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Impact of Cage Culture on Sediment Chemistry
A Case Study in Mjoifjordur

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ABSTRACT

Impact of Atlantic salmon (*Salmo salar*) cage culture in Mjoifjordur, Eastern Iceland on the chemistry of the sediment was investigated. Sediment samples were collected using a Shipek grab on 29.12.2003. A core sub-sample has taken from each grab for analyzing total organic matter, total organic carbon, total nitrogen and phosphorus in different depths of samples from three stations at various distances from the cage. These parameters were analyzed in the top layer of additional four stations. The results show a significant increase in all analyzed parameters in station 1, at 5 m from the cage ($P>0.05$). The difference between reference station (600 m from the cage) and station 2 at 95 m to the cage was insignificant, indicating localized impact of cage farming to the vicinity of cage ($P<0.05$). The analyzed parameters in various depth did not show a significant differences ($P<0.05$). The value of analyzed parameters in the perimeter of the cage and their differences with reference stations show small magnitude and localized impact on the chemistry of sediment. It might be due to deep water and moderate velocity of water current in this fjord. The magnitude of impact may differ during the summer season when biomass and feeding rate would be at the maximum level.

Keywords: Aquaculture, cage culture, salmon, environmental impact, sediment

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1 INTRODUCTION

Aquaculture has grown rapidly in the past two decades. Several techniques and new species have contributed to the increase in world aquaculture production from less than 10 million tons in 1989 to more than 24 million tons in 2001 (excluding aquatic plants) (FAO 2002). Cage culture, the practice of farming of aquatics in cages and nets, is widespread around the world.

Cage aquaculture is an old practice. It dates back to early 10th century when Chinese fishermen used to fatten fish fries in cages made of bamboo sticks (Beveridge 1996). However, expansion of cage aquaculture has taken place in the past three decades, particularly since the late 1980s. The growth is attributed to several factors (Eng and Tech 2002):

- High market value and demand for marine fishes
- Improvement of technology for cage culture in various oceanographic condition and going to offshore area
- Availability of suitable coastal area for cage culture around the world
- Availability of technical support and good quality input (feed, fry, etc.)

Tens of finfish species have been cultivated in various cage systems all around the world. Tilapia and carps are predominant in freshwater in Asia while salmonids are commonly farmed in Europe and America (Eng and Tech 2002). Total production of seabass and sea bream, milkfish, grouper, halibut, Atlantic cod, red drum, cobia and tuna is not comparable with the above mentioned groups (Weber 2003).

Salmon is the most important group of cage farmed species, cultivated in various environments from freshwater lakes to offshore oceanic areas. Atlantic salmon (*Salmo salar*), with annual production of more than 1 million tons has the greatest contribution (Figure 1). major part of the production comes from cage culture.

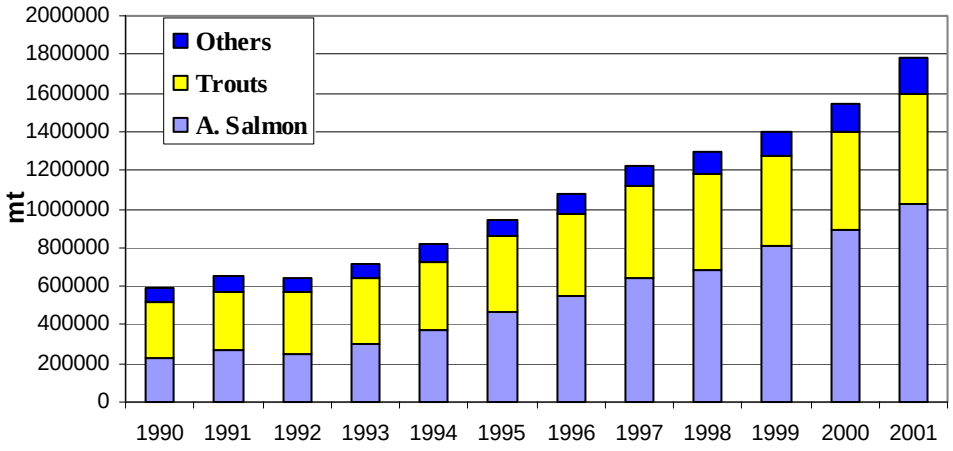

Figure 1: World production of farmed salmonid fish (FAO 2002).

Iceland is a new entry to the world of aquaculture. Atlantic salmon with annual production of some 2500 tons contributes to more than 50% of total aquaculture products of the country (FAO 2002, Figure 2). Production of cage farmed salmon is expected to reach to 40000 tons by 2005-2006 (Johansson 2001).

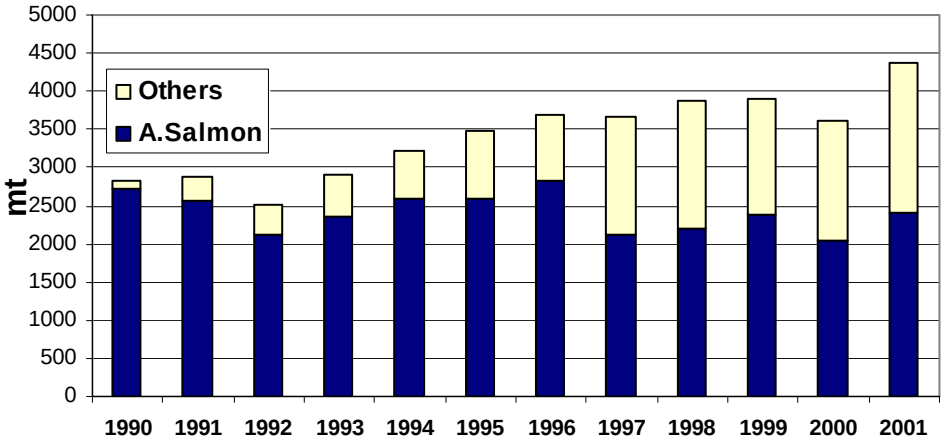

Figure 2: Aquaculture production in Iceland (FAO 2002).

On the other hand, in the I.R of Iran the annual production of aquaculture sub-sector is about 70000 tons and commercial cage culture is a new activity. Studies show that there is a good potential for development of the industry in the country. At present, a small number of companies have begun to experiment with cage culture in the Persian Gulf and Caspian Sea. The environmental impact of cage culture has been of some concern, especially the impact of waste material on the seabed and chemistry of the sediment.

The present work reviews major impacts of cage culture on the sediment with the emphasis on salmon cage culture. The findings will strengthen the personal understanding of the concepts, principles and processes of the impacts of cage culture. The case study “impact of salmon farming on sediment chemistry in Mjoifjordur (Narrow fjord), east of Iceland” provided an opportunity for both field and laboratory work, a proper approach for objective analysis of the impact.

2 REVIEW ON IMPACTS OF SALMON CAGE CULTURE

Impact of salmon aquaculture is well studied due to its expansion in developed countries or with the financial investment of developed countries in developing countries like Chile. Number of reports on environmental impact assessment of salmon cage farming in several countries are available, among them studies in Australia, Canada, Chile, Norway, United Kingdom and the United State could be pointed out (EAO 1996, Winsby *et al.* 1996, ASI 1999, Heining 2000, Nash 2001, Buschmann 2002, Crawford *et al.* 2002, SECRU 2002, Brooks and Mahnken 2003 a Carroll *et al.* 2003, Weber 2003).

Although the risks and degree of effects are site specific and may vary from place to place, all of these studies have pointed out similar risks and impacts. Nash (2001) has listed the risks of salmon cage culture in the Pacific Northwest in three major categories:

A. High risk

1. Impact of bio-deposits (fish faeces and uneaten feed) on sediment and consequent effects.
2. The impact of accumulation of heavy metals in the sediment on benthic communities.
3. The impact of therapeutic compounds on non-target organisms.

B. Low risk

1. Physiological effect of low dissolved oxygen levels in the water column.
2. Toxic effect of H_2S and ammonia from bio-deposit.
3. Toxic effects of algal bloom.
4. Changes in epifaunal communities in the seabed.
5. Proliferation of human pathogens in the aquatic environment.
6. Proliferation of fish and shellfish pathogens in the aquatic environment.
7. Increase in incidences of disease among wild fish.
8. Displacement of wild salmon in the marketplace by farmed salmonids.

C. Little or no risk

1. Escape of non-native species and subsequent effects on endemic salmon and trout species.
2. Impact of antibiotic resistance bacteria on native salmonids.
3. Impact on human health and safety.

Other studies did not present such a straight ordering of risks. However, they concur with Nash (2001) to some extent. The main difference lies in the last group of risks, particularly with regard to escaped fish and its potential effects on wild stocks.

EAO (1996) in a comprehensive survey has presented impacts of salmon culture in the region. In the list of risks of the industry, organic overloading of sediments and consequential impacts on benthic biota is deemed to be of the greatest importance. Meanwhile, effects on water chemistry and eutrophication have been identified as moderate or low risk impacts. Winsby *et al.* (1996) in a complementary review concluded that waste material from farms bring about highly important effects on physical and chemical properties of British Colombia's marine ecosystems. The sediment and benthic

communities near salmon cages receive the major impacts of the activity. Other impacts such as those associated with escapees either have lower priorities or need further evaluation. ASI (1999) in a short review on cage farming elicited general impacts of cage aquaculture on environment with emphasize on water pollution [eutrophication] and living organisms in the water column. However, risk or magnitude of predicted impacts was not presented. The field survey of environmental impact of Chilean salmon farming in lakes and coastal water ecosystems, has underlined the impacts on water and sediment chemistry and benthic community (Buschmann 2002). Heining (2000) gave a review on effects of salmon aquaculture in Maine, USA. He has focused on difficulties of standardization of the activity in order to decrease impacts on environment.

In an extensive review of environmental impact of aquaculture in Scotland, it was concluded that impact on seabed is the most obvious pollution effect from fish farms, and the particulate organic waste has a profound effect on the benthic environment. Other impacts, for instance eutrophication and algal blooms were given a low risk value, while escape of farmed fish has considered as a high risk impact (SECRU 2002). Carroll *et al.* (2003) presented the result of analysis of 168 sediment samples taken in the vicinity of Norwegian salmon cages. They reported a heavy impact of organic waste materials from the farms. This agree with a review by Weber (2003) on the impact of carnivorous fish farming who stressed on effects of aquaculture wastes on water and sediment quality. Brooks and Mahnken (2003a) have recently published the results of a long term study on impacts of salmon cage farming in the United States. They reported major impacts of organic waste materials, in particular causing seabed deterioration and chemical changes in the sediment. The most common, high risk impact cited in the literature is the effect of waste material on ecosystem components, particularly the sediment and the effects on benthic fauna and flora, which will be discussed in detail in the next chapter.

2.1 Waste materials in salmon cage culture and their environmental

The procedure of salmon cage culture is almost similar all around the world. The major inputs directly involved in farming process are feed, juvenile, chemicals and drugs. Dead fish, residuals of chemicals, uneaten feed and fish faeces are various types of waste coming from salmon farms, which enter the ecosystem in solid and/or dissolved form.

2.1.1 Solid waste

Uneaten feed and faecal pellets are the major sources of suspended solids in cage culture of Atlantic salmon and other finfish (EAO 1996, Winsby *et al.* 1996 and Nash 2001). Solid waste is dispersed through either the water column or it accumulates on the seabed (EAO 1996, Winsby *et al.* 1996 and Nash 2001) and /or wild fish may feed on it (Barg 1992). The quality and quantity of sediments and the rate of sedimentation - in terms of organic matters content - varies depending on several factors.

- **Quality of solids:**

Quality of solid waste is strongly correlated to feed quality (EAO 1996, Nash 2001, Chen *et al.* 1999 and 2003). Feed composition varies depending on various factors such as

nutritional requirements, life stage of the animal, fish health and environmental conditions, and level of applied technology for feed production. Digestibility of feed influences the quality of the solid waste as well.

