unuftp.is Final Project 2017

AN ENVIRONMENTAL APPROACH TO INLAND CAGE CULTURE IN SOUTH AFRICAN DAMS

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ABSTRACT

The expansion of aquaculture, to meet the national objectives without compromising the integrity of the environment, is achieved through application of proper management strategies. The current study investigates the potential environmental impacts associated with the introduction of cages in inland waters of South Africa. Through a literature review and visitation to Icelandic farms and government institution dealing with aquaculture, recommendations and guidelines were made. The guidelines provide suitable methods to implement models to monitor environmental impact. The Dillan and Rigger model forms the first basis of capacity estimation, while water quality and sediment analysis are crucial for ongoing monitoring of cages. The use of benthic invertebrates as bioindicators and simulating their abundance, diversity and biomass to environmental impacts serves as an indication of detrimental effects.

This paper should be cited as:
Seanego, K. 2018. *An environmental approach to inland cage culture in South African dams.* United Nations University Fisheries Training Programme, Iceland. Final project.
http://www.unuftp.is/static/fellows/document/Koena17prf.pdf

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1 BACKGROUND

The increasing development of inland aquaculture in South Africa was prompted by the need to address national policy objectives that include job creation and poverty alleviation. Initiatives have been made to expand on aquaculture and explore unexploited inland water resources with special interest on large water bodies such as dams. Many of the dams have been historically utilized for recreational, irrigation and domestic purposes (Galvin, 2011). One major challenge associated with the aquaculture industry, including the production of shellfish, and finfish, is finding ways of increasing fish production while minimizing the environmental impact. Aquaculture operations are known to generate dissolved and particulate waste to the surrounding benthic and pelagic ecosystems. This is particularly true for farms where high-protein formulated feeds are used for feeding. Considerable attention needs to be paid to assess the potential influence that organic matter and nutrients release from these operations have on the aquatic ecosystem. Research conducted in the early stages of the proposed finfish farming projects in South Africa could be beneficial and provide baseline data. Ongoing monitoring and the implementation of a modelling programme could aid in better regulation and prediction of the local and regional environmental impacts.

The Department of Agriculture Forestry and Fisheries (DAFF) is tasked with managing the development of the sustainable use of marine, freshwater and coastal resources. The economic growth potential of the aquaculture industry is dependent on the integrity and quality of the country's freshwater and marine ecosystems. Since the expansion of the government's mandates for fisheries, with a greater focus of aquaculture, several projects have been implemented. These are in line with the Operation Phakisa: Ocean's Economy, an initiative of the South African government which aims to implement priority economic and social programmes better, faster and more effectively. It was launched by the President of the Republic in October 2014. The department has identified several aquaculture projects that aim to empower communities through the transfer of technology, skills development, and job creation. Some of the proposed aquaculture projects include the implementation and potential expansion of existing finfish farms. There is also a shift to inland freshwater aquaculture as the sector has not progressed despite it being the earliest form of aquaculture in the country. Moreover, much of the inland water bodies remain unexploited in this regard. It is therefore prudent to put an environmental management strategy in place, to better manage the growth of the aquaculture industry and finfish industry within the country.

Environmental understanding allows for the sustainable development of the aquaculture sector through informed policy making and the application of both private and public regulation and standards (Neil et al., 2014).

2 RATIONALE

There is a need to understand and estimate potential impacts and the carrying capacity of the environment, including its ability to support the activity in question with minimal negative impacts. The use of tools to model environmental impacts has not been fully explored in South Africa. This will assist in guiding aquaculture development and ensure that production is maximized and sustainable.

3 RESEARCH OBJECTIVES

3.1 General objective

To develop an environmental monitoring protocol that can assist in the monitoring of freshwater finfish cage farms in South Africa. To assess the most appropriate modelling tool suitable for South African waterbodies.

3.2 Specific objectives

1. Identifying key environmental factors associated with cage culture farming of finfish and assess their impact in freshwater environments (large water bodies or lakes)
2. Develop a monitoring and evaluation sampling protocol
3. Evaluate the best-suited carrying capacity model

4 SOUTH AFRICAN AQUACULTURE & PROSPECTS FOR EXPANSION IN INLAND WATERS

4.1 South African Climate

South Africa is a semi-arid country that receives relatively low rainfall of less than 500 mm a year (Palmer & Ainslie, 2006). Generally, rainfall occurs during the months of November to March, but in the southeast region, rainfall occurs from June to August. The country experiences warm climate conditions throughout most of the year. This is accompanied by long sunny days and cool nights. Maximum temperatures above 32°C have been recorded. High warm temperatures are consistent with the inland provinces Limpopo, Mpumalanga, Northern Cape, North West and some parts of the Free State. While some areas in the south-west regions of the country, including the Western Cape, can get average annual temperatures of 17°C. This variation in the temperature is influenced by variation in elevation, terrain and ocean currents (Palmer & Ainslie, 2006). The rise of inland plateaus in some regions like in the northeast region results in average temperatures of 17°C. The warm Agulhas ocean current sweeps southward along the Indian Ocean coastline in the east for several months of the year, while the cold Benguela current sweeps northward along the Atlantic coastline in the west. Areas bordering the Indian Ocean can be 6°C warmer than those bordering the Atlantic Ocean. This causes variation in the temperature and rainfall between the east and western parts of the country. Evidence to this is in the eastern highveld areas receiving 500 to 900 mm of rainfall, while the central country receives around 400 mm, with much less rainfall further up north of 200 mm (Tshikolomo et al., 2013). These temperature variations and availability of water influence to a large extent the potential of different aquaculture species.

4.2 Hydrological characteristics of South African dams

Dams have been constructed for reservoirs, where half of the annual rainfall is stored. Historically, the construction of dams under the apartheid regime and colonial governments was as a means to curb the water scarcity, to generate electricity for growing cities, for agriculture and industries. However, some poor communities were negatively impacted, particularly those displaced during the construction of these dams. A large portion of South Africa’s rural population depends directly on natural resources for subsistence. As a consequence of extensive hydrological impacts of dams with large reservoirs, many of the downstream communities experience water-related problems. This has been further exacerbated by lack of expertise to manage resources (Galvin, 2011; Tapela, et al., 2015).

There were more than 4500 private and public registered dams in 2016 spread across the 9 provinces of South Africa (DWS, 2016). These have been classified into four categories; large, medium, small and unclassified, varying in capacity and length (Figure 1). Approximately 3 % of these dams are large and under the control of governmental institutions including; the Department of Water Affairs and Sanitation (DWS), Department of Agriculture Forestry and Fisheries (DAFF), Department of Transport and some municipalities, etc. These vary in surface area, ranging from 7000 to 23 000 ha. Many of these dams have multiple functions, other than those mentioned previously, some are used to generate hydro-electricity and for mine residue disposal. The small and medium dams have an average surface area of 70 and 270 ha respectively (DWS, 2016). Many of the public dams have been stocked with indigenous and alien fish species, predominantly for recreational angling (Hara & Backeberg 2014). Fish species such as tilapia (*Oreochromis mossambicus*, *Oreochromis niloticus* and *Oreochromis rendalli*), catfish (*Clarias gariepinus*), carp (*Cyprinus Carpio*) are some of the warm water species found in many of these dams, whilst rainbow trout and brown trout *(Oncorhynchus mykiss* and *Salmo trutta*) are found in colder regions of the country.

