Modeling the effects of dynamic marine environments on Atlantic Salmon (*Salmo salar*) populations raised in aquaculture pens

Chloe M. T. Hess

ABSTRACT

Aquaculture offers a unique opportunity for the growing salmon industry and is an effective alternative to commercial fishing. The maintenance of different water quality parameters is important in the rearing of aquatic organisms until adulthood. A combination of polynomial regressions and generalized additive models help show how these dynamic marine environments impact fish behavior. I defined fish behavior as the depth at which fish swam and related it with the temperature, dissolved oxygen, and salinity levels of the water. The relationships between fish behavior and the three predictor variables were not consistent with the original hypothesis that if conditions were not ideal, fish would swim at depths that increase their chance of survival. However, this study was based on a specific dataset from a cage at a SalMar farm in Norway and did not include many data points that were outside the Atlantic Salmon tolerance range. Based on the best produced generalized additive model, I found that temperature had the strongest impact on the depth fish swam followed by dissolved oxygen then salinity. Overall, this study has important implications for future research on the role of water quality regulation and maintenance in fish farms.

KEYWORDS

fish farming, environmental analysis, temperature, dissolved oxygen, salinity

INTRODUCTION

The commercialized fishing industry poses many interrelated environmental, humanitarian, and future economic concerns. One of the most serious environmental issues is overharvesting and overfishing which describes the scenario in which aquatic populations are removed from their ecosystems quicker than they are able to reproduce. In the fishing industry, overharvesting has resulted in the disruption of ecosystems, the collapse of fish stocks, and the extinction of some species (Sadovy de Mitcheson et al. 2020). Along with overfishing, there is also an issue of bycatch, or the capture of non-target species, which may include endangered species or keystone species whose absence likewise can greatly affect an ecosystem's food web (Graham et al. 2022). Along with the pressing environmental threats and the unethical working conditions of the fishing industry create economic instability (Iudicello et al. 2012). These concerns need to be further investigated, so proper action can be taken to promote ethical and sustainable fishing practices.

A popular alternative solution to overharvesting wild stocks that addresses issues in the fishing industry has been the establishment of fish farms. With the increased seafood demand and depletion of marine fisheries, many seafood producers are looking to aquaculture to increase yields. Aquaculture, or the rearing of commercial aquatic animals in pens, ponds, or tanks for slaughter, has been advertised as a more sustainable practice than commercial fishing, which contributes greatly to greenhouse gas emissions. Additionally, aquaculture has been viewed as a partial solution to some of the United Nations sustainable development goals regarding food security, climate action, and marine conservation (Jiang et al. 2022). One biological concern surrounds the escape of synthetically produced fish into native environments. The farmed species could act as invasive species that outcompete existing populations, decreasing biodiversity in the area (Brosse et al. 2021). Conversely, rather than acting as a competitor to native species, these new fish could interbreed and hybridize with endemic populations. Although aquaculture does offer a promising solution to address issues in commercial fishing, it also raises significant concerns surrounding fish growth and development into adulthood that can be addressed through environmental analysis.

The rise of fish farming has also drawn attention to the issue of biological waste production and nutrient loading. Nutrient loading by fish farms has impacted seawater's nitrogen and phosphorus contents, promoting the growth of periphyton and leading to eutrophication (Du et al. 2022). The dense growth of algae and periphyton from the increased availability of nutrients decreases turbidity and limits photosynthesis, creating unhealthy conditions that threaten fish survival (Chislock et al. 2013).

There is limited environmental modeling done on how different environmental conditions impact Atlantic Salmon populations in fish farms which has prompted me to explore the water quality and fish activity at a farm in Norway, the world's leading producer of *Salmo salar* ("Salmon - Main producers see record-breaking exports" 2023). In this study, I focus on the effects of different water quality parameters and ask how *Salmo salar* behavior correlates with varying conditions in their dynamic physical environment. I pose three sub-questions to address my central research question: (1) How does fish behavior correlate with varying water temperatures? (2) How does fish behavior correlate with varying dissolved oxygen levels? (3) How does fish behavior correlate with varying salinity levels? I predict that: (1) temperature will have a negative cubic relationship with the depth at which fish swim (2) dissolved oxygen will have a negative linear relationship with the depth at which fish swim (3) salinity will have a positive cubic relationship at which fish swim. I will evaluate my central research question by producing regression and generalized additive models based on the available acoustic sensor data, ecograms, and water quality data.

METHODS

Study site

The observed population of Atlantic Salmon (*Salmo salar*) was raised at a commercial salmon farm and research facility in Tristeinen i Ørland kommune (63° 52′ N, 9° 37′ E), an island in Norway located off the southeastern coast. Norway has a maritime climate characterized by harsh winters with extreme storms and cold temperatures. Generally, coastal areas have lower seasonal variation than inland regions. The average annual temperature is around 8.19℃ and the average annual precipitation is 5.61 cm, the majority of which occurs from September to November ("Weather statistics for Tristein as a graph" 2022.).

