Evaluation of Some Environmental Parameters for Salmon Aquaculture Cage Sites in Fortune Bay, Newfoundland: Emphasis on the Occurrence of Hypoxic Conditions

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EVALUATION OF SOME ENVIRONMENTAL PARAMETERS FOR SALMON AQUACULTURE CAGE SITES IN FORTUNE BAY, NEWFOUNDLAND: EMPHASIS ON THE OCCURRENCE OF HYPOXIC CONDITIONS

by

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ABSTRACT

Mansour, A., Hamoutene, D., Mabrouk, G., Puestow, T. and Barlow, E. 2008. Evaluation of some environmental parameters for salmon aquaculture cage sites in Fortune Bay, Newfoundland: emphasis on the occurrence of hypoxic conditions. Can. Tech. Rep. Fish. Aquat. Sci. 2814: vi + 21 p

Three Atlantic salmon marine cage sites at Fortune Bay, Newfoundland have been monitored by Fisheries and Oceans Canada in collaboration with fish farmers and the Newfoundland and Labrador Department of Fisheries and Aquaculture during the summer-fall of 2006-07 using real-time water quality monitoring equipment. The study objectives were to evaluate the water physical characteristics and the variability of dissolved oxygen (DO) concentration over time, the relationship with other water quality variables and the identification and characterization of hypoxic events on the monitored sites.

The study reported that one site suffered from an extended period of hypoxia (i.e. DO < 6 mg/L) and the industry intervened later by physically reorienting the site. Intermittent hypoxic events with a mean duration of approximately 2 hours were reported at the other two sites when fish were present. No such events were recorded on one of these sites when left to fallow in 2007. At all sites, hypoxic events are more prominent in warmer waters confirming the reduced capacity of water to dissolve oxygen during periods of high temperature.

Given observed weakening of linear relationships between dissolved oxygen concentration and other water quality parameters (e.g. temperature, salinity) at hypoxic conditions, the dedicated collection of continuous water quality data at critical sites should therefore be considered. In addition to providing early warning of impending hypoxic conditions (especially when real-time data communications are enabled), a continuous monitoring program would allow for the quantitative analysis of long-term trends, seasonal variations and cyclical phenomena. Other relevant variables mainly water current measurements as well as fish behavior and movement should be studied further.

RÉSUMÉ

Mansour, A., Hamoutene, D., Mabrouk, G., Puestow, T. and Barlow, E. 2008. Evaluation of some environmental parameters for salmon aquaculture cage sites in Fortune Bay, Newfoundland: emphasis on the occurrence of hypoxic conditions. Can. Tech. Rep. Fish. Aquat. Sci. 2814: vi + 21 p

Les conditions environnementales de trois sites d'aquaculture de la Baie de Fortune, Terre Neuve et Labrador, ont été évaluées par le Département des Pêches et Océans en collaboration avec des aquaculteurs de la région en été/automne de 2006 et 2007. L'objectif de cette étude étant la caractérisation des propriétés physiques de l'eau et en particulier des conditions d'oxygénation des sites.

Les résultats montrent que l'un des sites utilisés présentait des périodes de longue hypoxie (DO< 6 mg/L). Les cages de ce site ont fait l'objet de réorientation suite à ce constat. Des épisodes intermittents d'hypoxie d'une durée moyenne de 2 heures ont été observés aux 2 autres sites lorsque les cages étaient en place. Un de ces sites ne présentait aucune hypoxie en l'absence de cages montrant que c'est bien la présence de saumons qui déclenchait l'hypoxie. Á tous les sites observés, l'hypoxie était plus importante lorsque les températures de l'eau étaient élevées confirmant la capacité réduite de l'eau à dissoudre l'oxygène lorsque la température augmente.

L'hypoxie s'accompagne d'un effet sur la linéarité des rapports entre les autres paramètres de qualité de l'eau (température, salinité). Il est donc nécessaire d'évaluer régulièrement tous les paramètres aux sites considérés critiques. L'évaluation des courants ainsi que des mouvements des poissons dans les cages sont aussi nécessaires à une caractérisation des sites.

INTRODUCTION

Newfoundland salmon aquaculture industry is vastly expanding to new sites on the island south coast with a promising economic boost to the rural communities affected by diminished fisheries. The environmental qualities of those sites are vital to this development. Physical characteristics of the water including temperature, dissolved oxygen, salinity and other interacting factors have a limiting effect on the site viability and carrying capacity. Fish survival, growth and health condition may be affected with one or more of these factors. Evaluating the suitability of those new sites is necessary for aquaculture industry success.

Oxygen level is one of the key environmental factors that affect fish welfare and development (Kindschi and Koby 1994). In the marine cage environment, levels of dissolved oxygen (DO) are often unpredictable, as they depend on other environmental factors, such as light, tidal current, and wind for water flow and oxygen mixing (Braithwaite and McEvoy 2005). During periods of high temperature, the capacity of water to dissolve oxygen is reduced while the metabolic rate of fish rises (Davis 1975). If these conditions coincide with poor circulation low DO levels and hypoxic conditions may exist that can be detrimental or even lethal (Johansson et al. 2006) to raised fish. DO is thus considered a promising candidate for monitoring environmental quality in the coastal zone, especially, when monitoring impact of aquaculture over hard bottoms. Nonetheless, substantial effort and resources are required to monitor DO concentrations and determine background levels (DFO 2005).