Salmon feed has high level protein content and may contain up to 50% protein, 35% lipids and 30% carbohydrates depending on diet formulation (Winsby *et al.* 1996, Nash 2001 and Crawford *et al.* 2002). That means the diet feed may have up to 8.5% nitrogen, 2% phosphorus and 30-50% carbon. Protein content in recent feeds, produced by new technologies has decreased to less than 40% and the amount of nitrogen and phosphorus is significantly lower than in older formulated feed, even less than 6.5% and 1% respectively (EAO 1996, Winsby *et al.* 1996, SECRU 2003).

The quality of faecal material is quiet different from the feed particles in terms of energy, organic matters contents and degradation rate (Chen *et al.* 1999, 2003, Pearson and Black 2001, Nash 2001). Higher digestibility of feed brings about less faecal matter and N and C waste. Digestibility of high quality salmon feed is around 87 - 88%. In low quality feed, 25-33% of feed may eject as faeces (Nash 2001).

High energy feeds are more environmental friendly due to lower carbon and nitrogen contents of faecal matter. Chen *et al.* (2000) showed that high energy (lipid) feed of Atlantic salmon reduces the carbon and nitrogen content of faeces by 12 and 8% respectively in comparison with standard feed. It might be due to higher digestibility of high energy diet. Nitrogen and carbon contents of Atlantic salmon's faeces are 2.3- 3.7% and 27- 32% respectively, depending on feed quality (Chen *et al.* 1999,. 2003). In Tasmania, high protein (45%) feed containing relatively high level of nitrogen (8.13%) and carbon (~ 45%) have produced faeces containing 3.9-4.9% N and 31.8-40.3% C (Crawford *et al.* 2002). Einen *et al* 1995, has reported 15% and 66% loss of nitrogen and phosphorus of feed in faeces of, respectively (EAO 1996).

- **Quantity of solids:**

Physical properties of feed, farming systems and management practices, scale of activity and growth rate of fish influence the quantity of solid waste.

Stability of feed in water is an important factor in feed wastage. In wet feed, the stability is lower than in dry feed. On the other hand, sinking rate of wet feeds is usually less than dry ones. It gives fish more chance to feed on feed particles (EAO 1996, Nash 2001). Stability, sinking rate and dust level of dry feeds vary with production technology (Winsby *et al.* 1996).

Feeding rate in a cage farms, like land based cultures, is usually according to feeding tables provided by feed producers. Precise estimates of average body weight and survival rate of fish are of great importance in evaluating daily feed requirements. Feeding rate should be modified according to fish and environmental conditions (in particular temperature) in order to prevent overfeeding. Due to feed adjustment, a seasonal variation in sedimentation rate is observed in cage farming of Atlantic salmon. Feeding in excess

of sufficient level or any condition where the animal can not feed efficiently will increase the quantity of waste materials.

A practical approach for adjustment of daily feed in cage culture is video monitoring, which is becoming increasingly common in large, modern farms of Atlantic salmon in many countries.

Feed is always associated with some losses. In manual feeding loss of feed is 3.6%, which is significantly lower than automatic feeding with 8.8% wastage. Hand feeding permits the farmers to evaluate the feeding behavior of fish and prevents excess feeding (EAO 1996, Nash 2001).High loss in automatic feeding is correlated to feed abrasion and overfeeding. Some producers of modern feeders declare that their products decrease feeding waste to less than 0.5% (Nash 2001).

Stocking density has great impact on growth rate. Feed conversion ratio (FCR: applied feed (Kg)/ fish weight gained (kg)) in intensive culture is higher than in low density farms (ASI 1999, Tacon and Forster 2003). Therefore, the risk of deterioration of the environment in high density farms would be higher.

The amount of uneaten feed in Atlantic salmon cage farming varies from 1% in dry feed up to more than 30% in wet feeds (Barg 1992, EAO 1996, Winsby *et al.* 1996, Pearson and Black 2001, Nash 2001). Nowadays, Atlantic salmon farmers mostly use dry feed at the grow out stage. Average loss of good quality salmon feeds produced by new technologies is as low as 5% (EAO 1996, Winsby *et al.* 1996, Pearson and Black 2001, Nash 2001, SECRU 2002).

FCR is a reliable indicator, which integrates all farming condition into a quantitative scale. During the past 3 decades, FCR in salmon farms has declined significantly from 2.5 in 1974 to 1.0 to 1.2 in recent years (EAO 1996, Pearson and Black 2001).Lower FCR means less input of organic matter and consequently less waste. Holmer *et al.* (2002) found a general increase of sedimentation rate and total organic carbon and nitrogen of deposited materials with the increased input of fish feed.

Based on quantitative and qualitative criteria of solid waste, it might be concluded that 0.186 kg of solid waste will remain for every kilogram of fish produced by using modern dry feed and implementation of good management practices in the farm (Table 1). This amount is approximately 40% less than estimated waste in salmon cage farming in British Colombia in 1995 (Nash 2001). Progress in both feed quality and feeding management are essential to decrease waste.

Debris released by net cleaning originated from bio-fouling, as mussels, barnacles, ascidians, bryozoans and seaweeds sited on the nets could also be a source of solid wastes (GESAMP 1991, Nash 2001, Weber 2003).

Table 1: Mean contents of organic material in feed and waste solids in Atlantic salmon cage farming (based on average quantity and quality of solid wastes in a salmon cage farm, FCR=1.1)

	Carbon	Nitrogen	Phosphorus
Mean content in feed (%)	40	7.5	1
Mean content in eaten feed(95%) g /kg fish	418	78.4	10.45
Mean content in faeces (%)	30	3	5.3
Mean content in faeces(12.5%) g /kg fish	39.19	3.92	6.9
Mean content in uneaten feed (%)	40	7.5	1
Mean content in uneaten feed (5%) g/kg fish	2.75	0.52	0.07
Total solid waste produced g/kg fish	41.9	4.4	7

As net cleaning is a periodic activity (once a year or every two years) or nets will be cleaned on land, bio-fouling is considered a low risk source of impact. Fish mortality is another minor source of solid material. It is estimated that in 1994 some 2000 tons of salmon died in British Colombia's cages, approximately 9% of total harvested biomass (EAO 1996,). Usually dead fish are collected and disposed of on land (Nash 2001), Otherwise, it would be a significant source of pollution.

- **Sedimentation rate and spatial dispersion of solid wastes**

Horizontal distribution of a solid particles in seawater is a function of depth, water current and sinking rate of particles. On this base a simple model has developed for spatial dispersion of solid wastes of finfish aquaculture (Silveret and Cromey 2001, Barg 1992):

$$D = V \cdot d / v$$

***Where**: "D" = spatial dispersion (m),"V"= current velocity (ms^{-1}), "d"= depth of water (m) and "v" = sinking rate of particle (ms^{-1}).*

Depth of water and sinking rate determine available time for particle transfer by currents. Density and size of the solids influence settling velocity of particles. Sinking rate of a larger salmon feed pellet (10 mm) is approximately two times of smaller one (6 mm) (Chen *et al.* 1999).The correlation between velocity and size of faecal pellet is insignificant. Chen *et al.* (1999) concluded that sinking rate of faecal pellet of Atlantic salmon is 5.3 -6.6 cms^{-1}, while feed particles settle at the speed of 6-14 cms^{-1} depending on salinity and temperature.

Elberizon and Kelly (1998) have investigated the sinking rate of solid waste of fresh water trout feed in the laboratory. The estimated sinking speed of particles bigger than 2000 micron and between 500- 1000 micron were 0.029± 0.01 ms^{-1} and 0.015± 0.01 ms^{-1} respectively. Wong and Piedrahita (2000) reported that the sinking rate of manually stripped faecal matter of rainbow trout is 0.7 cms^{-1} and it will change with current velocity. Topography of the seabed affects the spatial deposition of the waste. Waste material will be transport further, where the bottom is steep than where it is more flat

(Winsby *et al.* 1996). Rocks and deep dips in the seabed change sedimentation patterns as well (Pearson and Black 2001).

Gowen and Bradbury (1987) estimated the organic sedimentation rate to be 27.4 $gm^{-2}day^{-1}$ under Irish salmon farms and of 8.2 $gm^{-2}day^{-1}$ at on average the cage perimeter. Morrisey *et al.*(2000) reported that underneath the New Zealand's salmon cages the sedimentation rate of total volatile solids (TVS) is between 8.84 and 18.5 $m^{-2}day^{-1}$ (Brooks *et al.* 2003a).

In a review, EAO (1966) reported that in the state of Maine, USA, 5-11% of solid wastes actually settled. Gowen *et al* (1991) cited. Particles may loss some nutrients during sinking period. Chen *et al.* (2003) showed that Atlantic salmon faecal pellets lost 4-14% of carbon and 9 - 16% of nitrogen in the first 2.5 minutes of sinking. After 5 minutes, the leaching of carbon and nitrogen had increases to 22% and 24%, respectively. Leaching of nutrients increases dissolved organic material and decreases organic load of deposited solids. Therefore, in deep water bodies waste material will lose more nutrients than in shallower ones. It will increase risk of sediment enrichment in shallow ecosystems. Changes in nutrient contents should be considered in theoretical calculation when laboratory experiments are used to quantify degree of enrichment.

- **Environmental impact of solid wastes**

Environmental impact of sedimentation of salmon cage farming is mostly limited to within 50 meters of the perimeter of the cage (Barg 1992, EAO 1996, Winsby *et al.* 1996, ASI 1999, Pearson and Black 2001, Nash 2001, Carroll *et al.* 2003). At further distances footprint of organic waste will become insignificant. Hall *et al.* (1992) found that sedimentation of nitrogen and carbon at 200 meter from the farm was 10 and 22 times lower than below the cage, respectively (ASI 1999). Less severe environmental effects may be spread over a large area (Carroll *et al.* 2003). Sara *et al*. (2004) found small traces of marked nitrogen ($\delta^{14}N$) at 1000 m from the cage. It is reported that waste deposition is limited to 1 km of the cage operation (ASI 1999).

- ***Effects on Sediments***

Sedimentation results in physico-chemical changes in seabed substrate and overlaying water on sea bottom. The magnitude of environmental impacts is site and farm specific (Winsby *et al.* 1996). Major changes associated with sedimentation may classified into physical, geo- and biochemical, and biological effects.

- **Physical changes:**

Changes in sediment particle size and texture are the most common physical changes due to solid waste deposition.
During farm operations, a fine, flocculent layer or organic material will overlay the natural substrate (EAO 1996, Winsby *et al.* 1996). The color of this layer ranges from

greenish to black (EAO 1996) and its thickness is different depending on sedimentation rate and the horizontal transportation model of particles. According to this model, lighter bio-deposit (faecal material, in particular) would be settling in a more distant area. Re-suspension and displacement of the sediment due to tidal turbulence, wind driven currents and storms may change this pattern (EAO 1996, Winsby *et al.* 1996).

- **Sediment geochemistry**

◆ Organic carbon

Increased organic carbon concentration in the sediments is a common effect of cage culture. Hargrave *et al* (1997) found that total organic carbon under salmon cages in Atlantic Canada was 40% higher than at reference sites. He and his co-workers reported in 1993 that the carbon accumulation rate under salmon cage culture ranges from 17 to 35 molC $m^{-2}day^{-1}$. In a recent study in Maine, US, TOC sedimentation was found to be 1.0 to 1.6 $gm^{-2}day^{-1}$ (Green *et al.* 2002). Accumulation of carbon depends on the composition and quantity of waste material, sedimentation rate and site characteristics (EAO 1996, Winsby *et al.* 1996, Crawford *et al.* 2002) and is estimated at 18 to 23% of the input in cage farming (ASI 1999). Deposition rates for optimal selected sites for fish cage in British Colombia ranged between 7 to 13 $gCm^{-2}day^{-1}$ or 50 to 10 $kgm^{-2}year^{-1}$ (EAO 1996). Therefore, organic carbon could be indicative for impact assessment of cage culture, in particular where sediments are heavily impacted. Low input of carbon could be consumed by the sediment inhabitants and would not be reflected in any significant changes in TOC (Pearson and Black 2001, Crawford *et al.* 2002).