The study site is located in Ørlandet off the coast of Vallersund. Tristein is one of the most exposed sites with occasional heavy waves and moderate currents. It consists of a feed barge, as well as a frame mooring for 10 cages which have a circumference of 157 meters, 15-meter sides, and come to a cone at 32 meters. Typically, a 7-meter lice skirt is used to enclose the space. The water depth at the site varies between 1-15 meters with dissolved oxygen and temperature being recorded at 1m, 5m, 8m, and 15m. The echosounder has data recorded for 1m, 3m, 5m, 8m, and 15m depth, and salinity is referenced at 3m, 5m, and 12m. The operation of the farm is characteristic of the other salmon farms in the region.

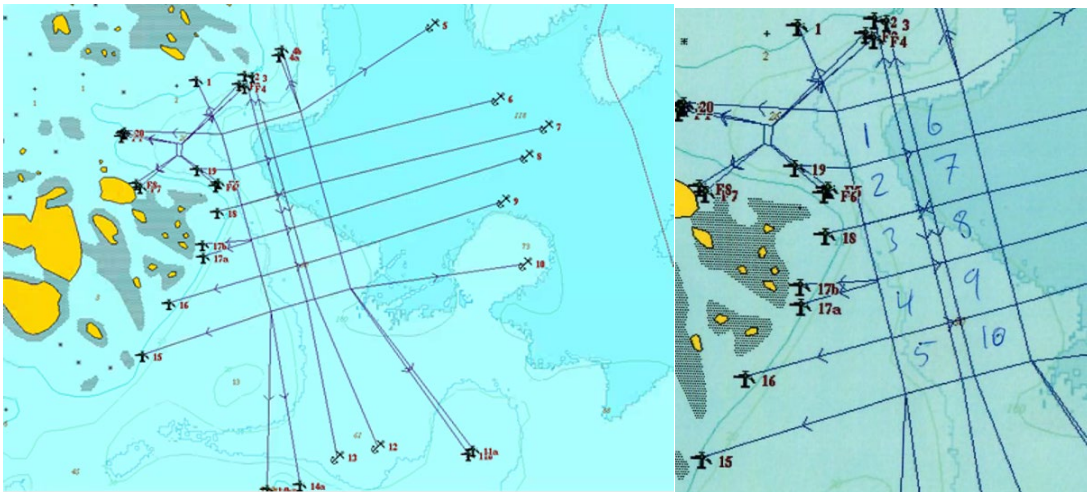

Figure 1: Fish farm facilities in Tristeinen. Left image shows the anchor placement of the site. Right image includes the cages and assigned numbers.

Figure 2: Drone image of the study site. The orange star marks cage number 8 where the data in this study was collected.