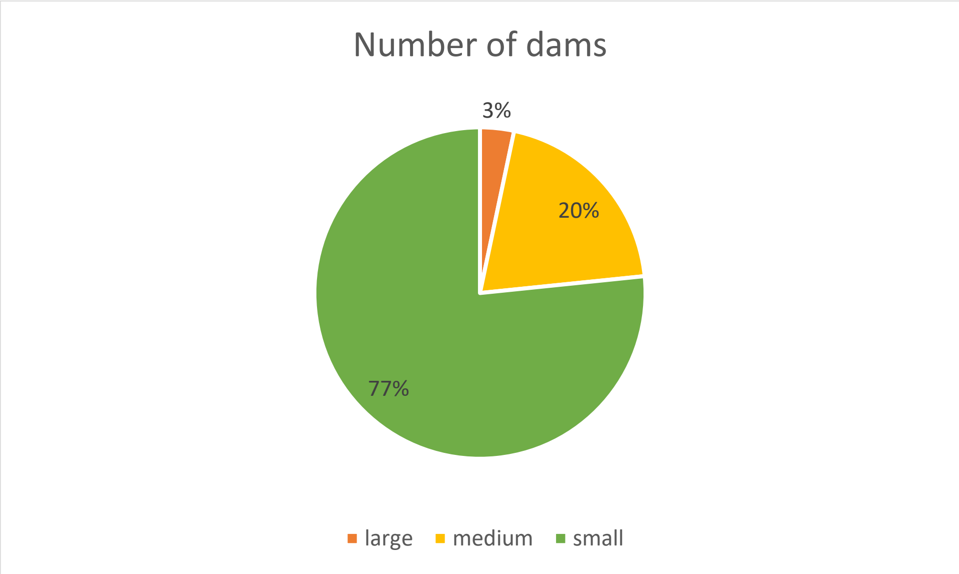

Figure 1: Percentage of registered dams in South Africa in 2016 (DWS, 2016)

4.3 **Water quality of dams**

The Department of Water and Sanitation (DWS) is the main statutory body responsible for the monitoring of surface water and groundwater. Their assessment of dams through the National Eutrophication Monitoring Programme indicates that many water resources are eutrophic. This is based on chlorophyll and phosphorus levels. The major cause like in most developing countries is inadequately treated sewerage effluents that are discharged into river systems. Other sources including industrial effluents, agriculture, households, and urban and road surface runoff have also contributed to the decline in water quality. The severity of impact is a function of their proximity to urban areas (Oberholster & Ashton, 2008). In some dams there is indication of high levels of nitrate and sulfates. This is indicative of a general lack of appropriate management. Such conditions limit the potential for fish farming and are a plausible reason for prior environmental assessment.

4.4 Fisheries activity in dams and a shift to aquaculture

Inland fisheries in South Africa, dates back to the colonial era. Marginalized poor communities were not afforded accesses to certain resources, including fishing rights. The growth of the sector was slow, despite several attempts to improve it (Tapela et al., 2015). While this might have changed over the years, it has taken a considerable amount of time for the fisheries sector to be defined as an economic sector and included as a priority by the government.

In 2005, the government adopted long-term fishing policies that made no provision for small-scale fishers. The major shortcomings identified include community consultation and a permit system for activities other than fishing. These challenges prompted a new policy that would result in improved and sustainable marine resource co-management. While this seemed to be the case with the marine sector, freshwater sector stagnated. So, in June 2012, the small-scale fisheries policy was finally adopted by the cabinet. Clear benefits for women in fishing communities from both fishing and value chain and greater access to markets and infrastructural support for the sector was made available (Sowman et al., 2011; Tunely, 2009).

Unlike most African countries where rural, small-scale aquaculture has been practiced for some decades, it is virtually unknown in most rural communities of South Africa. To develop the sector, the government made attempts to establish community-based small-scale aquaculture in some rural areas, in the form of providing start-up seed for pond culture. Many of the projects were unsuccessful. Issues relating to poor planning, lack of capacity of participants, lack of skills, low returns, and community conflict were some of the major bottlenecks. This then prompted a shift to more commercial aquaculture, where policy development of small-scale focused on developing an enabling environment for the promotion of commercial aquaculture. This has prompted a gradual growth in the sector, however not to its full potential (Shipton et al., 2009).

The aquaculture sector has grown over the years and about 233 aquaculture farms were registered in 2014, including 39 marine farms and 194 freshwater farms. The cultured freshwater species include rainbow trout, tilapia, catfish, carp, and marron crayfish (*Cherax tenuimanus*). The freshwater aquaculture industry accounted for 34 % of the total production that amounted to 5200 tons (DAFF, 2015).

The trout sub-sector contributed 86 % of South Africa's total freshwater production in 2014, recording a total production of 1497.30 tons (DAFF, 2015). The trout industry is currently operating on a commercial scale. Production has increased over the years, with major exports to Botswana and Ethiopia. Local demand for trout is expected to grow steadily with the trend of eating more high-value fish. However, the ability of the local industry to increase production is constrained by the environment. The expansion of the rainbow trout industry is restricted by high temperatures that occur in most parts of the country. Rainbow trout requires well-oxygenated waters with temperatures lower than 18°C (Shipton & Britz, 2007). Opportunities do exist for expansion of freshwater trout production in cool water dams. Government has undertaken an initiative to introduce trout farming in the Vanderkloof Dam, Northern Cape. It is the second largest (13 300 ha) and longest (114 km) water body in South Africa and was built as part of the Orange River Scheme. The potential growth in the freshwater sector would stimulate socioeconomic growth where there will be a change in the livelihood of many local people. Vanderkloof Dam is situated within a priority area for development. The nearby towns of Keurtjieskloof, Petrusville and Phillipstown have been reported to have high levels of unemployment and poor food security (van der Vyver et al., 2015).

Climate has been highlighted as one of the major constraints limiting the expansion of inland aquaculture in South Africa. Seasonal culture in ponds, particularly for small-scale farming has been a means of avoiding relatively low temperatures during the winter, which extends to most parts of the country. Recirculating culture systems are used in commercial production facilities all year round to maximize production without being limited by temperature fluctuations. Other issues such as spawning, fingerling production, nutrition, disease control and harvesting in all sub-sectors (except for marron, *Cherax tenuimanus*) are being tackled, with much of the expansion of freshwater shifting towards more environmentally controlled recirculating systems (Shipton et al., 2009).

With increasing aquaculture operations, it is important to ensure sustainable development of the sector through assessment of environmental impacts. Environmental impact assessments (EIA) are usually undertaken in aquaculture development zones prior to the commencement of any farming activity. These are however limited to aspects of water quality before farming. Once the farms have been established, the environment in and around the cages needs to be assessed.

There is a paucity of background information on environmental assessments of freshwater systems. It is therefore important that the environmental impacts of freshwater aquaculture operations on the water quality, benthic community, and sediment be assessed. Furthermore, no monitoring programme has been implemented to assess these impacts. There is a need to develop a more conservative, management-orientated monitoring programme for freshwater environments.

4.5 Environmental impact, farm monitoring and carrying capacity models

Aquaculture development does not come without its environmental impacts. In cage aquaculture, the most obvious change is the deposition of organic matter below cages caused by excess feed and faeces. This causes proliferation of algae, alters sediment condition and in severe cases causes anoxia and H_2S production. Parameters linked with aquaculture in dams, as in many other aquaculture operations include DO, pH, TAN, PO4, turbidity, H_2S and suspended solids (Maleri, 2008). The rate at which a waterbody can assimilate nutrients determines the environmental impact. In areas where water exchange is restricted, there is a risk of high levels of nutrient accumulation. In shallow waters with weak currents, particulate matter will settle to the bottom close to the cages. In such cases, continued production can give rise to a rapid local accumulation of waste material (MFFASA, 2011).