◆ Oxygen concentration and redox potential

Oxygen supply to the sediments is by diffusion from the water column and by mechanical infusion of water into sediments where it will be consumed through respiration of living organisms or through chemical oxidation in sediments. Bioturbation increases gas exchange between water and sediments and supply of oxygen to the sediments as well (EAO 1996, Brooks *et al.* 2003a). Accumulation of organic matter in sediments increases both biological and chemical oxygen demands (BOD & COD) (Brooks *et al.* 2003a). Increase of BOD is predominantly due to aerobic, heterotrophic bacterial activity (EAO 1996). Oxygen uptake by sediments under different Danish fish farms was 5 to 15 times higher than at control sites (Winsby *et al.* 1996). ASI (1999) indicated that due to biological activities, demand for oxygen in sediment underneath the cages was 2 to 5 times higher than at control site. High demand is dominantly due to increase of biological demands. In contrast, Hargrave *et al.* (1993) indicated that BOD represents only 20% of total oxygen demand. For heavily affected sediments, BOD may reach $400mgm^{-2}hr^{-1}$. Contribution of biological demand may depend on size of animals and availability of oxygen in the sediment. Small animals are more metabolically active per unit of biomass than large ones. Nickell *et al*. (2003) found oxygen uptake beneath a salmon cage in Loch Creran, Scotland was 434.9± 139.7 $mmolm^{-2}day^{-1}$, where oxygen was available because of deep-water currents.

While oxygen demand is equal to influx of oxygen, the sediments have the capacity to assimilate organic matter (Brooks *et al.* 2003a) and its productivity will increase (Pearson and Black 2001). If demand for oxygen exceeds the oxygen diffusion rate, sediments become anoxic and anaerobic processes will predominate (Redox Discontinuity Level, RDL). In this condition, anaerobic bacterial activity increases which are including three types of bacterial metabolisms, nitrate reduction, sulfate reduction and methanogensis (EAO 1996). *Beggiatoa spp.* is commonly found in sulfade reduction level, as it needs H_2S and a little oxygen, which it gets from overlaying water. White colored mat of bacterial excreted mucus is visible in this layer (EAO 1996, Pearson and Black 2001, Brooks *et al.* 2003a). Dark color of sediments is due to interaction of iron and sulfade and production of iron sulfade (Brooks *et al.* 2003a). Organic enrichment and microbiological process in the sediment could be summarized as follows (EAO 1996, Pearson and Black 2001, Brooks *et al.* 2003a):

- Aerobic respiration, ammonium oxidation (to nitrite) and nitrite oxidation to nitrate. Sediments are in oxic condition.
- Denitrification (production of N_2 from nitrate by aerobic bacteria).
- Nitrogen reduction (producing ammonium from nitrate) and manganese reduction. Release of ammonium from the sediment under cages may range from 0.5 to 13 $mmolm^{-2}hr^{-1}$ (Winsby *et al.* 1996).
- Iron reduction.
- Sulfate reduction and production of H_2S. The sediment is anaerobic/ aerobic.
- Methanogensis, producing of methane by fermentative bacteria. The sediment is extremely anoxic.

In extreme anoxic condition outgasing of carbon dioxide, hydrogen sulfide and methane would occur. The gas bubbles contain about 70% methane, 28% CO_2 and 2% H_2S (EAO 1996, Nash 2001). The latter one is toxic to fauna and flora (Nash 2001). It is highly soluble in seawater and quickly breaks downs in the presence of oxygen (EAO 1996, Winsby *et al.* 1996). It has been found that H_2S concentration dropped from 17000 ppm at the seabed to 20ppm at 9m above the bottom (EAO 1996, Winsby *et al.* 1996, Pearson and Black 2001). Bacteria contributes substantially in sulfate reduction. Desulfovibrio and desulfomaculum are two major sulfate reduction bacteria found in sediments underneath fish cages (EAO 1996, Winsby *et al.* 1996, Pearson and Black 2001).

This process is the usual trend in cage farming system. Where, as deposition of waste material continues oxygen demand increases and the sediment eventually enter an anoxic phase and the impacts will be visible as biological changes. Decrease in input of waste material from the farm or a resting period (fallowing) in between production seasons will postpone the anaerobic phase in the sediment. Oxidation-reduction potential (Redox potential) of sediment has been identified as a suitable indicator of organic accumulation in sediments (EAO 1996, Pearson and Black 2001, Crawford *et al.* 2002) representing oxygen demand (Telfer and Robinson 2003). Redox level is strongly correlated with sediment grain size (EAO 1996, Winsby *et al.* 1996). In coarse sediments, redox potential will be higher than in fine ones because of higher diffusion rate of oxygen into the

sediment. Karakassis *et al.* (2000) have observed this correlation in impact of cage farming in the Mediterranean.

A positive redox indicates that some oxygen is still in the sediments (EAO 1996). In undisturbed sediments, surface Eh is about 300 to 400 mV. (Winsby *et al.* 1996). Negative redox potential value (Eh) is generally indicative of organic matter enriched, fine size grains and/or poorly oxygenated, anoxic sediments (Winsby *et al.* 1996). The maximum acceptable level of redox in a profile of a core sample from salmon cages in Scotland is less than -150mV. The Eh should not be lower than -125mV at 0-3 cm depth of sediments (Heining 2000). Eh -150mV is indicative of anaerobic conditions in many salmon cage farms (EAO 1996). Figure 3 elicits the correlation between bio- and geochemical changes within the sediments.

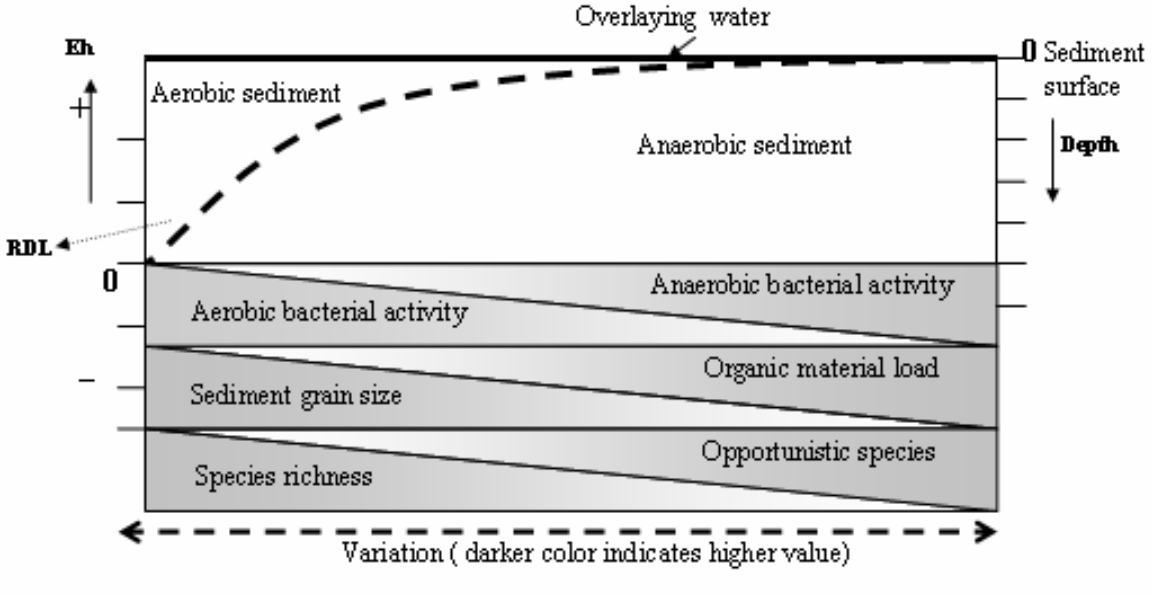

Figure 3: Diagram of geochemical and biological changes in sediments

- Biological Impacts

Natural input of organic matter provides conditions for various groups of organisms in/on sea bottom, such as macroalgae and benthic algae, bacteria, meiofauna (8 to 500 µ invertebrates) and macrofauna (larger than 500µ invertebrates). As input of detritus increases, it will impose some changes on the biological characteristics of the habitat. These changes are site specific. However, typical process of impact and modification is as following (EAO 1996, Pearson and Black 2001):

a. Normal , unpolluted environment with no impacts :
   Number of species (species richness) is high
   Density is moderately low
   Species mostly belong to higher taxa with larger body size and of high functional type

There are no or few opportunistic species

b. Slightly enriched with low impacts:
   - Biodiversity increases
   - Density increases
   - Some mobile epifauna and demersal fish immigrate to the disturbed area
   - Number of opportunistic species increase

c. Moderately enriched with moderate impacts:
   - Decrease in biodiversity
   - Decrease in larger body size animals (macrofauna and meiofauna)
   - Elimination of non-specified species
   - Presence of opportunistic meiofauna

d. Highly enriched with sever impacts on sediment and overlaying water:
   - Elimination of all macrofauna
   - Presence of small meiofauna
   - Elimination of infaunal metazoans
   - Abundance of *Capitella capitata spp.*

Changes in benthos communities depend on the geochemistry of the sediments. Karakassis *et al.* (2000) found that in coarse sediment with high redox the impact on fauna is less than in fine sediments.

As a general trend, larger and infaunal animals start to disappear at first, when sediments become too enriched. In anaerobic condition, smaller species, which live close to sediment-water interface, will exist and in extremely enriched sediments, almost all life disappears from the sediment habitat and only a limited number of well-adopted species can survive. Mazzola *et al.* (2000) Reported that 75% of total number of organisms under fish cage inhabited the top 1 cm layer of the sediments. Kempf *et al.* (2002) studied bio- and geochemistry of sediments under brown trout cage in a well-flushed marine site in the English Channel. They found a reduction in the number of species, an increased in migration of mobile fauna (like scavengers and carnivorous invertebrates) with mean biomass of 11.4 gm^{-2}. Small bivalves, crustaceans and polychaetes contributed 36%, 26% and 14% to the total biomass. Few invertebrates were found. Based on the slight changes in the geochemistry of the sediment, they concluded that the seabed was slightly enriched and the farm had little impact on the seabed. Pearson and Black (2001) reported that production of infaunal benthos close to a cage to be 4- 6 times the background level, causing a 50% increase in epibenthic predator productivity.

Table 2 shows list of species, which are generally found in various levels of sediment contamination. Although there are some specific organisms or groups of organisms associated with particular level of enrichment, there is no universal indicator for moderate to low levels of impacts. *Capitella capitata Sp.* (an opportunistic polychaete) is a worldwide indicator of highly enriched, anaerobic, heavily impacted sediments under fish cages (EAO 1996, Pearson and Black 2001, Crawford *et al.* 2002). Sulfide concentrations between 100 and 1000 mmol is optimal for *Capitella Spp.* (Macleod *et al.* 2002). Under these conditions the animal grows well and it may be get 3 to 5 times larger than in undisturbed sediments (EAO 1996).