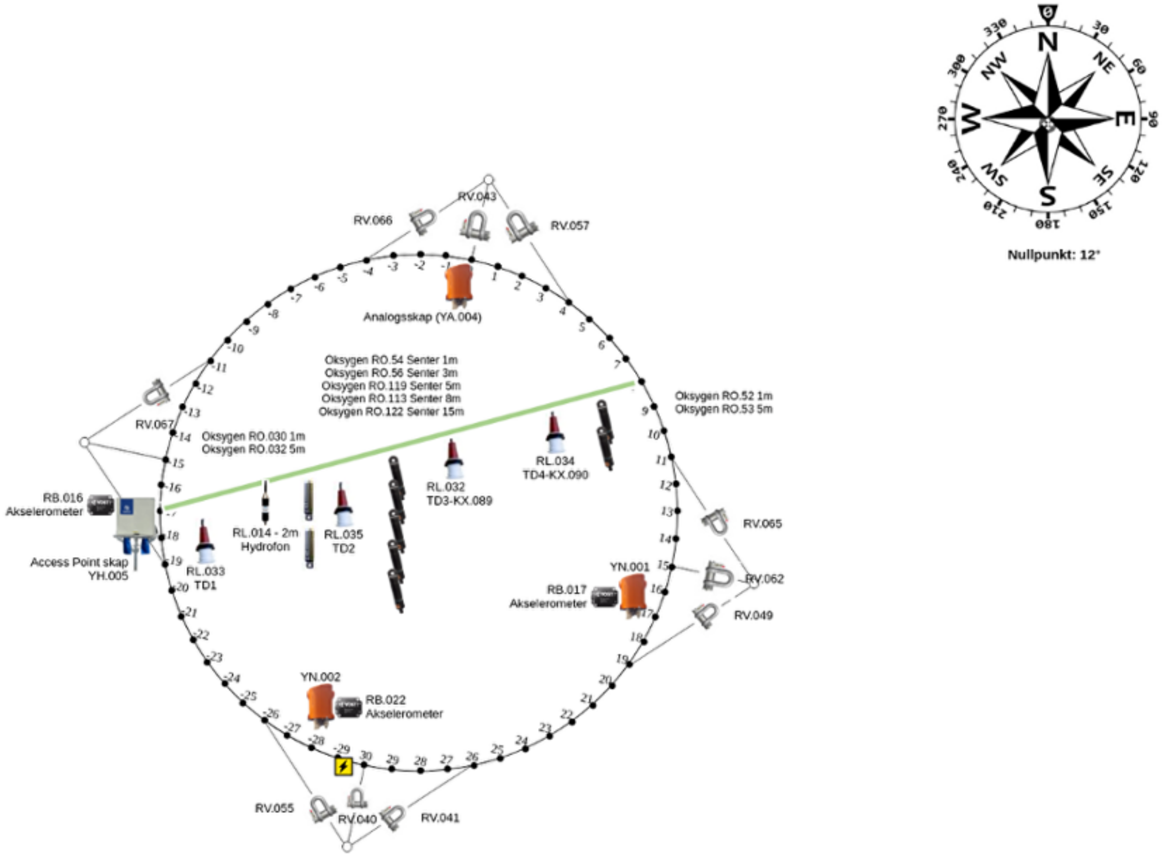

Figure 3: Equipment placement on the cages. The four red and white icons along the green line labeled RL.035, RL.033, RL.032, and RL.034 represent the echosounders.

Data collection

The Aquaculture Technology department in the Ocean Unit at SINTEF Ocean collected the data used in this study. The data used in this study is from a two-week time period in August 2023 (18/08-31/08). I chose this time frame based on the availability of temperature, dissolved oxygen, and salinity data. Temperature was recorded approximately every 10 minutes at each depth. The team collected echosounder data with the Transducer 200-28CM from Simrad, commonly referred to as the Simrad EK15 which has an operational frequency of 200 kHz and a small beam opening at 28 degrees ("Simrad EK15" 2014). For dissolved oxygen, I acquired the Seabird SBE 63 Optical Dissolved Oxygen Sensor data from the 1m, 5m, 8m, and 15m depths. This sensor has a 1 Hz sampling speed with RS-232 output and is used to assist in stoichiometric ocean chemistry research ("SBE 63 Optical Dissolved Oxygen Sensor" 2014). On average, sensors collected the dissolved oxygen content of the water 4,270 times a day. To get salinity and temperature data, I accessed data measured by the Seabird SBE 19plus V2 SeaCAT Profiler CTD sensor, commonly referred to as a CTD or a conductivity, temperature, depth sensor. This sensor measured at 4 Hz and minimized salinity spiking caused by ship heaves through pump-controlled, T-C ducted flow ("SBE 19plus V2 SeaCAT Profiler CTD" 2023.). The CTD data profiles the cage at 3m, 5m, and 12m depths. Sensors recorded salinity measurements 765 times a day on average across all depths.

Data analysis

I define fish activity in my project as the depth at which fish density is the highest. In order to interpret fish activity, I first visually inspected the processed echogram data and noted when density tended to be the greatest. SINTEF uses a program called Echoview to help process the extensive hydroacoustic data. Dr. Kristbjörg Edda Jónsdóttir cleaned the echosounder data and found a proxy for depth of maximum density by integrating a 10 min x 1 m, applying different window filterings, then employing an inbuilt algorithm to determine the depth at which fish density is the greatest. After examining the data visually, I began to plot the relationship between each of the three predictors (dissolved oxygen, salinity, and water temperature) and the fish density in separate scatter plots to see the overall trends. I used Python 3.9.6 as well as Pandas, NumPy, Seaborn, Matplotlib, Datetime, and Pygam to produce these plots and create regressions.

There were four channels in cage 8 that collected temperature, dissolved oxygen, and salinity data. My preliminary plots took these channels into account. However, there were no visually clear discrepancies between how the different channels affect the relationship between the water quality parameters and fish activity. As a result, I chose to take the average value across the four channels at a given timestamp for each water quality parameter.

I performed different polynomial regressions for each water quality parameter (temperature, dissolved oxygen, salinity). I tested models of different degrees (d=1, d=2, d=3, d=4) to represent relationships in the data. I opted for the mean squared error loss function to quantify the difference between predicted values and results because I want to penalize large residuals more than small residuals. To fit the model, I minimized loss by differentiating the equation $MSE(\theta_0, \theta_1) = \frac{1}{n}\sum_{i=1}^{n} (y_i - (\theta_0 + \theta_1 x_1))^2$ once with respect to θ_0 and again with respect to θ_1. After determining which polynomial regression model was the best fit, I plotted the equations on the scatter plots corresponding to the same water quality parameter.