In irrigation dams in the Western Cape province, diversified plant species of the genera Typha, Phragmites, Zantedeschia and Restio emerged as a result of nutrient enrichment from rainbow trout farm. It was however recommended that farms should always be closely monitored to ensure good water quality (Salie et al., 2013). In these areas it was also found that water quality did not influence yields of farms. However, this may not be the case for most dams in the country, as many have been defined as eutrophic and may not be conducive for farming. Setting up a farm in such conditions may be problematic as cage culture in general, as several studies have shown, contributes to the accumulation of organic waste (Hitching et al., 2011;

Kaushik, 1998). So potential aquaculture environments are assessed to ensure that they accommodate the species of interest and cause less impact on the environment.

Environmental impact assessment (EIA) regulations in Africa have not resulted in a large number of EIAs being carried out in aquaculture (Nugent, 2009). The probable cause is a low level of growth of aquaculture. In South Africa, EIAs are required by law before an aquaculture facility can be constructed. Potential environmental impacts can be highlighted prior to farming. During this process, potentially negative environmental and social consequences of the facility will be addressed. The biggest concerns are usually related to the discharge of effluent water and the handling of solid wastes (MFFASA, 2011). In addition, environmental legislation exists that regulates the impact of farming activity; Marine Living Resources Act, 1998 (Act No. 18 of 1998), The National Environmental Management Act, 1998 (Act No. 107 of 1998), The National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004) etc (DAFF, 2011). These aid in management and regulation; however further steps need to ensure sustainability of aquaculture operations.

Environmental indicators need to be well defined within the context of cage farming in freshwater environments. Estimations of environmental impacts can be done as precautionary measures, predicting change and allowing proper management and better utilization of resources (Neil et al., 2014). These are often achieved through carrying capacity models. In order to make more informed decisions that minimize environmental impact, continuous monitoring and prediction model studies need to be looked into. The quality and quantity of feed used, and the productivity of the site determines the carrying capacity of freshwaters for culture (Beveridge, 1984). Carrying capacity can be divided into four types; physical carrying capacity, production carrying capacity, ecological carrying capacity and social carrying capacity (McKindsey et al., 2006).

Several methods have been developed to estimate the organic load of aquaculture. Sediment carbon content and reactivity has been identified as a potential monitoring tool in transects around a fish farm in east Iceland (Eiríksson et al., 2017). This is after the authors found that strong negative correlation exists between benthic species diversity and reactivity of organic carbon, indicating a decline in species with an increase in organic loads.

Other methods such as ecological footprint analysis (EFA) where integrated ecological-chemical and ecotoxicological biomonitoring tools are used to assess both the short and long-term environmental impact of aquaculture farm site within different stages of the production (Gomiero et al., 2017). Nitrogen, phosphorus, energy fluxes and organic matter inside and outside the cages are assessed.

Other methods involve waste reduction through monitoring response of fish and feeding behaviour. This is through the placement of surveillance cameras at the bottom of cages. It also monitors any mortalities and escapes (Agustsson et al., 2016). The MOM (Fish Farm – Monitoring – Modelling) is another environmental monitoring tool of marine fish farms, where critical effect parameters associated with cage farming are evaluated to assess localized impact. Sediment analysis comprises of pH, redox potential, total organic carbon (TOC), hydrogen sulfide, presence, abundance and diversity of benthic invertebrates, are some of the critical parameters.

Most documented environmental data in South Africa relates to land-based farming, particularly of marine species. These are from monitoring of mollusks species, more specifically abalone (Haliotidae). There are very few carrying capacity studies on freshwater environments in South Africa, let alone cage farming.

5 ENVIRONMENTAL FACTORS, MANAGEMENT PRACTICES, AND MONITORING TECHNIQUES

5.1 Study design

Information relating to the environmental impacts associated with cage culture, aquaculture legislation, monitoring programmes and carrying capacity models have been gathered through reviewing of relevant published and unpublished literature from reports, journal articles, and official government documents. This information is interpreted and evaluated to generate information and knowledge on monitoring approaches and appropriate scientific models to apply for finfish culturing in freshwater dams in South Africa.

5.1.1 Environmental Assessment

Policies on freshwater aquaculture are currently unavailable and these are to be addressed in the Aquaculture Bill (DAFF, 2015). The Bill has not yet been passed. South Africa's marine aquaculture sector is however subject to various laws, policies and international agreements. The Department of Agriculture, Forestry and Fisheries (DAFF) is mandated to formulate policy, guidelines and protocols for aquaculture. Where necessary, the DAFF works cooperatively with other government authorities whose legislative mandates may affect aquaculture (DAFF, 2012). The laws and conventions that determine the environmental management requirements in marine aquaculture are summarised below (Table 1). It is for this reason that legislation relating to freshwater needs to be reviewed and incorporated in the framework of aquaculture legislation within the country.

Table 1: Aquaculture legislation (adapted from DAFF, 2012)

Legislation or Aspect	**Key content related to marine aquaculture**
The Constitution (1996)	The Constitution entrenches the right of all South Africans to an environment that is not harmful and which is protected.
National Environmental Management: Biodiversity Act (No.10 of 2004) (NEM: BA)	NEM:BA influences marine aquaculture as it prescribes procedures for the management and culture of exotic organisms (in terms of the Alien and Invasive Species Regulations) and the protection and restrictions pertaining to the farming of endangered or threatened species (in terms of the Threatened and Protected Species Regulations).
The Marine Living Resources Act (No. 18 of 1998) (MLRA)	The MLRA provides for the granting of a "right" to engage in marine aquaculture. Permission to exercise such a "right" is granted by means of a permit. Comprehensive guidelines, programmes and permit frameworks have been developed by the DAFF in terms of the MLRA to assist with compliance in the marine aquaculture sector.

5.1.2 Carrying capacity models

Predictions of the extent to which aquaculture activity can have on the environment have been assessed through carrying capacity models. McKindsey, et al. (2006) have outlined a hierarchical structure to determine the carrying capacity of a given area (Table 2). Production and ecological models are more often used, particularly in cage culture where the excess feed is of concern. Many research studies have narrowed down the models and have focused on production limiting factors, including nutrients, phytoplankton and oxygen (Eiríksson et al., 2017; McKindsey, et al., 2006).

Table 2: Carrying capacity models (McKindsey et al., 2006)

Carrying capacity	**Parameters**
Physical	Based on the natural conditions and on the needs of the species and culture system Water depth, current, temperature,
Production	Plankton, detritus, nutrients, Oxygen
Ecological	Community structure, mass balance models
Social	Traditional fisheries, recreation, charismatic species

In the case of freshwater environments, phosphorus is found to be the main nutrient that triggers eutrophication and therefore phosphorus inputs from farms have been modeled (David, et al., 2015). The Dillan and Riglers modification of the Vollenweider's model has been widely used for freshwater environments to model aquatic ecosystems response to phosphorus loading (Beveridge, 1984; Correll, 1998; David et al., 2015). The model states that the concentration of Total Phosphorus in a water body [P], is determined by the phosphorus loading, the size of the lake and (area, mean depth), the flushing rate (i.e the fraction of the water volume lost annually, the outflow) and the fraction of phosphorus permanently lost in the sediments (Dillon & Rigler, 1974).

$$[P] = \frac{L\,(1-R)}{\bar{Z}\rho}$$

Where; [P] is in gm^{-3} total P, L is the total P loading in $gm^{-2}yr^{-1}$, $\overline{Z}$ is the mean depth in m

R is the fraction of total P retained by the sediments, ρ is the flushing rate in volume per year.

