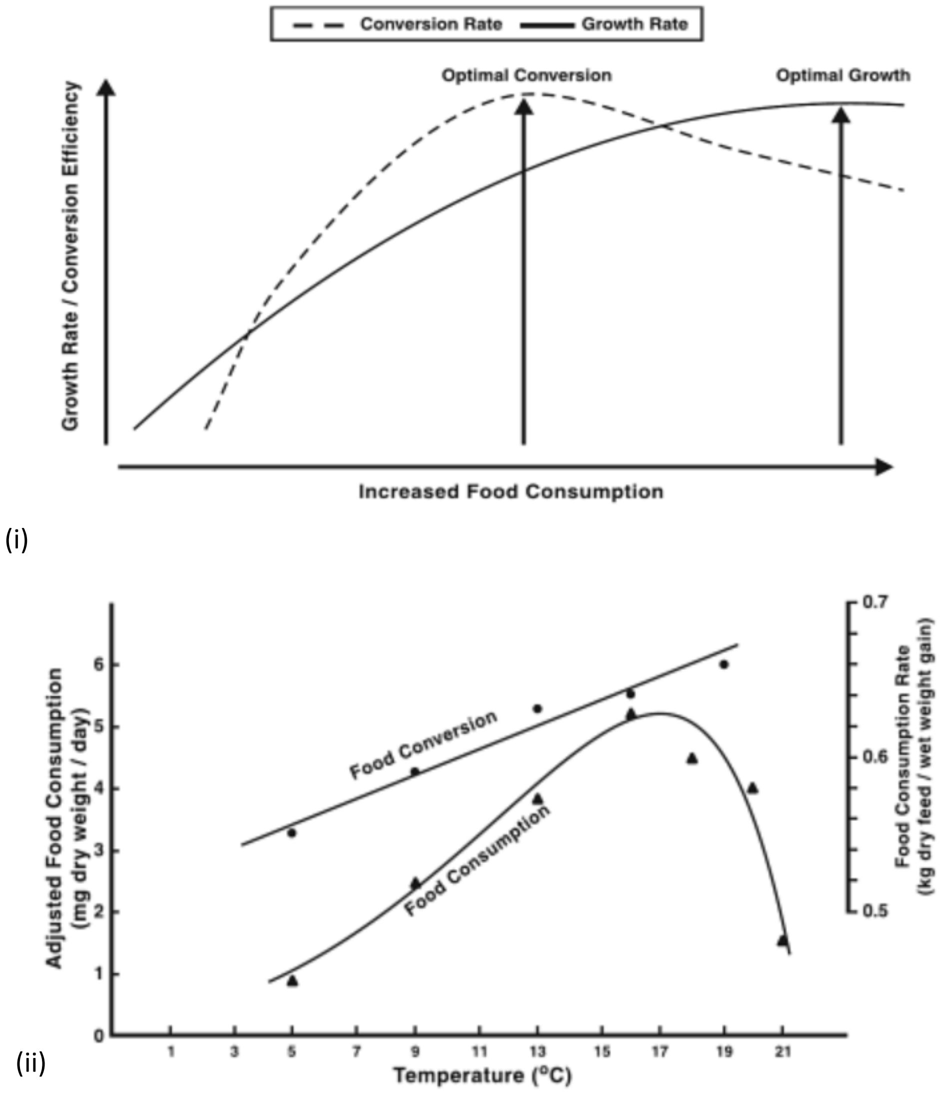

Figure 3. (i) Relationship of food intake to optimal conversion efficiency and optimal growth; (ii) Effect of temperature on feed consumption and FCR. (Johnston, 2002).

Culture conditions for Arctic charr are reasonably flexible when compared to those of other salmonid species. Wild populations of Arctic charr are known to tolerate extreme fluctuations in their environments, i.e. high densities, as well as fluctuations in temperature and water quality (Nattabi, 2007). As with all salmonids feed conversion efficiency in Arctic charr generally decreases with increasing body size (Johnston, 2002). However, given sufficient levels of DO and feed, water temperature is the primary factor that governs growth rate in Arctic charr, with fish displaying positive growth from 21^{o}C down to 0.3^{o}C (Johnston, 2002). charr exhibit more rapid growth at higher temperatures but require more feed to gain the same weight (lower FCR); Figure 3ii. Optimal growth is observed at water temperatures between 12-18^{o}C, however, most commercial growers opt for grow out temperatures of 10-13^{o}C, this allows for improved feed conversion but slightly simpler husbandry (Johnston, 2002). Feed conversion is approximately 10% higher at 9^{o}C than 15^{o}C; however, growth rates are around 50% slower (Johnston, 2002). Consequently, farmers must opt for a grow out temperature that allows for a compromise between rapid growth and efficient FCRs. At temperatures of greater than 18^{o}C sluggish behaviour increases, disease issues become more prevalent and maintaining sufficient levels of DO becomes increasingly problematic.