Table 2: Descriptive model of benthic faunal succession during sediment recovery from loading with fish farm wastes (Pearson and Black 2001)

Degree of enrichment	Highly enriched	Moderately enriched	Lightly Enriched	Normal
Characteristic species	*Capitella capittata* *Malacocerous fuliginatus* *Nematoda* *Ophryotrocoda sp.* *Pseudoploydora paucibranchiata*	*Apistobranchus tullibergi* *Spio decorata* *Mediomastus fuliginitus* *Protodervillea keferesteini* *Microspio sp.* *Prionospio fallax* *Cossura sp.* *Caulleriella sp.* *Meinna palmata* *Poloe inornata*	*Scoloplos sp.* *Thyasira ferruginea* *Diplocirrus glaucus* *Sphaerosyllis tetralix* *Abra alba* *Glycera alba* *Lepthognatia brevirostris*	*Glycera alba* *Migga wahbergi* *Ophelina sp.* *Perugia caeca* *Synelmis Klatti* *Owenia fusiform* *Magelona sp.* *Eumida sp.* *Lanice conchilega* *Amphiura filiformis*

Considering the spatial distribution of organic wasted from fish cages, a gradient of enrichment and impacts may be observed in the farming site. EAO (1996) reported such zoning in salmon cage culture, where there is an azoic zone underneath the cage (D), highly enriched zone from cage edge to 8m distance (C), slightly enriched area in 8 to 25m distance (B) and normal zone beyond 25m with no significant impacts (A). The zoning is site and farm management specific and it will alter depending on hydrography, topography, etc. Karakassis *et al.* (2000) have not observed the azoic zone underneath the fish cages in the Mediterranean.

Any farming activity that increases waste materials will be promoting azoic conditions in the sediment. In contrast, water currents may disperse or carry away waste particles and decrease the risk of anoxic conditions. In an area with high assimilative capacity, the risk of creation of azoic zone would be lower. This indicates the importance of site selection.

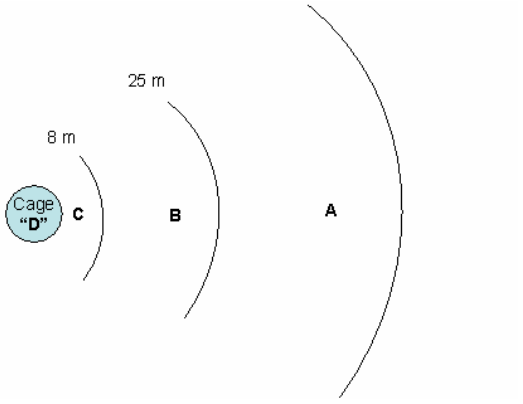

Figure 4: Zoning of organic enrichment and spatial impact of fish cage culture

2.1.2 Dissolved waste

Soluble nutrients in feed and faeces (EAO 1996, ASI 1999, Chen *et al.* 1999, Nash 2001, Pawar *et al.* 2002), fish respiration and metabolites and re-released nutrients from the sedimented wastes (EAO 1996, ASI 1999, Nash 2001) are major sources of dissolved nutrients from cage farming. Residuals of chemicals used for maintenance of nets and other physical structures in the farms, chemotherapeutics and additives in the feed might be considered as the second group of dissolved waste materials. Fertilizers are rarely used and only in extensive and herbivorous fish farms.

- **Nutrients**

- ***Phosphorus***

A large proportion of phosphorus in the feed is released into the environment, ranging from 66% to 88% in salmon cage. It is estimated that for every kilogram of salmon produced 7.8 to 12.2 grams of phosphorus are released into the marine environment, (EAO 1996, Nordrum *et al* 1997, ASI 1999, Rouhonen *et al.* 1999, Storebakken *et al.* 2000, Nash 2001).That means only a little amount of phosphorus is retained in fish.
Contribution of dissolved wasted phosphorous in salmon cage culture varies from 15% to 85% of total phosphorous in feed depending on feed quality, size of fish and also experiment condition. (ASI 1999, Nash 2001). Storebakken *et al.* 2000, Sumagaysay and Chavoso (2003) in their study on feeding of milkfish (*Chanos chanos*) found that excretion of nitrogen, phosphorus and digestibility of feed depended on feed quality and fish weight. Excretion of phosphorus in small fish was higher than big ones, ranging from 1.2 to 3.2 mmol PO_4-$Pkg^{-1}day^{-1}$. Guo and Li (2003), reported that for every kilogram of fish 35 g (89%) of feed's phosphorus was lost in cage polyculture of mandarin fish (Siniperca *chuatsi*), freshwater bream (*Megalobrama amblycephala*) and catfish (*Ictalurus punctatus*) fed on dry and fresh feeds.

Fish excrete soluble, inorganic phosphorus via urine (Green *et al.* 2002). Atlantic salmon urine 3-6 hours after feeding is estimated 234-255 μlkg^{-1} containing $1mmoll^{-1}$ of inorganic phosphate (Roy and Lall 2004). In anoxic conditions, the sediment releases phosphorus to the water (EAO 1996, ASI 1999). Following a period of anoxia, an 18% increase in dissolved phosphorus in freshwater lake is reported (ASI 1999). Re-release of phosphorus in anoxic conditions from deposition zone of cage farming is 7 mmol PO_4-$Pm^{-2}day^{-1}$. This is 2.5 to 5 times more than from oxic sediments in undisturbed substrate (EAO 1996).

- ***Nitrogen***

Total nitrogen loss in fish cage culture ranges from 72% to 79% of input (ASI 1999). Ruohonen and co-workers (1999) estimated that for every kilogram of Atlantic salmon produced, 53.4 to 68g of nitrogen were released. Storebakken *et al.* (2000) found in 200g

Atlantic salmon the nitrogen loss was 54% of total nitrogen intake. Some 82% of the waste was excreted in soluble form.

Ammonia and ammonium are the most common types of nitrogen waste which may include 65% to 90% of total nitrogen loss in fish, which is mainly in un-ionized form (EAO 1996, ASI 1999, Storebakken *et al.* 2000).Salmon fish excretes metabolites via gills and urine (Rouhonen *et al.* 1999). Sockeye salmon (*Oncorhynchus nerka*) excretes 8.2 (min.) to 35 (max.) mg N $kg^{-1}h^{-1}$. Urine excretion is relatively constant at 2.2mgN kg^{-1} (EAO 1996, Nash 2001). Total ammonia nitrogen excreted from the milkfish under laboratory condition varied from 333 in small fish to 60.8 $mgkg^{-1}day^{-1}$ in bigger individuals and was affected by quality of feed (Sumagasay and Chavoso 2003).

Re-release of nitrogen from bio-deposits in sediments is negligible. The amount of ammonium and ammonia entering the water column from mineralization is very little. Release of ammonium from Norwegian salmon farms ranges from 0.5 to 13 mmol NH_4-$Nm^{-2}day^{-1}$ and may exceed of 62mmol NH_4-$Nday^{-1}m^{-2}$ depending on management practices and environmental conditions (EAO 1996, Winsby *et al.* 1996).

- ***Impact of nutrient***

o **Water enrichment and phytoplankton growth**

Light, nutrients (phosphorus and nitrogen), temperature and salinity are the most important parameters affecting the growth of algae. Aquaculture effluents usually carry high concentration of nutrients. In freshwater systems, where phosphorus is a limiting factor (EAO 1996, ASI 1999), aquaculture discharges will increase phytoplankton. Diaz *et al.* (2001) concluded that an increase in density and biomass of phytoplankton in a freshwater reservoir, Alicura, Argentina was correlated to phosphorus originating from salmon cages and natural inputs. In contrast, Buschmann (2002) did not report any increase in abundance of phytoplankton in southern lakes of Chile.

N:P ratio of 16:1 is required for optimal growth of phytoplankton (Burford and Rothlisberg 1999). Phosphorus is generally available in a marine environment in high concentrations and nitrogen controls the growth of phytoplankton. Nitrogen in the form of ammonia and ammonium. (common types of nitrogen in salmon cage sewage) is readily available for uptake by phytoplankton (Winsby *et al.* 1996, ASI 1999, Nash 2001). Since the denitrification process is often slow in cage farming areas, it can promote phytoplankton growth (ASI 1999). However, significant increases in nitrogen and consequent algal blooms can take place in areas of poor flushing. In fact, concentration of dissolved inorganic nitrogen is very low at the perimeter of cages and nitrogen will be diluted to an undetectable level at distances greater than 9 meters from the perimeter (Nash 2001).
On the other hand, ammonium is released into the upper layers of the water column while phosphorus is largely remineralized in anoxic sediments below the cage and it will be

released during winter or fall turnovers, reducing the chance of proper nutrient ratio and environmental condition for rapid growth of the phytoplankton (EAO 1996, Winsby *et al.* 1996). In high latitude areas where salmon farming is most common, light would be a limiting factor for phytoplankton growth in the deeper layers. In addition, cloudiness reduces the light intensity as well (Nash 2001).

The rule of currents in reducing phytoplankton bloom in cage culture areas is well understood. At 10-15°C, it takes 1-2 days for algal cells to reproduce. In algal blooms, cell density increases from a few thousand to more than million cells per liter. It will take eight to nine generations requiring 8 to 16 days. In an open water body with current velocity of 2 cms^{-1} - like most of the coastal area- algal cells will move on 14 km in this period, while nitrogen will be diluted with in a few tens of meters from the cage. (Nash and Nahnken 2001, Brooks 2003a) Burford and Rothlisberg (1999) did not find a correlation between nutrient concentrations and chlorophyll *a* in the Gulf of Carpenteria, a tropical continental shelf ecosystem. Addition of nitrogen, phosphorus and silicate to water samples had little or no effect on primary production and light was more likely to stimulate production, except in shallow coastal water in which light is not a limiting factor. Arzul *et al.* (2002) in an *in vitro* study found that excess feed did not affect the growth rate of micro algae significantly. Alongi *et al.* (2003) reported no significant increase in phytoplankton production in the vicinity of fish cages in mangrove estuaries in Malaysia. They found light to be a limiting factor in phytoplankton growth as it is commonly found in most mangrove waterways.

In a review of phytoplankton blooms in British Colombia the EAO (1996) concluded that salmon cage culture does not have a significant impact on productivity. However, risk of impacts for semi-closed, poor flushing and shallow areas like fjords and lagoons, should not be neglected (GESAMP 1991, EAO 1996). Although the cage culture and other aquaculture systems may be affected by phytoplankton or harmful algal bloom, there is no evidence that it causes toxic blooms (GESAMP 1991, EAO 1996, SECRU 2002). Laboratory studies (in absence of grazers) show a correlation between nutrient enrichment and algae associated with eutrophication, red tides and substantial blooms in Scotland. However, a correlation between harmful algal bloom (HAB) species and nutrient level has not been reported under natural condition. In addition, in vitro study indicated that imbalance in nutrients can result in an increase in the toxic content of algal cells (SECRU 2002). However N:P ratio in salmon cage farming is close to optimal for algal growth. More research is needed for better understanding of the impact of cage culture waste on HAB.

- **Impact on dissolved oxygen**

Suspended and dissolved solids, re-release of chemicals from the sediments and fish respiration may affect water chemistry. Oxygen consumption by a mass of fish in a cage could be significant. A 4 kg Atlantic salmon consumes about 20 g O_2 per day. In one cubic meter of a cage the demand would be 500g $O_2 day^{-1}$ (EAO 1996). In areas with good circulations this amount would be easily supplied by water currents. Brooks and

Mahnken (2003) reported a 2 ppm decrease in dissolved oxygen (DO) level of the water passing through a large, poorly flushed farm. ASI (1999) suggested that 64% to 74% of this demand occurred due to fish respiration. DO depletion in the farm with high water exchange rate is not a concern. Monitoring of DO levels in Maine, USA, did not show a significant difference between DO concentrations in down current and up current of salmon cages and they were close to saturation level (Heining 2000). In general, risk and impact of salmon cage culture on DO level in the water column is very low. However, due to severe increase of biological and chemical processes in enriched sediments, the water next to the bottom may be affected, particularly in deep and stagnant waters with low exchange rates (GESAMP 1991, EAO 1996, Nash 2001). Under such conditions, DO concentrations may decline to 2.2 mgl^{-1}, a critical level for benthic fauna (Nash 2001). However, it is usually at a higher level. DO depletion at the overlaying water in vicinity of the Norwegian salmon cages was only 30% lower than the DO level in an undisturbed area but still above 50% of saturation level (Winsby *et al.* 1996).