In addition to regression analysis, I tested different generalized additive models to help explain the relationship between all three water quality parameters and fish activity. Generalized Additive Models (GAMs) is a nonparametric method that calculates the best function for each predictor term and the predictand (Vislocky and Fritsch 1995). I produced 12 different GAMs with three different sets of "lam" values to control the smoothness of an estimated function based on the scatterplots. Additionally, I employed tensor products and constraints for certain models to produce a better variety of candidate models. The following models had the same set of "lam" values: models 1, 4, 7, 10; models 2, 5, 8, 11; models 3, 6, 9, 12. Models 7-12 assumed collinearity between the water quality parameters. Models 4-6 and 10-12 included constraints based on existing literature on how a given water quality parameter affects the depth at which fish swim. To ensure I selected the correct model I used the Akaike Information Criterion (AIC) equation $AIC = 2K - 2ln(L)$, where K is 1 + the number of independent variables in the model and L is the likelihood the model could have produced the same result as the model.

RESULTS

Temperature and fish activity

I found that all four channels within cage number 8, had similar temperature measurements at a given time. The polynomial equation with d=4 was found to have the lowest mean square error value. However, the height at which fish swam was not strongly correlated with temperature levels (Figure 4). The relationship between temperature and the depth at highest density generally followed a convex parabolic relationship which is indicative of a polynomial regression with a degree of 2. The calculated mean squared error for the d=4 equation was about 6.955 and the value for the d=2 equation was about 6.983. An interesting observation to note is that the depth at highest density seems to vary more between the 13.25 and 14.00 degree Celsius range (Figure 4).

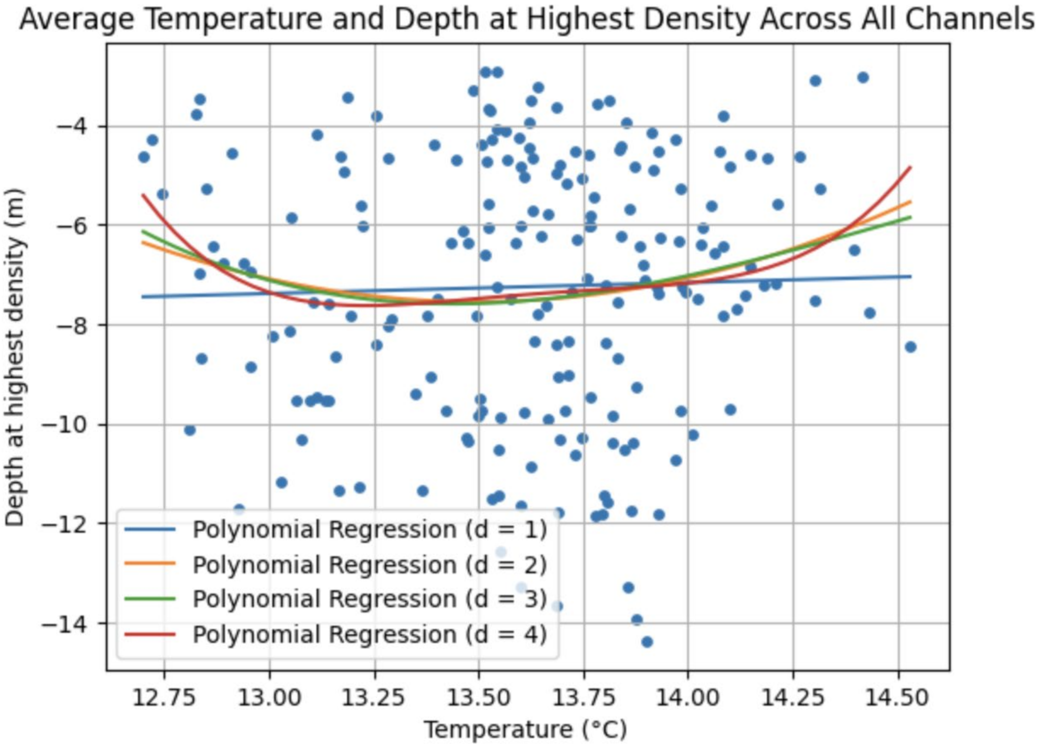

Figure 4: Polynomial regressions for temperature and depth. Scatter plot of average temperature data points for a given timestamp across the four channels vs. the depth at which the highest density of fish occurred with different polynomial regressions.

Dissolved oxygen and fish activity

I found that all four channels within cage number 8, had similar dissolved oxygen measurements at a given time. The polynomial equations with d=3 and d=4 were found to have the lowest mean square error values of about 6.078. However, the height at which fish swam was not strongly correlated with dissolved oxygen levels (Figure 5).During periods with lower dissolved oxygen levels, fish tended to reside at deeper depths, and during times of higher dissolved oxygen levels, fish tended to swim near the surface. An interesting observation to note is that the depth at highest density seems to vary more between the 60% and 80% dissolved oxygen range (Figure 6).