Modifications of this equation exist to determine the loading of phosphorus in relation to aquaculture. Syandri et al, (2016) has explored the use of this equation to evaluate the impact of net cages on Maninjau lake, Indonesia. These with further explanations from (Beveridge, 1984), are presented in to table below (Table 3).

Table 3: Carrying capacity estimation methods of inland waters (Beveridge, 1984; Syandri et al., 2016)

(Syandri et al., 2016)				**(Beveridge, 1984)**
No	**Parameter**	**Formula**	**Information**	
1	*The morphology and hydrology of the lake*			hydraulic loading
a	Average depth	= 100 x V/ A	The average depth (m) V: The volume of water (m^3) A: The surface area (Ha)	$z = \frac{V}{A}$, v is the volume of the water body (m^3), A = surface area (m^2)
b	The rate of turnover lake water	ρ = Qo/ V	The rate of turnover lake water (year -1) (m3/year)	$\rho = \frac{Q_o}{V}$, where Q_o is the average total volume outflowing each year, determined in two ways. 1) Direct measurement of outflows 2) Total long-term average inflow from catchment area surface runoff (Ad.r), precipitation (Pr) and evaporation (Ev) $Q_o = Ad.r + A(Pr - Ev)$,
2	*The allocation of load pollution phosphorus (P)*			

a	The allocation of the total P load from floating nets cages (FNC)	Δ [P]d = [P]f - [P]i	Δ [P]d: The allocation of the total P load from FNC (mg P/m^3) [P]f: Requisite levels of P-total max. In accordance with the farmed fish species (mg P/m^3) [P]I: levels of P-total monitoring results (mg/m^3)	The capacity of the waterbody for intensive cage culture $\Delta[P] = [P]_f - [P]_i$,
3	*Capacity of P-total pollution load of wastewater fish farming*			
a	Waste of fish per unit area of the lake	L_{fish}=Δ [P]• ρ/ (1- R_{fish})	L_{fish} : Capacity of P-total waste of fish per unit area of the lake (gr P/m2 year)	$L_{fish} = \frac{\Delta[P]\bar{z}\rho}{1-R_{Fish}}$ L_{fish} is largely in particulate form, and the proportion of the waste faecal and food P which contributes to the dissolved P (Factors; P content in feed, diet composition, pellet shape, temperature, depth of water under cages, presence and absence of scavenger fish. $R_{fish} > R$)
b	The proportion of total soluble P-to sediment after FNC	R_{fish} = x + [(1-x) R]	R_{fish}: the proportion of that dissolve P-total sediment to after FNC	
c	P total stay with sediment	R =1/ (1+ 0,747ñ^{0,507})	R: P total stay with sediment.	
d	Total capacity of P-total waste of fish in the waters of the lake	La_{fish} = L_{fish} x A	x: proportion of total P-total permanently into the bottom of the lake ranges from 45 to 55%.	

			La_{fish}: the number of P-total capacity of fish waste in the waters of the lake (g P/year)	
4	*Feed and P waste from fish farming FNC*	P_{LP}=FCR ×	P_{LP}: P-total entering the lake from fish waste (kg P/ton fish) FCR: Feed Conversion Ratio (ton feed/ton fish)	
	P-total entering the lake from fish waste	$P_{feed} – P_{fish}$	P_{feed}: levels of P-total in feed (kg P/ton feed) P_{fish}: P-total levels in fish (kg P/ton fish)	
5	*Aquaculture*			
	Total fish production of FNC	$LI = La_{fish} / P_{LP}$	LI: FNC fish production (tons /year) La_{fish}: The total capacity of P-total	
	The total feed to the fishing FNC waste fish in the waters of the lake (g P/year)	LP = LI x FCR	LP: Total feed the fish with FNC (ton / year)	

5.1.3 *Cage and sampling area*

There are various factors to take into account when establishing a cage farm. Huguenin, (1997) has identified ways in which cages can be classified (Table 4). Environmental conditions of the proposed farming area, species and operational scale dictate to a large extent the type of cage used and expected waste generated from the operation (Huguenin, 1997).

Table 4: Means of classifying cage systems (Huguenin, 1997)

Where operated	Surface Submerged Marine, estuary, freshwater
Means of support	Fixed to bottom (via pilling) Floating (buoyancy)
Structure	Rigid (usually structure and mesh) Flexible (usually mesh only)
Access to service	Catwalk No catwalk (usually boat/barge serviced)
Operating parameters	Biomass loading (intensive-extensive) Species Feeding practices (fed/unfed) (hand/auto)
Environmental severity	Sheltered/exposed/open water

The following are factors that should be considered when assessments are done.

- the number of cages
- cage orientation along the length of cage group
- depth under cages
- current velocity/flow rate

In most developed countries, there are regulations set for cage culture installations in varying environments. The Norwegian government has a manual, *Technical requirements for fish farming installations NS 9415:2003*, regulating the technical requirements on the dimensioning, design, installation and operation of floating fish farming installations (Standard Norge, 2009). These regulations are useful and have been used by other countries such as Iceland. The greater purpose of these regulations is to prevent escapees and to prevent the use of material that could contribute to heavy metal accumulation such as copper.

Cage sampling varies with the layout of the farm. Sampling stations can be defined based on proximity to cages; close, located directly beneath the cages, intermediate, 50 – 100 m distance and a reference site at a distance of 1000 m (Carroll et al, 2003).

5.1.4 *Environmental aspects of aquaculture*

Environmental background data is important for the precise output of a model (White, 2009). The most important parameters for environmental monitoring and modeling are:

- Bathymetry (depth profiles) of the area

Detailed knowledge about the bathymetry in an area is crucial for being able to model the water exchange in an area. Bathymetry includes depth profiles in and around the culture area. These are usually taken with the aid of echo sounders (Bengston, 2014).

- Flow rate direction and dispersion

In the case of freshwater environments, velocity or flow of water around the cages is very important. It is vital for modeling the water exchange. It not only provides information about water oxygenation but also about how the waste from the aquaculture activity is dispersed. The decline in oxygen levels around fish cages due to the accumulation of organic matter and subsequent microbial degradation has been reported in several freshwater environments (Kirkağaç et al., 2009; Mahboobi et al., 2012). Conversely, high flow rates may cause waste resuspension and deposition to occur because of waste typically having a low critical erosion shear stress. Moreover, oxygen carried by the weak currents is insufficient to support aerobic metabolism in the sediment resulting in anoxic conditions, leading to hydrogen sulfide, ammonia and methane gas production and a dramatic decline in biomass and biodiversity (Enviornment Canada, 2009).

- Physico-chemical parameters

Information about temperature and oxygen in the water column is important for understanding the condition and the dynamics of an area. In addition, these parameters are essential for fish production. Temperature of the water body is important for optimal growth of cultured fish. In uncontrolled environments such as open cage operations, it is important to assess the suitable temperature for the proposed culture species. The use of a Secchi-disk is a well-known method for measuring the water-transparency and the colour of the water. The data generated gives information about the amount of particles in the water. The particles are either related to production in the water column (phytoplankton) or particles which come from the drainage area or sediments (sand, dust, feed) (Bengston, 2014). High turbidity means less light penetration through the water column affecting fish feeding and clogging of gills.

Phosphorous and nitrogen are linked with uneaten feed and fecal matter. These cause enrichment of the water body and the proliferation of algae, which in turn causes a depletion of oxygen levels in the water column.