- **Chemicals and drugs**

Several chemical compounds are used in aquaculture to control pests and diseases, improve flesh quality or to promote growth. Some compounds are administered through the feed and the other ones via a bath or injection. Depending on the purpose of chemical and drug treatments these compounds enter to environment through uneaten feed, faeces or water (Cannavan *et al.* 2000, Weber 2003).

- ***Antibiotics and synthetic antibiotics***

Farmed salmon are vulnerable to bacterial infections such as bacterial kidney disease, furunclosis and bacterial septicemia (Weber 2003). Various antibiotics and antimicrobial compounds are administered in order to control outbreaks of diseases in salmon cage farms (EAO 1996, Winsby *et al.* 1996 and SECRU 2002 for a comprehensive list of antibiotics and their application). Oxytetracyclin (OTC), Erythromycin, Oxolinic Acid, Sulfadimethoxine+ ormetoprim and some sulfonamide compounds are the most common antibiotics used in salmon culture (EAO 1996, ASI 1999, Winsby *et al.* 1996, Cannavan *et al.* 2000 and Nash 2001). In 1987, 48000kg of antibiotics were administered in the salmon aquaculture industry in Norway. It declined to 680kg in 1998 (Weber 2003). Antibiotics are usually applied orally incorporated into feed. Uneaten feed, faeces and leaching from these particles and feed carry the chemicals to the surrounding environment (Winsby *et al.* 1996, Weber 2003). About 62-86% of oxolinic acid ingested by rainbow trout is excreted through the faeces (EAO 1996). The situation for OTC is almost the same as Winsby *et al.* (1996) reported 70% to 80% loss of the OTC administered in Norwegian fish farm. Since antibiotics bind with particles, they will accumulate in the sediment beneath the fish cages (Chelossi *et al.* 2003, Weber 2003). The residual is mostly found in the top 4 cm (Winsby *et al.* 1996). Several studies have reported that concentrations of OTC between 1- 4 $mgkg^{-1}$ in sediments under salmon cages (EAO 1996, Kerry *et al.*1996). It may even reach 11 $mgkg^{-1}$. However, it should be harmless as it makes complexes with magnesium and calcium (EAO 1996).

Antibiotics may persist in the environment from a day to 15 or even 18 months, depending on type of components and site condition (Winsby *et al.* 1996, Weber 2003).

For instance, in seawater and under exposure of light, OTC degrades in 30 hours. However, in darkness and fresh water its degradation will take 2 month. Removal of antibiotics from the sediments depends mainly on: re-suspension and replacement of sediment, dilution of sediment with additional antibiotics free sediments and the dissolution of antibiotics (Winsby *et al.* 1996) or deactivation by forming complexes with calcium and magnesium (EAO 1996).

Depending on environmental conditions, type and level of accumulated antibiotics, several changes may take place in the microbial structure of the sediment. Major chain of impact is the following (Winsby *et al.* 1996, Chelossi *et al.* 2003, Weber 2003):

- A dramatic reduction in the total number of bacteria and elimination of sensitive species.
- An increase in population of resistant bacteria.
- Elimination or decrease of aerobic bacteria involved in the biodegradation of organic matter, which may foster anaerobic condition.

Some studies indicate that antibiotics do not influence the rate of microbial degradation (EAO 1996, Winsby *et al.* 1996). Chelossi *et al.* (2003) has depicted changes in bacterial structure in sediments in a fish farming area in Italy. They found bacteria in impacted sites to be more resistant to antibiotics. This resistance was transmitted to the bacteria in unpolluted area, which suggests widespread antibiotic resistance in areas surrounding fish farms. Their finding concurs with those of Miranda and Zemelman (2002), who reported antimicrobial multiresistance of bacteria in Chilean salmon farms. An increase in resistance of bacteria to OTC is reported in several studies (Kerry *et al.* 1996, Winsby *et al.* 1996).

Some human bacterial pathogens occur in aquatic environment. Many of the antibiotics applied in aquaculture are the same as those used in human disease control. Considering the ability of bacteria to transmit their resistance to other bacterial strains, that may be a risk of resistance transmission to human pathogens (GESAMP 1991, Winsby *et al.* 1996). Some antibiotics are toxic to invertebrates. *Daphnia magna* nauplius is sensitive to erythromycin (Winsby *et al.* 1996). In addition, degradation of antibiotics may produce some toxins (ASI 1999). Residuals of antibiotics are found in tissues of fish, crab, mussels, oyster and some other invertebrates (EAO 1996, Winsby *et al.* 1996, Coyne *et al.* 1997, Chelossi *et al.* 2003, Weber 2003). Residuals of OTC have been found in oysters (C*rassostrea gigas*), Dungeness crab (*cancer magister)* in less than 0.1 $\mu g g^{-1}$ (Capone *et al.* 1996, EAO 1996). Coyne *et al.* (1997) detected significant Oxytetracycline concentrations in blue mussel (*Mytilus edulis*) near an Atlantic salmon farm, both during and after application of OTC. The half-life was less than 2 days.
Risk of transmission of deposited antibiotics to humans and subsequent effects on human health and rejection of contaminated products by strict markets should be considered in

application of antibiotics in fish farming. Considering the short half life of antibiotics, it is very easy to reduce this risk.

- ***Parasites***

Sea lice (*Caligus elangatus, Leptophtherius salmonis, and Ergasilus labracis*) are common ecto-parasites in salmon cage culture (Winsby *et al.* 1996, Nash 2001, Weber 2003). Infested fish fetch up to 20% lower price in the market (Weber 2003). Ivermictin, cypermethrin (dichlorvos), azamethiphos, calicide (teflubenzurn) and several different chemicals are used for sea lice treatment all around the world. Almost all of these compounds are broad spectrum biocides that can to affect many aquatic species, in particular crustaceans (Nash 2001, Weber 2003). For instance, ivermectin (22,23-dihydroarermectin β_1) is a pesticide widely used in salmon farms (Nash 2001). Lethal concentrations for marine organisms range from 0.022 μgl^{-1} for *Mysidopsis bahia* (LC_{50},96 hrs) to more than 10000 μgl^{-1} for nematodes. Ivermectin that is not absorbed by fish is incorporated into sediment (Nash 2001). Therefore, benthic organisms are most likely to be affected by this chemical (SECRU 2002). Residuals of ivermectin have been found in sediments 22.5 m from salmon cage (Cannavan *et al* 2000). Mean concentration in the top 3cm was $5ngg^{-1}$. In general, significant concentration of this chemical is limited to a 10-20 m perimeter of a farm. Degradation of ivermectin in the sediments is very slow and depends on light and temperature; its half-life may be more than 100 days (Nash 2001).

An organophosphate insecticide, dichlorvos, is an approved chemical in Europe, which is toxic to marine invertebrates (Winsby *et al.* 1996). High mortality of shrimp and lobster has been observed when they were exposed to a bath of dichlorvos solution, but the effect has not been observed outside cages. Dichlorvos is toxic to crustaceans in concentrations greater than 10 ngl^{-1}, while the concentration of this chemical can rise up to 187 ngl^{-1} , 25 m downstream of a salmon cage (Nash 2001). Medina *et al.* (2004), found a decrease in the density and biodiversity of 19 taxa of zooplankton exposed to 5 μgl^{-1} cypermethrin. The total number of rotifers however increased significantly. Phytoplankton density measure on chlorophyll *a,* did not change significantly. Like other vermicides, dichlorvos is deposited in sediments around the farm area. The function of other compounds like emamectin and calicide in the environment are similar to ivermectin and dichlorvos (Nash 2001).

- ***Disinfectants***

Varieties of chemical compounds are used for disinfection or treating external pathogens. Benzalkonium chloride, iodophore, chlorine and formalin are the most common disinfectants in salmon aquaculture. They are very toxic to aquatic organisms. However, they are usually applied in small quantity under controlled conditions (EAO 1996, Nash 2001). As a matter of fact, application of antibiotics and some other chemicals in cage cultured can not be easily eliminates from the farming practices, in particular in intensive

systems. Optimal site selection and responsible farm management are the practical approaches to reduce risk and impacts of chemicals on the environment.

- **Heavy metals**

- ***Copper***

Antifouling agents are widely used to prevent growth on nets and cages. Copper containing compounds are the most common chemicals used in net cleaning. In 1985 the aquaculture industry in Norway used 47 tons of copper in antifouling agents. This amount increased to 180 ton in 1998 (Solberg *et al.* 2002). 25 antifoulings are licensed by SEPA for application in the UK. The primary active ingredient in all but five of these products is copper, copper sulfate and copper oxide (SEPA 2003). However, the environmental impact of copper in aquaculture is not sever. Winsby (1996) reported a concentration of copper inside a treated net as no different from a control 700 m away. Buschmann (2002) found that the increase in concentration of dissolved copper in Chilean marine salmon farms is not correlated with aquaculture activity. Solberg and co-workers (2002) found no significant difference between copper concentration in samples of blue mussel (*Mytilus edulis*), brown seaweed (*Ascophyllum nodosum*), saithe (*Pollacius virens*), farmed Atlantic salmon and sediments from sampling stations in five copper treated nets and an untreated reference net.

Despite of the use of copper in antifouling agents and feed, high concentration of this metal was not reported in sediments in British Colombia (EAO 1996). Copper, in certain concentrations, is toxic to algae and some other aquatic organisms, in particular embryonic and larval stages of invertebrates (Nash 2001, Brooks and Mahnken 2003b). Embryos of *Crassostrea gigas* are very sensitive to the Cu ion (LC_{50}= 10 μgl^{-1}) while herring larvae have a very low sensitivity (LC_{50}= 10-2000 μgl^{-1}) (Brooks *and* Mahnken . 2003b). In the United States, the maximum approved level of copper in the marine environment is 3.1 μgl^{-1}. Various studies have shown the levels of copper in fish cages to be less than standard norms (Nash 2001).

Copper is added to the feed in 1-4 gkg^{-1} dry feed, depending on fish species and environmental condition (Berntssen *et al.* 1999, Brooks.and Mahnken 2003b). Berntssen and co-workers (1999) in their laboratory study added copper to the diet of Atlantic salmon parr in 3 different concentration, 5, 35 and 700 $mgkg^{-1}$ dry feed. They reported no increase of copper in the water column in their 4 week experiment. High rate of dilution of copper and flushing out of residue by current or binding of copper with organic and inorganic material in the water column, which precipitates the metal into the sediment will reduce risk of environmental impacts.

- ***Zinc***

Zinc is an essential element added to salmon feed at 30 to 100 $mgkg^{-1}$ to prevent impaired growth, increased mortality, eyes cataract, short body dwarfism and low tissue zinc (Maage *et al.* 2001).

In fish culture, zinc may accumulate in the sediments via faeces and uneaten feed. High concentration of zinc in the sediments of salmon farms has been found in Canada and the US. The concentration of zinc in the sediments at the perimeter of the fish cages in British Columbia measured at 200 $mgZn\ g^{-1}$ (Brooks and Mahnken 2003b). Chou *et al.* (2002) studied trace metals in the sediments around a salmon cage in New Brunswick, Canada. They found a drastic increase in both copper and zinc concentration in a heavily sedimented area. In anoxic conditions, zinc and copper concentrations increased to 253±85.7 μgg^{-1} and 54.5± 5.1 μgg^{-1} respectively, while in normal conditions beyond 50 m from the cage the concentrations were 2 to 3 times lower.