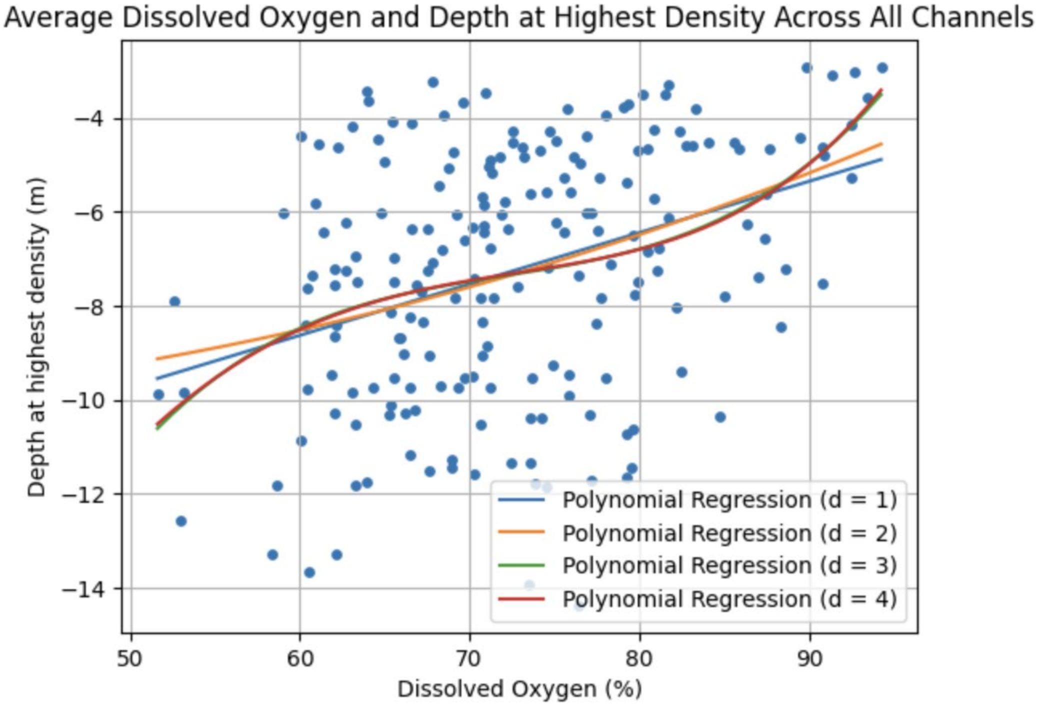

Figure 5: Polynomial regressions for dissolved oxygen and depth. Scatter plot of average dissolved oxygen data points for a given timestamp across the four channels vs. the depth at which the highest density of fish occurred with different polynomial regressions.

Salinity and fish activity

I found that all four channels within cage number 8, had similar temperature measurements at a given time. The polynomial equation with d=4 was found to have the lowest mean square error

value of about 6.637. However, the line equation does not visually appear to fit the data where the majority of data points fall between the 34 and 34.5 ppt salinity range
(Figure 6).