- Sediment analysis

Monitoring programs based on sediment quality parameters are an effective evaluation tool to determine the environmental conditions, that is, the local impact of cage farming (Dogukan & Serap, 2017). Changes in sediment quality are observed as variations in total nitrogen, total phosphorus, total carbon, organic matter and redox potential. Photosynthesis, respiration and oxidation-reduction reaction of sulfur and iron influence redox potential and pH in marine sediments. Reducing conditions are formed through sulphate reduction, both pH and oxidation-reduction potentials decrease. The MOM environmental monitoring system uses pH, redox potential and hydrogen sulfide as primary variable to identify acceptable and non-acceptable benthic conditions associated with organic enrichment due to salmon farms (Hargrave et al., 2008). In Turkey's freshwater bodies, the MOM B-investigation, which contains methods that determine pH, redox potential, and benthic community, has been a useful way to improving the monitoring of cage farms (Dogukan & Serap, 2017).

Increased organic matter in sediment may at the initial stages increase benthic communities, however prolonged exposure gives rise to more opportunistic species. Diversity indices, such as the Shannon Index, Marine Biotic Index (MBI) and others have shown to be a good monitoring tool for assessing environmental impacts from point source pollution and cage farming operations (Borja et al., 2000; Gharibi, 2011).

The distribution and abundance of organisms, numbers of species and community structure are some of the conditions to be assessed. These parameters give a good indication of the environmental state of the area. Decrease in nematodes and crustaceans have been linked with an increase in sediment sulfides (Sutherland et al., 2007). In South African river systems for instance, the South African Scoring System (SASS) is used tool for monitoring impacts of pollution (Seanego & Moyo, 2013). The species-abundance-biomass (SAB) model (Figure 2) adopted from Pearson & Rosenberg (1978), is useful in assessing the temporal and spatial impacts of organic matter on benthic communities (Rakocinski et al., 2000). The graph represents a model of microbenthic sequence along an organic enrichment gradient. The species richness (S) and biomass (B) as well as moderate total abundance (A) are represented. A peak of opportunists (PO) represents the point along the enrichment area dominated by a few opportunistic species of relatively small body-sizes, causing a secondary biomass maximum. The point where there is a decrease in opportunistic species coincide with increase in species richness due to decrease in organic load is referred to as the (E). The transitional zone is characterized by an increase in species richness, decrease in total abundance and decreasing in organic enrichment. This zone comprises of both pollution tolerant and intolerant species. A primary peak in biomass within this region represents the point where some larger-bodied taxa respond to the bio-stimulation provided by moderate organic enrichment (Rakocinski et al., 2000). Species response has been with the used of the SAB model proven useful in predicting adverse environmental conditions associated with organic enrichment (Weisberg et al., 1997).

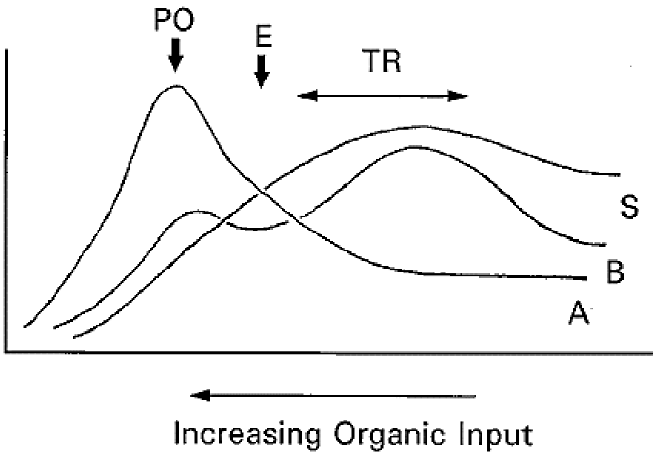

Figure 1. Graphical model of SAB responses to an organic enrichment gradient adapted from Rakocinski et al., (2000) (PO = peak of opportunists; E = ecotone point; TR = transition region; S = species richness; A = total abundance; B = total biomass)

- Escapees

Escapees can have detrimental genetic and ecological effects on wild populations. Escape incidents may increase the potential for the transfer of diseases and parasites, compromising the sustainability of aquaculture (Jensen et al., 2010). Other related issues include interbreeding and increased competition for food with the possible depletion of wild stocks.

- Heavy metals and other chemicals

Metals present either in feed, antifouling agents or equipment pose a threat to the aquatic environment. Benthic communities are affected because the residues are highly persistent. They bioaccumulate through the trophic levels and may also pose a danger when consumed by humans.

5.1.5 Management Practices

Farm management practices such as stocking density and feeding rates influence the severity of environmental impact (Carroll et al., 2003). Improper feeding practices have been outlined extensively as the major contributor to the accumulation of organic waste. Carroll et al. (2003) highlighted three management variables of importance when assessing cage culture operations.

1. Feed consumption over the last 12 months
2. Number of years in operation
3. Management techniques that allow for the recovery of site

A common practice that has been used as a means to allow the environment to recover from accumulation of organic waste is fallowing (Macleod et al., 2007; McGhie et al., 2000). An operation should be able to operate in more than one site in order for fallowing to take place, where a period of accumulation will be followed by a period of restoration. This can also be achieved through seasonal culturing. Once the production cycle ends the area is allowed to rest. The seeding of tubificid worm such as polychaetes, in organic sediment beneath cages in freshwater during the first year of operation can stimulate degradation of organic matter by allowing seepage of oxygen (Enviornment Canada, 2009). Organic waste underneath cages can also be harvested and used as organic fertilizers.

All these environmental parameters vary with their level of importance however each needs to be considered when coming up with monitoring protocols and carrying capacity model.

6 MONITORING: AN ICELANDIC PERSPECTIVE

6.1 Farm inspection

Visual inspection of farm monitoring protocols in Laxar fiskeldi ehf. in Reydarfjordur (Figure 3), East Iceland and Habrun ehf in Skutulsfjordur, Westfjords were conducted to give a practical understanding of farm operation in relation to environmental impact and monitoring.