Toxicity of zinc is correlated to concentration of sulfide (H_2S, S^{-2} and HS^-) and TVS. Interaction of the metal and sulfide renders the zinc harmless to benthos (EAO 1996, Pearson and Black 2001, Brooks and Mahnken 2003b). Studies show the zinc does not accumulate in aquatic organisms or the food chains (Brooks and Mahnken 2003b). Risk of high accumulation in semi closed water bodies with low water exchange should be considered in site selection and farm management practices. In the past few years zinc sulphate in salmon feed has been successfully substituted with organic source of zinc as methionine analog and Zn-gluconate to reduce the risk of environmental impacts (Maage *et al.* 2001, Brooks and Mahnken 2003b).

- **Feed additives**

Antioxidants, pigments and hormones may be added to formulated feed as preservation, to give red colour to the flesh of fish and in order to promote growth. Application of these materials is usually well organized and regulated in various countries and they carry little environmental risk.

In the last few years presence of dioxins in farmed salmon has gained considerable attention because of potential effects on the immune, endocrine and reproductve functions and development of fatal tumors in humans (Nash 2001, EU 2001). Basic feed ingredients are virtually all contaminated with dioxin to varying degrees (Nash 2001). For instance, a typical diet for carnivorous fish containing 50% fish meal and 2.5% fish oil originating from Europe contains 1.82ng$WHO\text{-}TEQkg^{-1}$ dry matter. At least 60% of total dioxin in fish feed is likely to be transferred to the fish (Nash 2001) which is less than the dioxin concentration in wild fish (EU 2001).

Considering feed wastage in salmon farms, a huge amount of dioxin is released into the oceans. Dioxin accumulates in the food chain and is likely transferred to human as the final link. Some vitamins are known as growth promoters of algae. Winsby (1996) and

ASI (1999) reported phytoplankton growth promotion due to biotin in fish feed and faecal matter. However, further investigation is needed before firm conclusion can be drawn.

2.2 Evaluation of impacts on sediment

Impact of cage culture on sediments is much greater than its effects on water quality. Analyses of physical, geochemical and biological characteristics of the sediment are sensible approaches to evaluate impacts on sediments and the surrounding environment. There are several methods and indicators for estimation of environmental impact on sediments from simple visual analysis to sophisticated methods. Some criteria like legislation, duration of the farm operation and site specification (depth, currents, seabed structure, etc.) might be considered in selection of the methods and indicators (Carroll *et al.* 2003). The most common indicators for analysis of impact on sediments are the following:

- Biological indicators like species richness, abundance, etc. in and on the sediment
- Organic materials (in terms of total organic material, organic carbon, total volatile solids, organic phosphorus and organic nitrogen in sediment)
- Sediment grain size
- Redox potential and RDL in sediment
- Benthic oxygen uptake of the sediment
- Free sediment sulfides
- Concentration of heavy metals in the sediment
- Concentration of antibiotics in the sediment
- Visual and organolepthic analysis of sediment

Each method has some advantages and disadvantages. Biological indexes (composition, abundance and species richness) are generally considered to be the most sensitive, accurate and reliable method to evaluate the level of organic enrichment and disturbance associated with cage farming practices. It reflects the integration of the impact of all factors, including chemical and physical changes in the environment. On the other hand, this method is expensive and time consuming (Nash 2001, Crawford *et al.* 2002, Carroll *et al.* 2003). It could be inaccurate in sediments, which have been exposed for a short time to severe natural or unnatural pollution. In this condition carbon could be a good indicator to use to assess the impacts (Pearson and Black 2001).

Crawford *et al.* (2002) in their study on the impact of cage culture in Tasmania found that carbon content is a good indicator in heavily enriched sediments. It may be less accurate at further distances from the cage farm (Carroll *et al.* 2003). Low level of carbon input might be consumed by the detrivorous organisms and would not show the effect of the farming practices (Crawford *et al.* 2002, Carroll *et al.* 2003). ASI (1999) suggested that due to fast decomposition of carbon and nitrogen in marine sediments, phosphorus is a more accurate index for impact assessment. Organic carbon contents will be more accurate indicator if C:N ratio is taken to account (Winsby *et al.* 1996). The ratio shows the age of the sediment, its digestibility for the benthic fauna (EAO 1996) and its possible

origin (CSIRO 2000). Sediment particle size is a good indicator when combined with organic carbon contents and infaunal community structure (Crawford *et al.* 2002).

Almost all studies refer to redox potential as a quick, simple and inexpensive indicator of enrichment of the sediment. (EAO 1996, Nash 2001, Pearson and Black 2001, Crawford *et al.* 2002). However, its efficiency is low in very fine sediments where RDL is close to the surface of the sediment (EAO 1996). In addition, improper calibration of instruments may cause an error in measurements. Sensor of the instrument may also not be able to penetrate into all kinds of sediments (Crawford *et al.* 2002, Carroll *et al.* 2003). Benthic oxygen uptake and H_2S concentration reflects bio- and geochemical activities in the sediments. Chemical indicators have been integrated and a pollution index for the degree of sediment pollution developed (Table 3) (Carroll *et al.* 2003).

Visual analyses including scuba diving and sediment profile imagery (SPI) are some direct methods to analyze sediments. Photographs and motion pictures give a permanent and readily interpretable record. Availability of software maximizes the benefit of digital images and makes it a quantifiable parameter (Crawford *et al.* 2002, Carroll *et al.* 2003). However its sensitivity is low and usually only reflects major impacts (Crawford *et al.* 2002). In addition, required equipment expensive (Carroll *et al.* 2003). In rocky bottom areas is the imaginary methods are inefficient. Application of remote sensing and GIS in evaluation of the impact of cage culture has been pointed out in several recent studies (Perez *et al.* 2002).

Table 3: Shaanning pollution index of sediment (Carroll *et al.* 2003)

Degree	Index	pH	pS	pE	N(mgg^{-1})	P($mg\ g^{-1}$)	Zn($\mu g\ g^{-1}$)	Cu($\mu g\ g^{-1}$)
Large	3	<6.9	<2	<-2	>16	>10	>650	>150
Moderate	2	6.9-7.2	2-4	-2 – 0	8-16	2-10	150-650	25-150
Small	1	7.21-7.7	4-7	0-2	2-8	0.5-2	5-150	5-35
No	0	> 7.7	>7	>2	<2	<0.5	<5	<5

pH: alkalinity, pS=-log$\Sigma[H_2S]$, pE: redox potential=-log {-e} =E_h (V)/0.059

3 CASE STUDY: IMPACT OF ATLANTIC SALMON CAGE CULTURE ON SEDIMENT CHEMISTRY IN MJOIFJORDUR, ICELAND

Mjoifjordur is a narrow fjord in east Iceland. It is deep and about 18 km in length. The width of the fjords decreases gradually from 3.5 km at the mouth to 600 m at the end (Figure 5). The maximum surface temperature is about 9°C during the summer and decreasing to 1°C in winter season (MRI 2004). The area is rather windy. Average wind speed in autumn for 10 years is 6.8 ms^{-1} with the maximum speed of 12.3 ms^{-1} (IMO 2004). Prevailing current at the farm site is from the east into the fjord along the northern shore. The average velocity at 10 m depth is 4.1 cms^{-1} and the recorded maximum 36.6 cms^{-1} (Samherji hf. 2003).

The farm is composed of 14 circular cages moored in two rows. The operation started in late July 2002 when the cages were stocked with Atlantic salmon smolts. The farm is at 65° 12’ 027’’ N and 13° 46’ 632’’ W (coordinate of farm’s center) close to the opening of the fjord (Figure 5).The minimum distance of the farm from the northern coast is approximately 300m. Total carbon and nitrogen input from the feed was estimated 2625 and 278 tons, respectively. Based on minimum rate of feed waste (Table 1), some 305 tons of carbon and 31.4 tons of nitrogen have been released in to the fjord as faecal matter and uneaten feed.

3.1 Materials and methods

Cage No. 6, in the middle of the block of cages was selected as the target cage. Seven sampling stations were selected based on depth, prevailing current in the fjord, specification of the waste materials and distances of the cage from the coast and the next farm. The farthest station (S7) upstream of the cages was chosen as the reference station. Depth of water and position of the sampling station were read on the GPS screen of the sampling vessel (Figure 5 and Table 4 and Appendix 1).

3.2 Sampling

Sediment samples were collected 29.12.2003 using a Shipek grab sampler with a footprint of 0.044 m². Almost all the grabs were of good quality with minimum leakage or flushing out of sediment. Low quality samples were discarded. The weather was calm, partly cloudy and temperature about -5.7 °C at the time of sampling. The wind speed varied between 2.5 in early morning to 4.1 at the end of sampling period. Wind direction changed from 340° to 250° during the same period (IMO 2004).

A sub-sample was taken from each grab using plexiglas corers (inner diameter: 6 cm). The length of the sediment in cores was 9 to 10 cm. The cores were packed immediately and kept at – 0°C on deck. When at shore the cores were frozen at – 20°C (Karakassis *et al.* 2000, Zitko 2001, and Carroll *et al.* 2003) until transported to the Icelandic Fisheries Laboratories in Reykjavik by air.

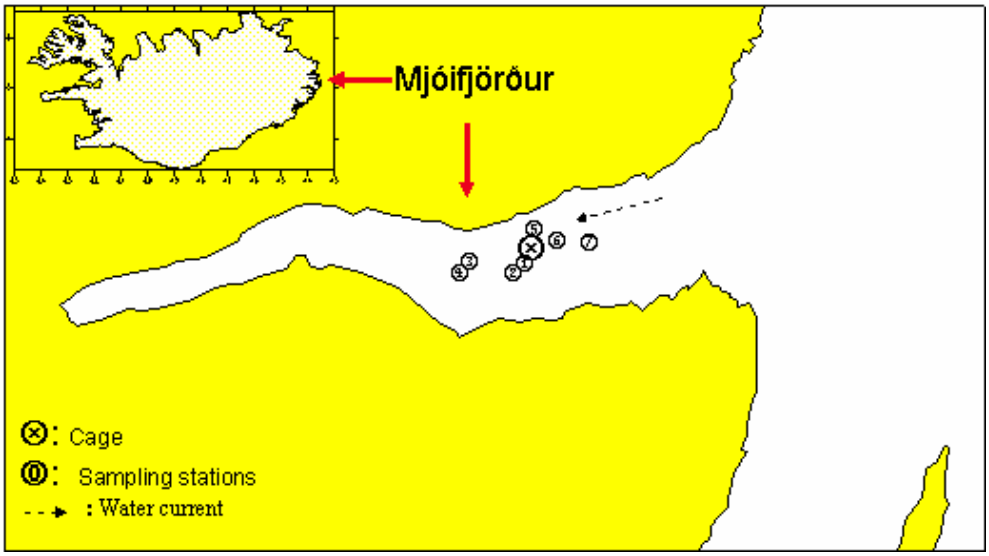

Figure 5: Position of the farm and sampling station in Mjoifjordur (not in scale)

In the laboratory, the top 0.5 cm layers of all the core samples were cut by stainless steel saw and placed in plastic bags. Three cores from station No. 1 (at the edge of cage), No.2 (at 95 meter of cage) and No.7 (reference, at 600m from the cage) were selected for complete layer analysis and those cores were dissected in 1 cm thick slices. Sub-samples were placed in plastic bags and kept frozen (at – 20 °C) until analysis.

Table 4 : Depth of water and distance from the coast at sampling stations

Station	Depth, m	Approximate distance in meter		
		To the edge of cage	To the reference station (No.7)	To the North coast
1	85.5	5	600	410
2	88.1	95	650	470
3	85	320	900	380
4	88	350	930	400
5	74	150	570	270
6	66	200	580	450
7	87.3	600	0	480

3.3 Sample chemistry analysis

The appearance of the samples was examined and they analyzed for total dry weight, organic matter, total organic carbon, total phosphorus and total nitrogen. Organic matter was calculated as a percentage of dry weight (% DW) of the sediment.