Despite having little if any effect on overall health, fish raised in systems where solid waste is kept to a minimum display the best feeding efficiency and thus feed conversion rates (Johnston, 2002; Nattabi, 2007). A further means of optimising feed conversion is the institution of forced swimming; i.e. forcing the fish to swim against a moderate current. This has been demonstrated as improving the overall FCR substantially (for all sizes) the hypothesis being it allows less dominant individuals to feed equally while minimising the energy the larger, more dominant fish have to expend maintaining their position in the social standing (Johnston, 2002). This is of further benefit in an aquaculture scenario as it increases the marketability of the fish by reducing instances of external damage through antagonistic interactions and results in a population with a more uniform size distribution. The relationship between growth rate, conversion efficiency and food intake is displayed in Figure 3i.

For salmonid species optimal DO levels should be between 70-80% of oxygen saturation (6.0 - 9.0 mg L^{-1}), oxygen saturation below this range decreases the maximal growth rate and higher saturation levels (exceeding 120-140%) can compromise the welfare of the fish causing oxidative stress and increasing susceptibility to diseases and mortality (Molleda, 2007). With regard to ammonia, NH_3 concentrations should be maintained at less than 0.025 mg L^{-1} and Total Ammonia Nitrogen (TAN) concentrations at less than 3.0 mg L^{-1} (Molleda, 2007). In the case of nitrite nitrogen (NO_2) levels below 1.0 mg L^{-1} are recommended in freshwater salmonid aquaculture systems. Nitrate, the by-product of the conversion of NH_3 and NO_2 within the system biofilter (nitrification) is not an issue in high flow systems, however, in those with low water flow rates it has become an increasingly important parameter and concentrations no higher than 10 mg L^{-1} should be maintained (Molleda, 2007).

3.3 Monitoring in Recirculating Aquaculture Systems

The decision as to where to employ automation within RAS may be dependent on numerous factors. These include the availability of sufficiently qualified and affordable staff, the size/turnover of the facility, the robustness and value of the species under cultivation and the installation/maintenance costs of any instrumentation/systems.

At a minimum all environmental parameters classed as high priority in Table 1. should be continually monitored. Given the unreliability and cost of having this level of monitoring performed by staff, in the case of all but the smallest facility, the most cost-effective and practical solution would require the use of automated systems monitoring software such as the type of highly customisable product available from Traceall Ltd.

With regard to some of the lower priority parameters (i.e. nitrite and nitrate) it is in some cases more practical to utilise monitoring by staff. Highly efficient, self-contained handheld devices for ammonia monitoring are available (e.g. IQ SensorNet AmmoLyt Sensor from YSI Ltd.) however, in large facilities this may not be sufficient. Another critical factor when evaluating monitoring solutions is the degree of maintenance, primarily the amount of checking/calibration of sensors necessary. It is somewhat pointless having a state of the art monitoring system if it requires near constant checking and adjustment by staff.

3.4 Examples of commercially available water quality sensors and sensor packages of the type employed in RAS

The commercial products outlined in this section have been selected to give an indication of the type of instrumentation/systems currently available. It should by no means be considered exhaustive and was included to provide examples of the type of hardware any monitoring/control software would need to integrate with. Most of the companies mentioned in this section offer a high degree of customisation with their products, this reflects the main determining factor in relation to the design of monitoring systems, that is the facility and species under cultivation.

- **YSI - 6920 V2**: The YSI 6920 V2 is a compact data sonde designed to be an economical water quality logging system, ideal for long-term *in situ* monitoring and profiling. The sonde is customisable with the option of fitting optical sensors for; dissolved oxygen (ROX optical), blue-green algae, chlorophyll, turbidity, specific conductance (i.e. salinity & ionic concentration), nitrate, ammonia, or chloride. The device possesses self-cleaning optical sensors and an anti-fouling component for extended deployment, RS-232 and SDI-12 communications as well as a back-up battery. In its basic configuration the sonde provides real-time turbidity, DO and algae growth monitoring.

- **YSI - IQ Sensor Net VARiON Plus 700 IQ**: the 700 IQ is a calibration free combination sensor sonde for the online determination of ammonium and nitrate ions.

- **Hach Hydromet Inc. - Hydrolab DS5 Multiparameter**: the Hydrolab DS5 water quality sonde offers the choice of any of Hydrolab's seventeen superior sensors for either profiling or unattended monitoring. Configuration includes seven built-in expansion ports allowing simultaneous measurement of up to 16 water quality parameters, optional built in battery pack and RS-485 communications available.