6.1.1 Laxar Fiskeldi

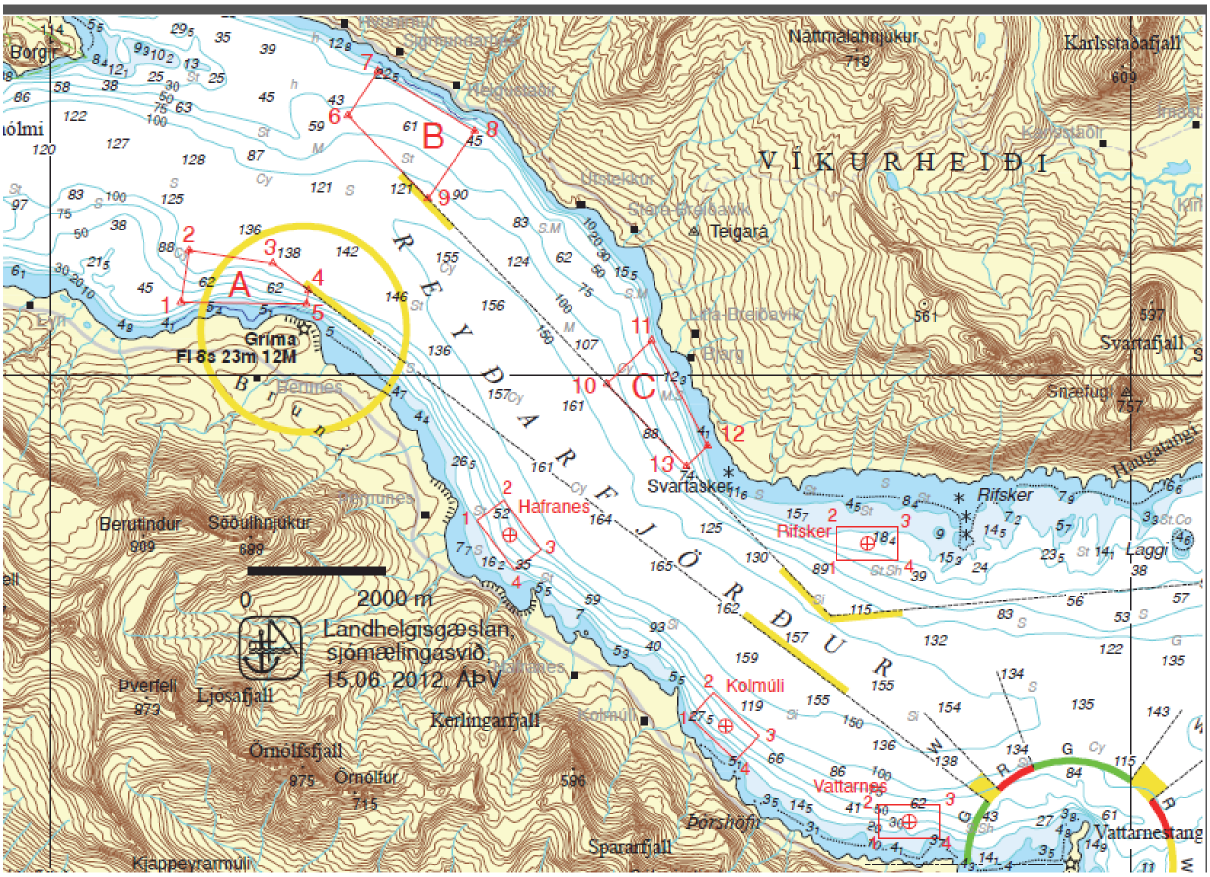

Figure 2: Laxar Fiskeldi Farm in Reydarfjordur at Gripaldi site A (Figure from farm)

Laxar Fiskeldi is an Atlantic salmon cage farm in Reydarfjordur, in the East Fjord of Iceland. It is currently in its first phase of production with an estimated production capacity of 6000 tons. About 8 surface cages are used, which are 160 m in circumference and 50 m in depth. Each cage holds 750 tons of fish. During this survey only five cages had fish. The cages are in an open sea area exposed to continuous ocean currents. At 15m depth velocities recorded are as follows; average: 6,8 cm/sec, max: 31 cm/sec and min: 0,1 cm/sec

To maintain control of the operation and allow comprehensive management, the farm uses the Fishtalk software tool. The overall farm equipment consists of plastic cages and nets, a camera system, environmental sensors, underwater lights, feed barges, feed systems and boats (Figure 4).

Feed wastage is avoided by use of an automated feeding system, while feed intake by fish can be monitored with the aid of cameras. This allows for optimum feeding. Fish are graded monthly taking a sample of ±100 fish. Growth rate of the fish through input of growth measurements into the software are used to prediction the slaughter time. It is estimated that they use 1,17 tons of feed to produce 1 ton of fish, as per the model software prediction.

Environmental data collection is done on a regular basis when weather conditions permit. Temperature sensors are constantly in water and they are integrated into the feeding system as data is transmitted wirelessly to the barge. Oxygen is also monitored on the farm. Farm nutrient release or accumulation has not been determined yet.

Mortalities are continuously inspected, and dead fish are removed from cages. The number of fish mortalities is then entered into the software. Hygienic practices are applied to prevent disease spread from one cage to the other. These include disinfection of farming equipment and removing mortalities. In instances where some a disease is found in fish in certain cages, non-disease infected are fed first and equipment are disinfected. Nets are cleaned using net cleaning equipment.

The farm plans to have a fallow period between production cycles to allow restoration of bottom sediment faunal communities. They have environmental agencies checking the farm every month or so.

Figure 3: Laxar Fiskeldi farm operation in the Ísafjördur, Iceland. a) Feeding system, b) Atlantic salmon plastic cage, c) Net for removing mortalities

6.1.2 Habrun ehf

Habrun ehf is a rainbow trout farm located in Skutulsfjordur, in Westfjords in Iceland. The farm started in 2002 farming only Atlantic cod. However, currently farms predominately Rainbow Trout (5 cages) with just a few cod (two cages). The current production capacity is 400 tons. The cages used are 90 m in circumference and 50 m depth. Like at Laxar, the cages are in an open sea area exposed to continuous ocean currents (Figure 5). The farm equipment consists of plastic cages with nets, feed containers and boats. Feeding of fish is done manually and fish are fed until they stop responding to feed. The fish are fed with pellets from Laxa hf. Eyjafjordur, which uses only natural ingredients in feed. The farm utilizes Fish Control software (now referred to as FishWise) for data input and analysis. Currently there is no equipment to detect water quality parameters, however, previous measurements were taken of oxygen and temperature. Nets are cleaned and fixed mechanically by divers. Mortalities are removed as regularly as possible.

Figure 4: Habrun ehf is rainbow trout farm located in Skutulsfjordur, in the West Fjords in Iceland

6.2 Environmental monitoring organisation

Umhverfisstofnun, the Environment Agency of Iceland based in Reykjavik has been visited to gather more information about monitoring programmes. Matvælastofnun, Icelandic Food and Veterinary Authority (MAST) which monitors and control the spread of disease cross farms has also been consulted.

6.2.1 Icelandic Food and Veterinary Authority (MAST)

MAST is an inspection and administrative body and the competent authority (CA) in Iceland in the field of food safety, animal health and welfare, control of feed, seed and fertilizers, plant health and water for human consumption. The Icelandic Act on animal welfare 2013 No 55, is a legislative framework that promotes animal welfare. The Act on animal diseases, 1993 No 25 is also used for monitoring and prevention of disease spread from farm to farm and from farmed fish to wild stocks. MAST ensures that farmers adhere to standards set in these acts.

Inspection of farms is done annually and more frequently in disease risk areas or places where disease outbreak has occurred. Farms may be categorized on a risk basis and that also determines the frequency of inspection. Farms are expected to keep records of daily farm activities. These include biomass, mortality, the cause of mortality, use of chemicals, storage of chemicals, disinfection, the quality of feed and storage details and cage cleaning frequency. Farms should comply with health and welfare regulations and have a biosecurity management protocol in place. More importantly, movement of fish should be recorded as this allows for tracing back of diseases and prevention of further spread of disease.

The nature of cage culture requires more stringent regulation to prevent deterioration of natural water bodies as the production is in direct contact with water. Use of legislation requires that cages be setup in a manner that they can withstand harsh weather conditions and sustain farming for extended periods. Avoidance of the use of heavy metals on equipment is important, copper in particular, as they accumulate in fish and affect its health. As such, the Norwegian Standards NS 9415, along with Law on fish farming no. 71/2008 and Regulation on fish farming no. 1170/2015 are strictly applied and followed.

Recent trends in consumer preference to certified products and increased market-driven certification, has put pressure on farmers to practice sustainable farming. A farm’s compliance to regulations set by certification bodies such as Global GAP (Good Aquaculture Practices), Aquaculture Stewardship Council (ASC) and many others affects their ability to enter the global market. This market trend influences farmers to improve management practice. Some of the regulations set by these institutions are more stringent than those enforced by government or their parastatals. Many of the Icelandic communities practice farming and the communities are aware of certifications and follow a similar trend of consumer preference on certificated products. Such market-related sustainable farming practices can be seen as external quality control, which proves to be beneficial particularly if a farmer's cooperation with regulatory bodies is poor.