3.3.1 Dry weight and total organic matter (TOM)

TOM was determined by loss on ignition. A 500 mg sample from each dissected layer was oven dried for two hrs. at 105 °C, weighed and subsequently placed in a furnace at 550 °C for 2 hrs. then reweighed. Dry weight was determined as the difference between weight of wet sample and oven dried one. TOM was calculated from the difference between the oven dried weight and weight after being in the furnace. TOM is expressed as the percentage of the oven dried weight.

3.3.2 Total organic carbon (TOC)

The determination of TOC was based on chemical oxygen demand (COD). Two samples, approximately 100 and 200 mg wet weight from each layer were digested in 250 ml flask containing 10ml dichromate 4M, 30 ml sulphuric acid (95-97%) and 20 ml Milli-RO/Milli-Q water for 2 hours. Some 200 mg of mercury sulphate was added to the flask in order to prevent interference of natural chloride in the sediment. COD was calculated based on volume of standardized FAS used in the titration and then converted to percentage of organic carbon content based on the chemical balance of carbon oxidation.

3.3.3 Total phosphorus and nitrogen

- **Sample preparation**

200 and 400 mg wet weight of samples were digested in 6 ml sulphuric acid (36M) for 5 minutes and then oxidized by adding 15 ml hydrogen peroxide (30%) using HACH Digestdal instrument. The solution was diluted to 100 ml and left overnight for precipitation of suspended material.

- ***Total phosphorus (TP)***

Exact volume of 0.5 ml of prepared sample solution was pipetted into 50ml flask and diluted to 25 ml with water. TP was determined by spectrophotometery (Cary 1E, 880 nm) after formation of the molibdate complex and reduction by ascorbic acid.

- ***Total nitrogen (TN)***

Due to low concentration when using 0.5 ml of the solution, the initial volume of sample was increased 10 times and 5 ml of processed sample were pipetted to 50 ml flask. 3ml of NaOH (4M) was added to adjust the pH. TN determined by spectrophotometery (Cary 1E, 630nm) by the phenate method.

3.3.4 Statistical analysis

To determine the significance between the stations, and between the layers within a station one way analysis of variance (ANOVA) and ANOVA single factor was used respectively. Duncan multiple range test (DMRT) applied for comparison of the means between three stations at 95% level of confidence using SPSS version 10 and Excel software. Correlation between variables were analyzed using Pearson 2 tailed test in two level of confidence (*a*=1% and 5%).

3.4 Results

3.4.1 Top layer of sediments

Percentage of all analytes studied in top layers (0- 0.5 cm depth) was the highest at in station 1. ANOVA single factor analysis shows TN and TOC at this station was significantly different from the other stations. Total phosphorus and TOM does not however show any significant differences in the top layer of station 1 as compared with the other stations (*a*=5%).

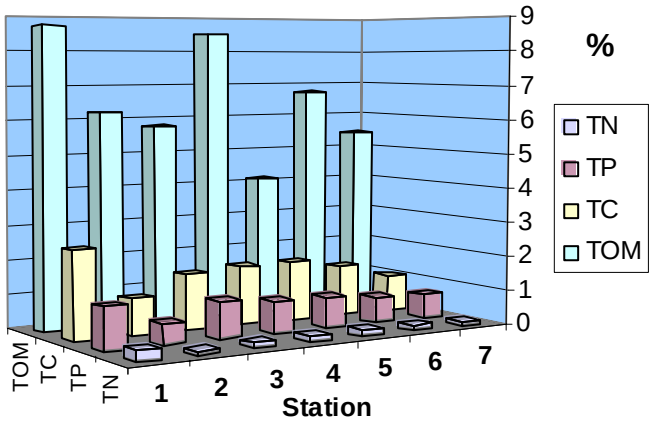

Figure 6: Analysed parameters in top layers of different stations

3.4.2 Stations 1, 2 and 7

One way analysis of variance (Table 5) revealed no significant difference between means of analyzed parameters in different depths of sediments at station 1, 2 and 7 ($P<0.05$). Although the TOM, TOC, and TP all show a decreasing gradient with depth at station 1. They are however approximately at the same level in the other two stations at all depths of sediments (Figure 7).

The mean and standard deviations of the parameters analyzed at these 3 stations are presented in Table 6. One way analysis of variance revealed significant differences between the stations in terms of the means of all parameters ($P>0.05$). DMRT shows that difference of mean of analyzed parameters at station 7 and 2 are insignificant ($P<0.05$).

However, station 7 and 1 are significantly different, except in the mean of TOC. Mean of TOC at station 7 is higher than S2. Station 1 and 2 shows significant differences in TOC, TN and TP. Difference of the mean of TOM between two stations is insignificant. TOM value is the highest at the station closest to the cage.

(C:N) ratio found at station 1 is significantly different from other two stations (P>0.05). However, carbon, phosphorus (C:P) ratio in all three station is very similar and does not show significant differences (P<0.05).

Pearson test indicates a positive and significant (P>0.05) correlation between the parameters analyzed. Total organic matter, carbon and phosphorus show higher correlations (P>0.01) (Table 7).

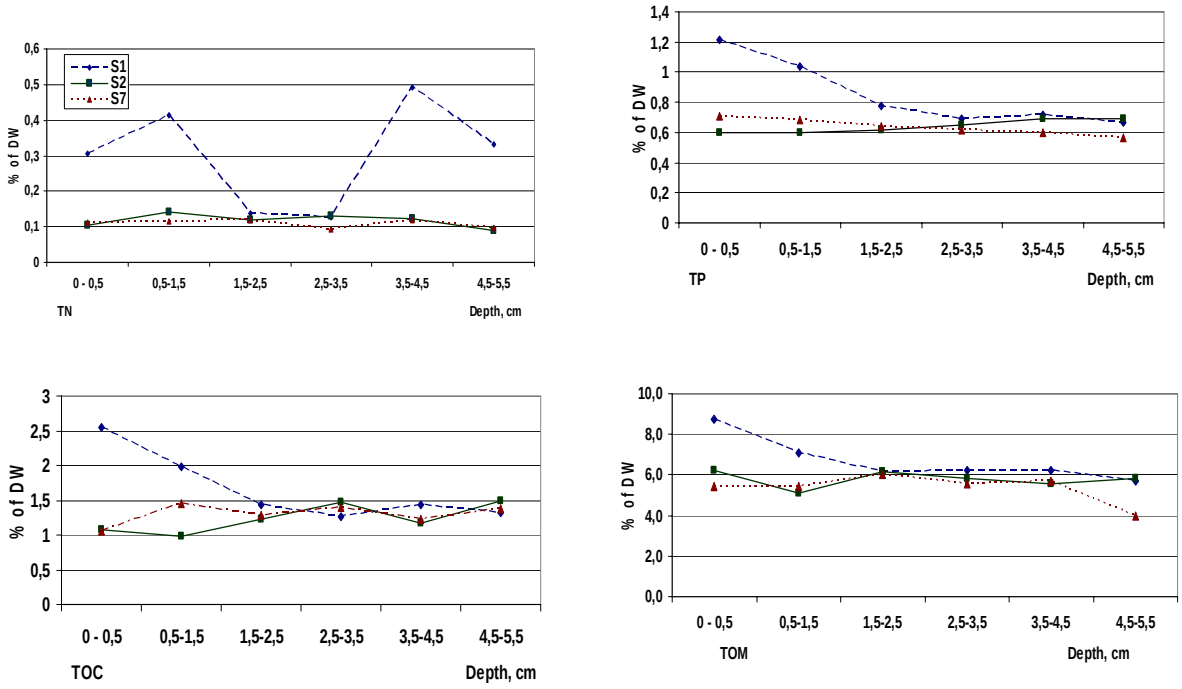

Figure 7: Variation of analyzed compounds in different depth at station 1, 2 and 7

Table 5: Mean and standard deviation of analyzed compounds in different layer of sediments in 3 stations

Sediment depth (cm)	Nitrogen	TOC	Phosphorus	TOM	C:N ratio	C:P ratio
0- 0.5	0.1735± 0.1146	1.5588±0.8543	0.8377± 0.3285	6.7930±1.7099	9.4053± 1.0389	1.8047±0.3073
0.5- 1.5	0.2243± 0.1653	1.4748±0.4996	0.7706± 0.2326	5.8667±1.0788	8.0872±4.0306	1.9009±0.2575
1.5- 2.5	0.1253± 0.0116	1.309±0.1085	0.6777± 0.08427	6.1137±0.05816	10.4584±0.3125	1.9416±0.07492
2.5- 3.5	0.1162±0.215	1.3718±.103	0.6503± 0.0379	5.8593±0.3185	12.125±2.7470	2.117±0.2524
3.5- 4.5	0.2444±0.2133	1.2756±0.1453	0.6675± 0.0601	5.8193±0.3304	11.5310±6.6527	1.9191±0.1935
4.5- 5.5	0.1762±0.1214	1.3986±0.0866	0.6395± 0.06627	5.1637±1.0512	9.8587±3.6113	2.2118±0.2181

Table 6: Mean and standard deviation of analyzed compounds in different station

Sampling station	Nitrogen	TOC	Phosphorus	TOM	C:N ratio	C:P ratio
S1	0.3014±0.1460 a	1.6646±0,5016 a	0.8475± 0.2236 a*	6.6743±1.1007 a	6.7182±3.2058 a	1.9594±0.1090 a
S2	0.1181± 0.0191 b	1.2327±0,2082 b	0.6393±0.0 4402 b	5.7827±0.4114 ab	10.7968±3.2149 b	1.9217±0.2518 a
Reference (S7)	0.109± 0.01142 b	1.2969±0,1417 ab	0.6349± 0.05315 b	5.9359±0.7214 b	12.0612±2.2397 b	2.0664±0.3257 a

* The same letter indicate insignificant difference (P<0.05)

Table 7: Pearson, 2 tailed analysis for correlation between variables (N=18)

		TN	TP	TOC	TOM
TN	Pearson Correlation	1.000	0.565(*)	0.513(*)	0.487(*)
	Sig. (2-tailed)	.	0.015	0.030	0.041
TP	Pearson Correlation	0.565(*)	1.000	0.904(**)	0.852(**)
	Sig. (2-tailed)	0.015	.	0.000	0.000
TOC	Pearson Correlation	0.513(*)	0.904(**)	1.000	0.758(**)
	Sig. (2-tailed)	0.030	0.000	.	0.000
TOM	Pearson Correlation	0.487(*)	.852(**)	0.758(**)	1.000
	Sig. (2-tailed)	0.041	0.000	0.000	.