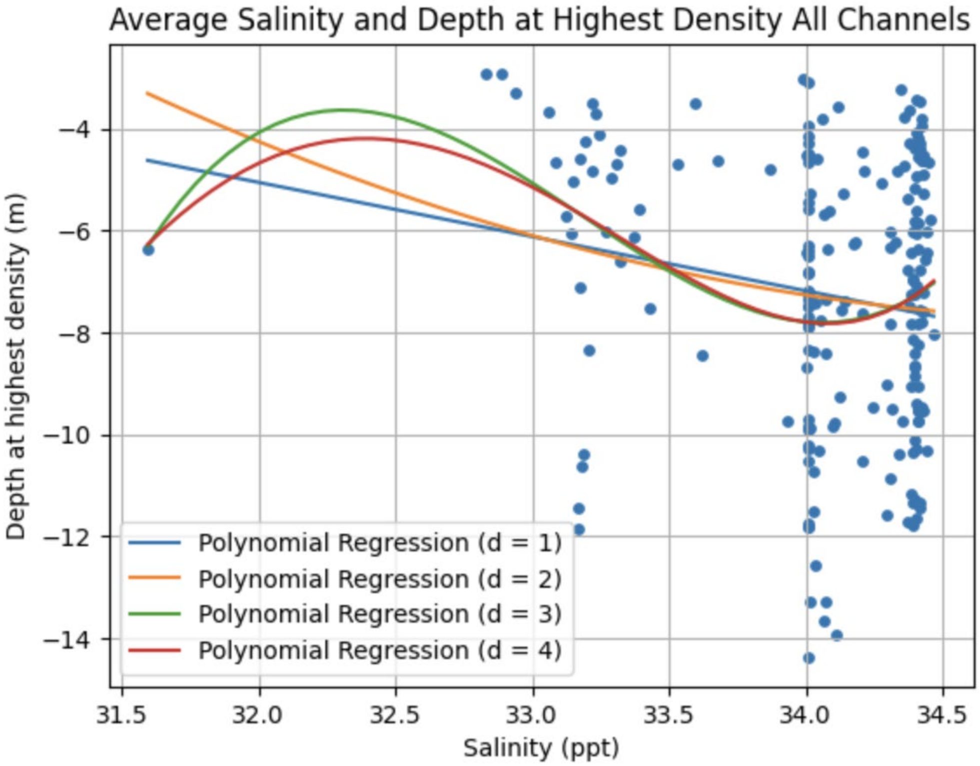

Figure 6: Polynomial regressions for salinity and depth. Scatter plot of average salinity data points for a given timestamp across the four channels vs. the depth at which the highest density of fish occurred with different polynomial regressions.

Generalized additive models

I found that the GAM 3 had the lowest AIC value and was therefore the best model out of the candidates (Figure 7, Table 1). Models 10-12 that assumed collinearity and included constraints did not converge which is why they are not included in the partial dependence plots. Model 3, similarly to models 1 and 2, assumed no collinearity and did not include constraints. Additionally, model 3 included a "lam" value of 10 to temperature, 1 to dissolved oxygen, and 50 to salinity. This set of "lam" values were the same set that was applied to models 6, 9, and 12. These values were chosen based on how correlated the different parameters were to the depth at highest density. A higher "lam" value was assigned when there was not a strong correlation observed to penalize "unsmooth" data. Conversely, a lower "lam" value was assigned when there was a relatively stronger correlation between a water quality parameter and depth at highest density. The equation for model 3 is $y = -0.28i + 2.41x_1 + 1.47x_2 + 0.54x_3$, where i is an intercept term, x_1 is the function relating temperature to fish activity, x_2 is the function relating dissolved oxygen to fish activity, and x_3 is the function relating salinity to fish activity.