6.2.2 Umhverfisstofnun, The Environment Agency of Iceland

The Environment Agency of Iceland promotes the sustainable use of Icelandic natural resources through the guidance of the Ministry for the Environment and Natural Resources. It also ensures that public welfare is maintained through healthy environmental conditions. The permitting process for aquaculture is rigorous and thus requires the cooperation of other governmental departments. The agency works together with MAST and Skipulagsstofnun, the Icelandic National Planning Agency, to carry out its mandatory obligations (Figure 6). The National Planning Agency is responsible for administration and implementation of the environmental impact assessments through the Environmental Impact Assessment Act (EIA). Location of cages and capacity, pollution prevention equipment, BAT (Best available technology), feeding (frequency etc), water quality, wastewater and condition of receptor, release of chemicals, displacements of cages and measures regarding leftovers of feeding, dead fish and waste are some of the fish farming permit conditions assessed through the EIA.

Environmental carrying capacity studies are carried out by the Icelandic Marine and Freshwater Research Institute (MFRI). However, the aquaculture industry in Iceland is relatively new and sedimentation distribution models commuted from Auto Depmod software are amongst some that are carried out.

Farmers are responsible for doing their own water quality analysis as per their permit requirements. Complexity of monitoring and environmental parameters varies with the scale of farm and potential environmental impact. Farmers usually make use of external experts if analysis cannot be done in-house. Farm monitoring is done based on the ISO 12878 standards. Benthic fauna monitoring is also done where species such as *Capitella capitate* and *Malacoceros fuliginosus* are used as indicators. Environmental variables assessed include, ocean currents, ocean temperature, salinity, oxygen (Redox), chemical measurements in sediments heavy metals, TOC, N, P and hydrogen sulphide in sediments, odour, colour etc. The Environmental Agency collects reports from the farms and makes an assessment. However, site inspections are conducted depending on the scale of the farm, more frequent monitoring is done when production capacity is high (Table 5)

Table 5: The frequency of control visits and control measurements for aquaculture operations in Iceland (Jonsson, 2000).

Size Category	Annual Production (tons)	Control Visit (months)	Control Measurement
I	>1000	Every 5	Every 2 years
II	200-1000	Every 12	Every 4 years
III	100-200	Every 12	Every 10 years
IV	100	Every 24	Never

The following mitigation measures (Figure 6) are taken if evidence of detrimental impacts on the environment are observed; cages are moved, and a fallowing period is allowed, the carrying capacity can be reviewed, the smolting may be delayed and the permit can be reviewed.

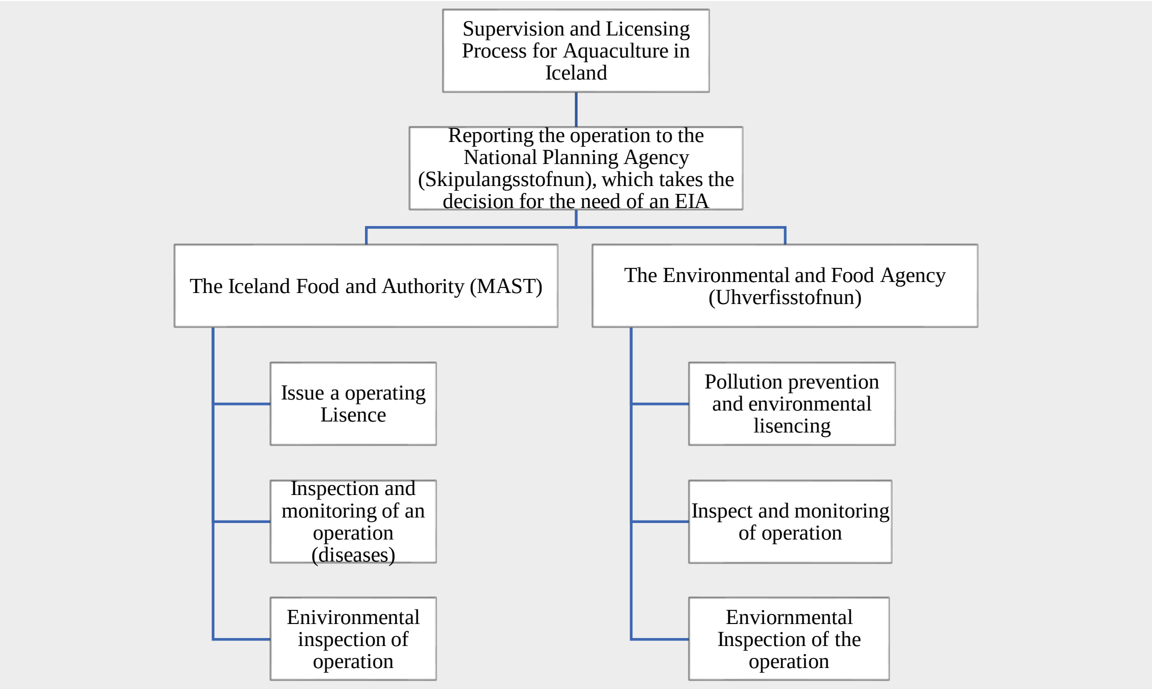

Figure 5: Aquaculture permitting process as per the Icelandic Environmental Agency Outline

7 SUMMARY OF APPLICABLE METHODS

Based on the gathered information, the below methods and procedures will serve as a guideline to possibly adress the challenges that may be encountered in South Africa. These are adaptations of other monitoring programmes.

- Determination of the phosphorus load of the waterbody using The Dillan and Riglers modification of the Vollenweider's model (1974).
- Determination of carrying capacity of the waterbody as described by Syandri et al., (2016) and Beveridge, (1984).
- Determine baseline environmental parameters
    - bathymetry
    - flow rate
    - Analytical colorimetric analysis of N and P
    - Sediment fraction analysis
    - Sediment chemical analysis (TOC, TN, TP)
- Cage installation
    - The Norwegian Standards can be used as a guide where applicable until national standards are developed.
- Farm level inspection
    - Feed composition (TN, TP)

- Stocking density
- Dissolved oxygen
- FCR
- Mortalities
- Environmental inspection
    - Water quality parameters (oxygen, temperature, N, P, TSS)
- Sediment
    - Sediment analysis done following methods by Eiríksson *et al*., (2017)
    - Organic carbon, phosphorus and nitrogen
    - BOD
    - Benthic macrofauna

8 GENERAL DISCUSSION

8.1 **Icelandic cage culture farm management and monitoring**

Through the visual inspections of farms and visitation to the environmental agencies, a general overview of the Icelandic aquaculture industry from a productive, legislative and environmental perspective was evaluated. This was further supplemented by literature obtained from the various government organisations and research publications. Laxar fiskeldi and Habrun ehf are typical Icelandic farms, with production being on a large scale and small scale respectively. One is a high-tech company while the other employs manual practices. Each has undergone a permitting process by the regulatory bodies, National Planning Agency, Food and Veterinary Authority (MAST) and the Enviroment Agency of Iceland. The potential risk of the operation, related to culture species and site-specific environmental setting to the ecosystem are assessed prior to the commencement of farming. The assessments are usually done on an individual case level.

The threshold of the ecosystem to sustain any form of activity through defined tolerance range is determined by carrying capacity models (Taylor & Kluger, 2017). This is done to minimize the environmental impacts related to farming. Additionally, it also reduces the conflicts with other users for natural resources. The environmental carrying capacity studies are carried out by the Icelandic Marine and Freshwater Research Institute. While most farms are already in process, the models used, assess impacts relating to organic sedimentation and nutrient release.