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

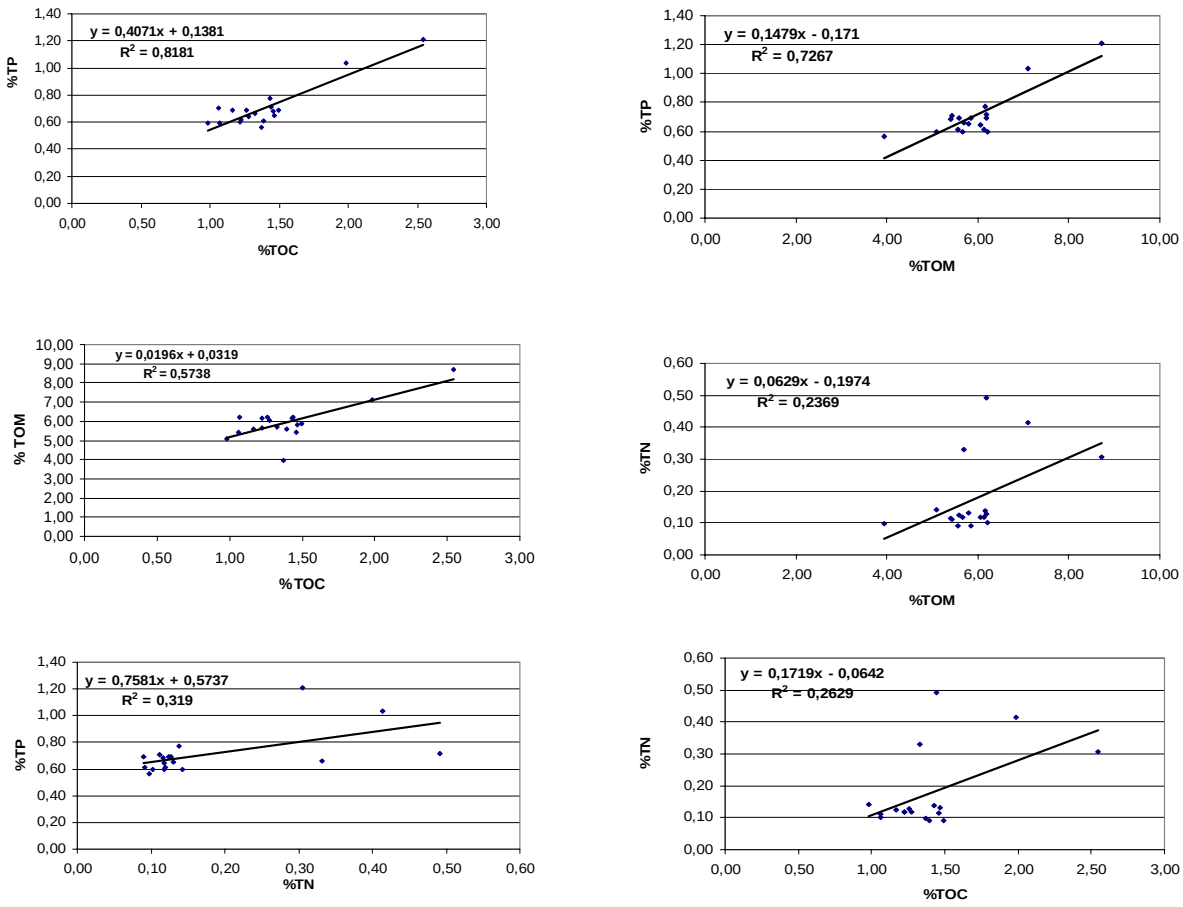

Figure 8: Correlation of analyzed compounds in various layer of sediment in different station

3.5 Discussion and conclusion

Based on the feed quality and site characteristics, spatial dispersion of the major part of uneaten feed and faecal matter in the studied area in Mjoifjordur should be restricted to 55 m downstream from the edge of cage. Uneaten feed accumulates at closer distances to the cage than faecal mater, since faeces have a lower sinking rate and should therefore settle further away. The current at the farm area will probably interfere with the sedimentation behavior of solid wastes.

The nitrogen content of the sediment is often used as a good indicator of sediment enrichment, due to the fact that this is mostly derived from external inputs (CSIRO 2000, Telfer and Robinson 2003). At station 1, total nitrogen in the surface layer and the mean of TN in the whole sediment exceeds 0.3%, which is in accordance with the results of other studies. Karakassis *et al.* (2000) and Kempf *et al.* (2002) reported concentration of organic nitrogen as low as 0.3% in sediments in close vicinity of the marine fish cages in both shallow, slow current and steep bottom, strong current areas. McGhie *et al.* (2000) indicated higher value of TN in Huton Estuary, Tasmania as great as 1.3%. They found

that TN did not decrease to less than 0.4% after 12 month after farming had ceased. On the other hand, Crawford *et al.* (2003) reported very low nitrogen content (0.15 to 0.4%) in the sediment in the vicinity of salmon farms in Nubeena, Tasmania. In Mulroy Bay, UK, nitrogen showed the same range from 0.14 to 1.73% in different sites and distances from salmon farms (Telfer and Robinson 2003).These result point to the influence of both site and farm conditions on the magnitude of accumulation of waste material and their impact on the environment.

Crawford *et al.* (2002), in their evaluation of techniques for environmental monitoring of salmon farms, concluded that nitrogen is a proper indicator in highly impacted sediments. In our case, where the water is deep and the moderate current may flush out the waste materials, nitrogen might be a less qualified index. According to the Shaanning pollution index (Table 3) and considering the mean nitrogen concentration at station 1 (0.314 ± 0.146 mgg^{-1}), this station would be classified as a slightly impacted area. By the same criteria stations 2 and 7 should be regarded as undisturbed sites (less than 2 mgg^{-1} N).

Total organic carbon in the surface layer of the sediment at station 1 was considerably higher than at the other six stations (Figure 6), indicating an external input of carbon and accumulation of organic matter on the seabed. The mean of TOC in Station 1 was 1.66%, some 28% greater than at the reference site 600 meter from the cage. However, the difference between the two stations is insignificant. McGhie *et al.* (2000) reported high TOC value (4.05%) at a reference site in the Huton Estuary, Tasmania, where TOC was almost 30% lower than underneath the cage. Hargrave *et al.* (1997) obtained a similar result in their study on cage farming in New Brunswick. Carroll *et al.* (2003) in their study on Norwegian salmon cage farming concluded that in approximately 10% of 168 samples, TOC values had increased because of natural processes. Sara *et al.* (2004) found that 47.9% of carbon in sedimentary organic matter in Mediterranean area originated from cage farming and the rest was of terrigenous (about 33%) and autochthonous (about 19%) origins.

C:N ratio can be a useful indicator of the source and age of organic matter in estuaries and coastal areas (Winsby *et al* 1996, CSIRO 2000, Telfer and Robinson 2003). C:N ratio of 6 to 10 is generally reported for autochthonous marine- derived organic matter (CSIRO 2000, Sutherland *et al.* 2001) whereas values greater than 11 (Telfer and Robinson 2003) and/ or 12 (CSIRO 2000) are usually found in terrestrially derived organic matter and external input of nitrogen.

In our study, mean of C:N ratio in different depths at station 1 was 6.7182 ± 3.2058, showing accumulation of highly labile material. This is lower than calculated C:N ratio of the feed (9.4). Deep water at this station provides a condition for leaching of nitrogen during sinking (Section 2.1.1) and decomposition of uneaten feed results in the increase in C:N ratios. It is as high as 8.32 in the top layer at this station. High C:N ratio at station 2 and the reference site indicates the presence of poorer quality organic material.

Numbers of studies show a wide range of TOC value in vicinity of cage farms. Heliskov and Holmer (2001) report values for organic carbon as 1.2 to 2.2% of dry weight in

affected sediments near a trout cage farm in shallow coastal waters of Denmark. In Tasmania, organic carbon contents in the sediments around the salmon cage farms varies from less than 1% to more than 6%, depending on the site and farm condition (Crawford *et al* 2002). The variability of TOC can be accounted for the varying proportion of fine clays and silts (CSIRO 2000). Svavarson and Helgason (2002) reported that sediment grain size in Mjoifjordur varies along the fjord. The fraction of fine particle (< 0.063 mm) changes from 47.5% 1300 m upstream from our reference site (S7) to 27.9% 1300 m downstream. However, the organic carbon was very high (5.7 - 5.9%) and did not show considerable changes in different places. The results of the present study are closer to the average organic carbon content in the sediment of the coastal area of Iceland.

Microscopic examination of the sediment showed a difference in grain size between the three stations 1, 2 and 7. The second station looks more silty than station 1 while reference station had finer grains. Total phosphorus at station 1 was significantly higher than at stations 2 and 7, reflecting the disturbance of the sediment at this station. The reference station and station 2 are not significantly different which means that the impact of the cage culture is restricted to a short distance from the cage. TP shows high correlation with total organic carbon ($r^2 = 0.904$). Carbon: phosphorus ratio in the feed is almost 56.5, while the C:P ratio in the sediments is approximately two and the difference between the three stations is insignificant. Nickell *et al.* (2003) in their study of impact of salmon cage culture in moderately deep (25 m) water of Loch Creran, Scotland, found that C:P ratio describes the quality of carbon in the sediment as phosphorus is more sensitive to degradation. The result of this study does not show such a correspondence.

Holmer *et al.* (2002) found large accumulation of phosphorus in the sediment nearby a milkfish cage farm in moderately shallow water. They suggested that phosphorus was either buried with the organic matter or bound to carbonates. In our study, we observed high level of phosphorus in surface layers of all samples. Therefore, the probability for burying of phosphorus is very low. Available information is not sufficient to discuss the binding capacity of the sediment in this area. Guo and Li (2003) found that solid wastes of cage farming lose their phosphorus content in the first 50m depth of water. Leaching and decomposition rate depends on temperature, salinity and environmental parameters. So it might be concluded that the difference between the average phosphorus content originated from other source of pollution and waste materials from the farm do not significantly impact phosphorus in the sediments. According to the Shaanning pollution index (Table 3), station 1 would be classified as slightly impacted group and two other stations are very close to being in the undisturbed category.

TOM in station 1 is significantly different from reference station. Higher TOM at station 1 shows an accumulation of organic material nearby the cage. The reference site and station 2 do not show considerable differences. Several researchers have found organic matter measurements by loss on ignition to be accurate only if the sediments are highly enriched or the carbonates and clay concentration are in low levels (Crawford *et al.* 2003). That is because of ignition of carbonate and interference with the loss of organic carbon.

Karakassis *et al.* (1998) found no significant difference between sites 5m, 10m, and 25m from the cage and the reference site. In our study, the magnitude of enrichment is low high. The results show a high correlation between TOC and TOM indicating a similar source of carbon and organic material.

In summary, the results show the Atlantic salmon cage farming in Mjoifjordur has affected the chemistry of the sediment close to the farm. However, the magnitude of impact is low. It might be due to moderate current velocity and great depth of the fjord, which provides a suitable condition for leaching and decomposition of organic material during the sinking period and flushing out of the deposited waste from the fjord as well. It concurs with the other studies (Barg 1992, EAO 1996, Winsby *et al.* 1996, ASI 1999, McGhie *et al.* 2000, Pearson and Black 2001, Nash 2001, Carroll *et al.* 2003 and Crawford *et al.* 2003) and the results indicate localized impact of cage culture , restricted to few tens of meters from the cage. It should be noted that samples were not taken from underneath the cage. The impact on the sediment below the cage might be higher than observed at the station nearby the cage.

3.6 Recommendation

- This study was done in the autumn, 1.5 years after installation of the cage in this area when the biomass was close to the maximum level. Samples could not be taken directly under the cage. These points should be considered in interpretation of the results.
- Study on local water current nearby the farm and prevailing sea current in the fjord would be helpful for demonstration of the sedimentation behavior in the vicinity of the farm.
- Application of some other indicator such as redox potential or trace elements will provide information for drawing a precise picture of accumulation of organic wastes from the cage.
- The results indicated a high concentration of phosphorus in the sediment. Further study on the source of phosphorus is recommended.

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APPENDIX

Appendix 1: Geographical position of the sampling stations

Station	Latitude North	Longitude West	Depth m	Approximate distance in meter	
				To the edge of cage	To the reference station (No.8)
1	**6511926**	**-1346781**	**85.5**	5	600
2	**6511885**	**-1346847**	**88.1**	95	650
3	**6511917**	**-1347018**	**85**	320	900
4	**6511904**	**-1347211**	**88**	350	930
5	**6512008**	**-1346733**	**74**	150	570
6	**6512028**	**-1346732**	**66**	200	580
7	**6511932**	**-1346027**	**87.3**	600	0