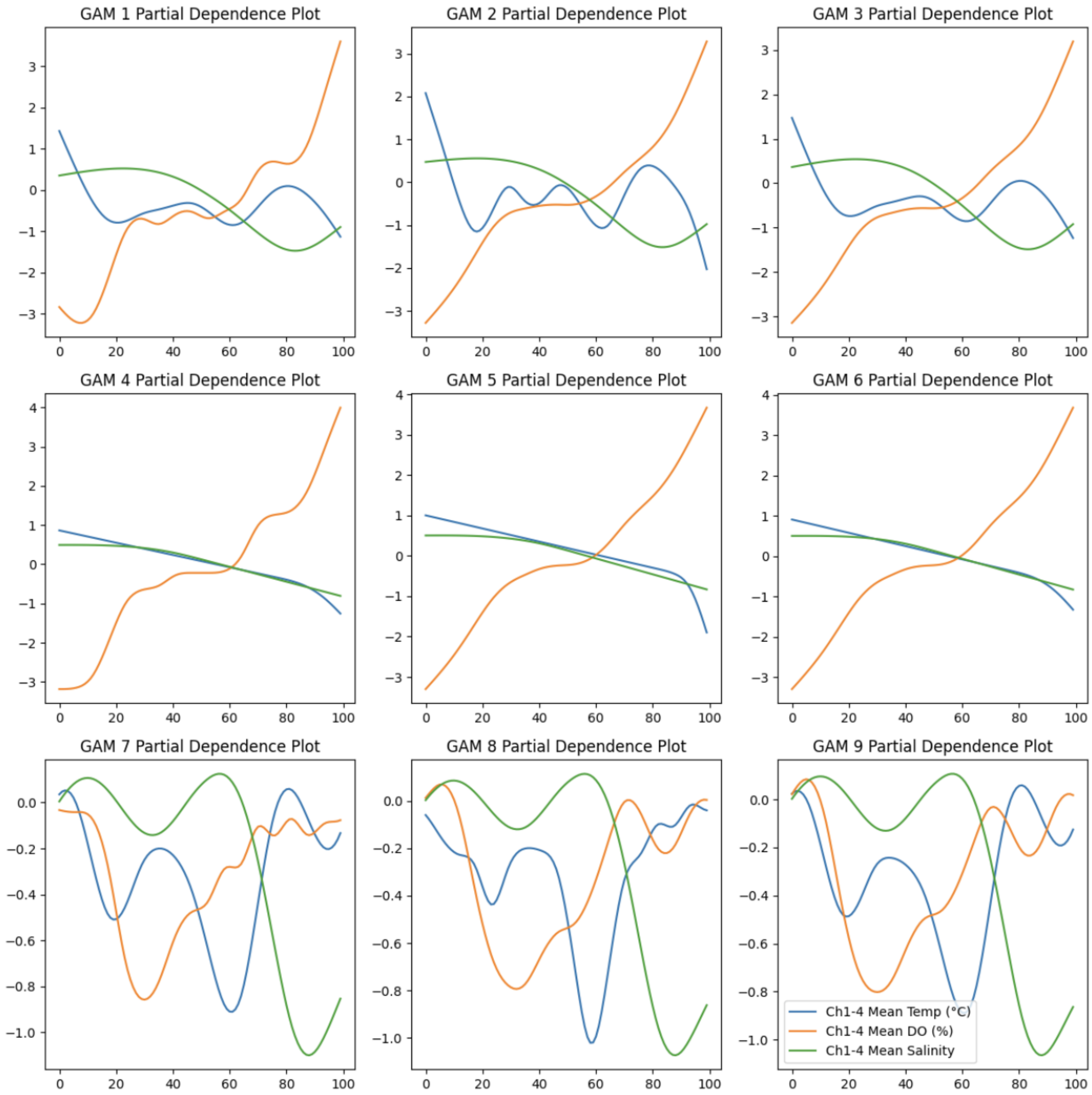

Figure 7: Partial dependence plots. GAMs include temperature (blue), dissolved oxygen (orange), and salinity (green).

Table 1: GAMs and their calculated AIC values given different conditions. Models in the same LAM group were assigned the same set of values for the temperature, dissolved oxygen, and salinity functions. Three different sets of

LAM values were explored. GAMs that included constraint terms were assigned a 'Y' while GAMs that did not include a constraint term were marked with a 'N'. GAMs that assumed collinearity and therefore included a tensor product were denoted with a 'Y', and GAMs that did not assume collinearity represented with a 'N'.

Model	LAM Group (#)	Constraints (Y/N)	Collinearity (Y/N)	AIC Value
GAM 1	1	N	N	370.54738
GAM 2	2	N	N	369.26308
GAM 3	3	N	N	367.01724
GAM 4	1	Y	N	368.95338
GAM 5	2	Y	N	368.55233
GAM 6	3	Y	N	368.45129
GAM 7	1	N	Y	376.79485
GAM 8	2	N	Y	378.65457
GAM 9	3	N	Y	376.94681
GAM 10	1	Y	Y	N/A
GAM 11	2	Y	Y	N/A
GAM 12	3	Y	Y	N/A

DISCUSSION

Temperature

Temperature had a quartic relationship with the depth at which fish swam in this study, but this result may have occurred due to overfitting. Based on the literature, I had expected during warmer time periods, fish would swim at deeper depths where the temperature was lower. When temperature levels were lower than the optimum range for mature Atlantic Salmon, fish would swim at shallower depths. Regardless of the life cycle stage, Atlantic salmon need cool, but not freezing cold, water to survive. During the incubation period, salmon eggs should remain in the 5-10°C range with increased mortality and deformity rates occurring at temperatures above 12°C (Solomon 2008). Atlantic salmon alevins can withstand temperatures up to 22°C, and the upper fatal range during the parr stage is 29.5°C. Ultimately, the ideal temperatures for growth are between 6°C and 22.5°C. All the recorded temperatures data points fell in this range which may have contributed to these not strongly correlated results. Fluctuating water temperatures can arise from a variety of factors and have devastating effects on Atlantic Salmon populations. Maintaining temperatures within the ideal range for Atlantic Salmon is important for proper growth and existence until adulthood. Modeling the relationship between these two variables offers key insight into *Salmo salar* activity which can be useful for fish farmers as they refine their aquaculture methods.

Climate change is already threatening the environments salmon require to survive. With rising mean atmospheric global temperatures, water temperatures are also increasing. Water temperature can affect the development of young salmon by speeding up their incubation stage and causing defects and/or death (Crouse et. al). Again, the dynamic qualities of the ocean and the impact of humans will continue to influence water temperatures and Atlantic salmon well-being.

Dissolved oxygen

Dissolved oxygen had a cubic correlation with the depth at which fish swam. Dissolved oxygen levels in Atlantic Salmon sea cages, such as the ones the investigated population currently resides in, fluctuate greatly (30-120% O_2) depending on tidal, seasonal, and spatial variations. At the minimum, oxygen content for water that supports Atlantic Salmon populations should range from 68-120% O_2 (Remen 2012). Oxygen is vital for the growth and survival of living organisms that perform cellular respiration such as salmon. With lower-than-optimal oxygen levels in sea cages, these fish are at risk of stunted growth, slower metabolic rates, increased stress, and premature death. Maintaining dissolved levels within the ideal range for Atlantic Salmon is important for proper growth and existence until adulthood. Modeling the relationship between these two variables offers key insight into *Salmo salar* activity which can be useful for fish farmers as they refine their aquaculture methods.