Concerning the operational setup, all cage culture operations follow the standards stipulated in Norwegian Standards NS 9415 for cage installation and operation. Once the aquaculture operation is in place, farmers employ management practices that are stipulated within the guidelines and standards set within individual permits, together with the national standards. Compliance is ensured by the regulatory bodies, MAST for disease control and Umhverfisstofnun for environmental impact (organic waste and nutrient enrichment). It has been noted that there are few regulations for continuous environmental impact monitoring

(Allison, 2012). Even with the monitoring frequency done based on farm capacity in relation to risk implications, some warning signals may be detected if more frequent monitoring, particularly of the sediment are done.

While feed waste and fecal matter are the major contributors to organic waste accumulation, the use of an automated feeding system that has cameras, such as in the case of Laxar, has been used to assist in waste reduction. The effectiveness of the system cannot however be evaluated at the moment since the farms have only been in operation for a short period. While it remains unclear of the impact posed in terms of sediment accumulation on both farms, the farms have indicated that a fallowing period will be employed for benthic restoration as a management tool. Previous studies such that of Fossfjordur in Iceland have obtained evidence of organic accumulation in salmon cage farms (Allison, 2012). In the study, it was noted that due to increased feeding rates caused by temporal changes, waste accumulated underneath the cages and anoxic conditions were noted through hydrogen sulfide production. The author also indicated that the sediment were greater than what the benthic community could decompose (1.0 g of organic carbon/m^2/day). While in Berufjordur, east Iceland organic carbon concentration has been associated with the decline in benthic communities (Eiríksson et al., 2017). This emphasizes the importance of sediment analysis in measuring temporal and spatial enviornmental changes in aquatic environments. The Environmental Agency also indicated the use of indicator based assessment, where species such as *Capitella capitate* is used as an indicator.

Certification standards by certification bodies are usually set so that farm management practices have no negative social or environmental impact. These have been useful in the regulation of goods and also ensuring sustainable farming in Iceland.

8.2 Adaptations of farm management practice and monitoring

The water bodies for potential inland cage farming in South Africa have already been identified. The suitability of sites for the preferred culture species and experimental trials are underway. While the expansion of the sector may address the socio-economic challenges within the immediate surrounding, the environmental challenges of cage culture still needs to be addressed, particularly since cage culture in the freshwater sector is still at its infancy. Based on the reviewed literature, there are several environmental implications associated with cage culture. Organic waste accumulation, oxygen reduction, hydrogen sulphide production, depletion of benthic communities and nutrient enrichment are the major indicators of environmental impacts. Conditions may be exacerbated in freshwater environments where the flow rate is lower, and eutrophication is much higher due to other pollution sources.

The capacity of unexploited water bodies to sustain aquaculture activities is determined by predictive models. Phosphorus models have been identified as most suitable for freshwater environments. Phosphorus was identified as a limiting factor and thus discharges should remain within the acceptable limits. Although it is stated that acceptable limits vary with environment and national standards, it is important that both the cultured fish and environment are not negatively affected, since both nitrogen and phosphorus are released through organic break breakdown. However, there are other factors that need to be considered because there could underestimate or overestimate the waste contribution of the farming activity. Once the capacity is estimated, it important to assess the suitability of the area, considering the targeted species requirements. The physico-chemical parameter and sediment quality are some of the factors to assess.

Organic waste accumulation influences chemical composition in the area beneath, around and up to 100 km from the farming area. An upsurge of algae occurs as a consequence of nutrient fluxes followed by decrease in oxygen levels. There are even more dire consequences affecting the benthic communities, in particular, microinvertebrates that form a fundamental part of the ecosystem. These organisms function as biological indicators of pollution. The abundance, biomass and species composition are greatly influence by sudden changes in their environment. Organic pollution give rise to opportunistic species, reduces the species composition and cause a decrease in pollution intolerant species. SAB models have been developed to monitor the impacts of accumulation on benthic communities. These can be very useful particularly if robust sediment chemical analysis cannot be done. Benthic community analysis may not provide a holistic view of the underlying environmental conditions. As such, these should be supplemented by sediment pH and redox potential. Modelling organic accumulation and benthic community structure would assist in the assessments.

Although there is a well-established macroinvertebrate monitoring tool to assess pollution impacts in South Africa, the method of sampling was designed for river systems and not large water impoundments. Limited literature if any exists on its use in such water bodies. Additionally, the community structure may vary in such low current and deep waterbodies.

Environmental conservation is not limited to fish production management only as undeveloped legislation may hinder the progressive growth of the sector. Existing laws in marine aquaculture may not fully address the challenges faced in freshwater environments. This is the case in South Africa where the standards for aquatics ecosystems do not assist in regulation of impacts associated with aquaculture. In certain instances, laws that were not originally written for aquaculture are being applied to cover management related issues, such as the control of pollution from farms and protection of sensitive habitats from aquaculture development (Taylor & Kluger, 2017).

9 RECOMMENDATIONS

Setting up a monitoring programme where water quality standards are not clearly defined or absent creates a challenge. However, in the absence of such, following international standards and also conducting research would assist. Not all the legislation that is found in marine environments is applicable in freshwater. Standards should be set on a national level to allow for thorough compliance.

Monitoring of farms is important to ensure that management practices are in compliance with standard protocols and minimize negative impacts. Therefore, monitoring of individual farms is important. Frequency of visits should be set depending on the risk-associated impact. Allowing the farmers to conduct regular analysis themselves and keeping records is useful, particularly if there is a lack of capacity within the designated department. It also allows the farmer to detect early warning signs. In cases where accumulation of waste occurs, a fallowing period should be introduced if the possibility exists for the farming operation to take place in another location. Seasonal farming also allows for the restoration of benthic communities and dissolution of nutrients. In instance where that may not be possible, physical removal of waste can be employed.

The quality of feed used and feeding practices is crucial in determining to expected environmental impacts. Thus, the quality of feed is important and studies of feed assimilation, digestion and waste dispersion maybe useful. High FCR are indicative of overfeeding, which ultimately leads to waste accumulation. It is in such instances where production models become important. To determine the extent to which feed is utilized and how much is wasted and accumulated on the cage bottoms.

The use of indicator species such as those of the Oligochaeta class maybe useful when developing a monitoring programme. They are detritus feeders and will thrive in high organic pollution areas where most species would not survive. Their abundance, biomass and diversity sever as critical measures to detect changes in environmental condition.

10 CONCLUSION

This document was created to assist in the management of cage culture operations in South African inland environment and to promote sustainable farming of aquatic animals. The methods were consolidated from various literature and observations made in Iceland and have indicated that sediment measurements are the most appropriate and useful when determining cage culture impacts on the environment. Further research needs to be done, to test the effectiveness of the methods in freshwater environments, and to standardize sampling methods and procedures that would be carried out by farmers. Practical assesment of methods would give a more viable approach to determining the type of monitoring. As the above literature only provides a structural basis on what needs to be done.

ACKNOWLEDGEMENTS

I would like to thank the UNU-FTP programme organizers for affording me the opportunity to participate in the programme. Their comments were very useful for the project. My supervisor Dr Thorleifur Eiriksson for his guidance and support. My gratitude goes to the following farms and organisations that have taken their time in providing information and also allowing me to partake in their daily activities; Manager of Habrun ehf. Farm in Skutulsfordur, Mr. David Kjartansson along with the site manager Sigurdur, Site manager of the Laxar fiskeldi ehf. farm, Gunnar Steinn Gunnarson along with his very friendly staff Kristjan Ingimarsson and Gudjon Hallodorsson who provided some of the farm figures, Sigridur Gisladottir form MAST, Gudbjorg Stella Arnadottir and Halla Einardottir from the Environmental agency of Iceland and Andreas Macrander from MRI. I would also like to extend my appreciation to my colleagues at home in the Aquaculture Department (Hlengiwe Mbanjwa and Mxhoba Jezile) for providing me with information.

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