- **IN-SITU Inc. Aqua TROLL 400**: the Aqua TROLL 400 multiparameter instrument eliminates complicated set-up and provides instant access to data for real-time water quality monitoring in aquaculture facilities. The instrument houses six water quality sensors and monitors 12 parameters; actual and specific conductivity, salinity, total dissolved solids, resistivity, and density; DO; Oxidation Reduction Potential (ORP); pH; temperature; water level and water pressure (absolute). The instrument incorporates open communication protocols allowing easy interfacing with any system.

Other similar customisable sensor sondes are manufactured by YSI, Hach Hydromet and In-Situ Inc. (e.g. YSI EXO1, 6600V2 & 600OMS V2 sondes; Hydrolab Quanta & DS5X Multiparameter sondes; In-Situ RDO PRO probe & TROLL 9500 Water Quality Instrument). Individual sensors as opposed to multiparameter sondes are also available from numerous companies, including In-Situ Inc., Four Point Systems Inc. and Campbell Scientific Inc. YSI and Hach Hydromet also offer a range of manually operated, hand-held monitors as well as fully integrated monitoring and control systems, incorporating sensors, software and control system, some of which are described below;

- **YSI 5200A Multiparameter Monitoring and Control Instrument**: Engineered specifically for recirculating aquaculture systems, the YSI 5200A continuous monitor and AquaManager® Software can be used to integrate process control, feeding, alarming, and data management into one product or can be used to simply monitor one tank. Powerful enough to manage a full scale farming operation from anywhere in the world yet simple enough for anyone to use. Allows access to a facilities water quality data at any time through the Aquaviewer App. Capable of monitoring DO, temperature, conductivity, pH, ORP and salinity and capable of networking up to 32 instruments per comm port. Can utilise either Ethernet TCP/IP or wireless communications. Allows event logging, calibration and the setting of high and low conditions and E-mail and SMS alarming. Also incorporates a conditional feed timer through the included Feed SmartTM software. AquaManager desktop software provides the ability to instantly see an overview of your facility, manage parameter set points, and conveniently manage data to make informed operation decisions.

- **YSI 556MPS Handheld Multiparameter Instrument**: Featuring a waterproof IP-67, impact-resistant case, the YSI 556MPS simultaneously measures DO, pH, conductivity, temperature, and ORP. Features; field-replaceable DO, pH, and pH/ORP probes, RS-232 and compatible with EcowatchTM for WindowsTM data analysis software, easy-to-use, screw-on cap DO membranes and user-upgradable software from YSI website.

- **In-Situ Inc. Con TROLL PRO Model AC-L**: The Con TROLL® PRO Model AC-L is designed for process control applications with access to line power. In addition to displaying and reporting data, this model logs data into internal memory. The Con TROLL PRO System can be used to; display and report multiple parameters to process controls, log data for complete, error-free records, access sensors and data via Bluetooth® Wireless Technology, interface with RuggedReader® Handheld PC or laptop via Win-Situ® Software, calibrate or reset factory defaults on site, measure ambient temperature and barometric pressure and power any attached instruments.

- **Thermo Scientific Orion Star meters**: Three models available (5, 4 and 3 Star) featuring In-Situ RDO sensor technology. Star meters are ideal for measurements from effluent, aeration basins and even influent, as the sensor is not affected by colour or turbidity. Ideal for spot-checking in aquaculture facilities the 5 Star model measures DO, pH, conductivity, salinity, total dissolved solids (TDS), resistivity and temperature.

4. SUMMARY

Although many sensor manufacturers (e.g. YSI and In-Situ Inc.) offer integrated monitoring systems, including software packages, there are several advantages to utilising a third party monitoring application such as that offered by Traceall Ltd. Primary amongst these must be the degree of customisation and flexibility offered by such a tailor-made software solution. A company specialising in the design of tracking and monitoring software would be better positioned to offer innovative solutions to individual customers as well as being in a position to offer continued real-time product development and future-proofing.

A further advantage would be the potential to integrate products (i.e. sensors and controllers) from multiple manufacturers to harness the best-suited/most cost-effective hardware to create a truly customised solution that meets all of the customer’s needs. Most facilities have to rely on separate monitoring systems for water quality, ozone and UV system monitoring. This is not only less efficient but also more costly, both in terms of set-up, maintenance and monitoring (staff time). This high degree of customisation also dovetails with the future proofing aspect and would allow total flexibility to account for any changes in the aquaculture market, which for example may necessitate a change in culture practice (e.g. species under cultivation).

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