Dissolved oxygen content in sea cages depends on algal photosynthesis, biological oxygen consumption, vertical and horizontal mixing of water and air, and solubility of oxygen (which decreases with temperature and salinity) (Remen 2012). In many areas around the world, dissolved oxygen levels have dropped with low-oxygen events becoming more frequent. As greenhouse gasses warm the planet, ocean temperatures also increase. Warmer waters tend to hold less oxygen and increase the rate at which marine organisms consume oxygen (Monserrat 2022). Another factor impacting the decreased dissolved oxygen levels is large nutrient discharges which can lead to eutrophication and hypoxic regions in the ocean. With low marine dissolved oxygen levels becoming a larger issue, it’s important to reflect on the impact these environments will have on Atlantic Salmon populations.

Salinity

Salinity had a quartic relationship with the depth at which fish swam in this study. However, the line equation does not visually appear to fit the data where the majority of data points fall between the 34 and 34.5 ppt salinity range. Based on the literature, I had expected that during time periods with higher levels of salinity, fish would swim at shallow depths where salinity tended to be lower. When salinity levels were lower than the optimum range for mature Atlantic Salmon, fish would swim at deeper depths. Likewise with temperature, the ideal salinity range for Atlantic Salmon (*Salmo salar*) depends on the life cycle stage a fish is at. Eggs should remain in pure freshwater after fertilization for egg swelling but can tolerate minute levels of salinity (1 ppt) afterward. High levels of salinity too early in the life cycle could result in stunted growth in *Salmo salar* parr and smolts (Duston 1994). As body size in freshwater parr increases, fish are able to survive in more saline environments. However, survival in seawater (> 30 ppt) is only attained after undergoing full smoltification at which case their optimum salinity range is 28-33 ppt (“The Farmed Salmonid Handbook”). Maintaining salinity levels within the ideal range for Atlantic Salmon is important for proper growth and existence until adulthood. Modeling the relationship between these two variables offers key insight into *Salmo salar* activity which can be useful for fish farmers as they refine their aquaculture methods.

Ocean salinity fluctuates in response to a variety of other water quality parameters, as well as biogeochemical pathways such as evaporation, precipitation, and ice melting. As climate change becomes more prevalent, ocean salinity levels will rise (Oslen et. al). The changing conditions will no doubt have an effect on Atlantic Salmon populations, thereby influencing different economies, cultures, and diets around the world.

Limitations and future directions

The data analyzed is taken from a specific sea cage off the coast of Norway that is regulated by SalMar, one of the world's largest salmon farming companies, and SINTEF Ocean. According to some of the scientists who work closely with the cages, the sensors have the capacity to be faulty. Additionally, the echo sounder which was used to record the depths fish are swimming at is dependent on sonic waves. Therefore, the device can likely experience inaccuracies for the estimated highest density depths. Another important detail to note is that the data being analyzed was taken over two weeks in August 2023. These numbers may vary depending on the time of the year and location. In summary, the generalizability may be low for this particular project.

Temperature, dissolved oxygen, and salinity all influence the depth at which this Atlantic Salmon population tends to swim. These three water quality parameters are also impacted by each other, creating a complex environment. As the effects of climate change are experienced more dramatically in the coming years, we need to investigate how these factors will be impacted since they are strong indicators of the survival of Atlantic Salmon, a species that has great environmental, economic, and cultural value.

I recommend that major fish farms continue to monitor the water conditions their fish are experiencing and partner with different research institutes like SINTEF Ocean. The data and insight scientists could provide can not only help the environmental science community but also offer fish farms important information that dictates their aquaculture operations. Also, as climate change rears its ugly head, the research could aid politicians in passing policies to help regulate these farmed salmon communities.

CONCLUSIONS

In this study I used echosounder and sensor datasets to study how fish behavior correlates with varying (1) water temperatures, (2) oxygen levels, and (3) salinity levels. I found general trends in the data and observed that dissolved oxygen was the most strongly correlated with fish activity in polynomial regressions, but the function for temperature had the largest coefficient in the best generalized additive model. This prompts us to reflect on how aquaculture for other species in Norway and the rest of the world should be managed and regulated.

Current literature suggests that the ocean conditions are changing as a result of climate change which in turn affects marine species. These findings underscore the importance of examining and adapting current fish farming methods. This study adds to the discussion surrounding advantages, disadvantages, and considerations of aquaculture by delving into effects of dynamic marine environments on Atlantic Salmon populations.

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