Over the past decade, real-time water quality (RTWQ) monitoring has emerged as an efficient and effective operational approach for the surveillance of critical water quality parameters at remote or inaccessible locations (Christensen et al. 2000). RTWQ systems consist of probes that measure water quality parameters at pre-defined intervals and store the information on digital data loggers without the need for any operator intervention. The data are either retrieved at the end of the measurement campaign, or transmitted in real-time via satellite or terrestrial communications networks which permit mitigation measures against unfavorable conditions to be taken immediately. While primarily used to monitor critical parameters affecting the quality of freshwater for human consumption, the potential of RTWQ for coastal zone and aquaculture applications is increasingly recognized.

In this study, three Atlantic salmon cage sites at Fortune Bay, Newfoundland (Maps 1 and 2), have been monitored by Fisheries and Oceans Canada in collaboration with fish farmers and the Newfoundland and Labrador Department of Fisheries and Aquaculture during the summer-fall of 2006-07. The study aims to evaluate the water physical characteristics and the variability of dissolved oxygen concentration over time, the relationship with other water quality variables and the identification and characterization of hypoxic events on the monitored sites.

MATERIAL AND METHODS

Three Atlantic salmon marine cage sites at Fortune Bay were monitored using YSI® 6600 series and 600 XLM sondes. Sites A and B were each monitored in summer-fall 2007 with three sondes hanging in the middle of the site next to a cage on three different levels, (2 m, 8 m and 14 m). Depths were chosen on the basis of our previous work that determined the preferable depth Atlantic salmon choose to spend most of its time at marine cages (Pepper et al. 2003). Both sites were active with 450,000 fish introduced in 2006 at Site A, and 500,000 fish introduced at Site B in 2007. Cage Site C was monitored at 5 m and 8 m depth during summer-fall 2006 where it was stocked with 550,000 fish. It was monitored again in summer-fall 2007 where it was left to fallow with no production fish at the site, only about 2000 brood stock fish where kept at about 100 m downstream from the sondes. Due to batteries defects, some sondes failed to record and their results were omitted from this study. Table 1 shows detailed information about dates, sites, depths and parameters recorded every 20 minute intervals at each site location. Data collected for each environmental parameter were then statistically examined.

Water depth was expected to remain relatively constant, with variation solely attributed to tidal movement and wave action. However, in several cases the probes had been displaced by man-made activities, which was clearly identifiable as spikes in the depth measurements. All cases affected by man-made displacement were removed from further analysis.

STATISTICAL ANALYSIS

Time series data acquired by water quality probes are characterized by a high degree of correlation. In addition, the distributions of individual water quality parameters are frequently non-normal (McLeod et al. 1983; Berryman et al. 1988). A statistical analysis of time series data typically aims at identifying the underlying trends as well as cyclical or periodic properties of the series. This requires usually the collection of data over sufficiently long time frames to capture yearly as well as seasonal variability (Loftis et al. 1991). Since the time series acquired for this investigation are comparatively short, an analysis of trends and seasonal variability was not feasible. Emphasis was instead placed on non-parametric methods of exploratory data analysis, concentrating on dissolved oxygen concentration as indicator of hypoxia and temperature as an important controlling variable of dissolved oxygen. For each site, the variability of dissolved oxygen and temperature over time was investigated and the number and duration of hypoxic events identified. Hypoxic conditions were assumed to be present at dissolved oxygen concentrations of less than 6 mg/L. Below this concentration, salmon have been shown to exhibit symptoms of oxygen distress (Davis 1975) and usually the industry stops feeding the fish as a precautionary approach.

The linear correlation between water quality parameters was assessed using Spearman's rank correlation coefficient and bivariate scatter plots. The water quality regimes between the different sites were compared using graphical summary plots. The interaction of different water quality variables and their relationship with dissolved oxygen concentration was further investigated using decision tree analysis (DTA). DTA allows the formulation of relationships between one response (i.e. dependent) variable and several predictor (i.e. independent) variables by dividing a data set recursively into smaller, increasingly homogeneous portions. The final result constitutes a division of the original data set into mutually exclusive and exhaustive sub-sets (Morgan and Sonquist 1963; Kass 1980; Breiman et al. 1984; Biggs et al. 1991). Performed for either exploratory analysis or predictive modeling, DTA requires no limiting assumptions about data distributions, allows the simultaneous handling of categorical and continuous variables in the same data set, and permits the detection of non-linear interactions between variables (Lees and Ritmann 1991; Amrhein et al. 1999; Crall et al. 2006). These properties make DTA ideally suited to problems with limited or no a-priori knowledge about the distribution and interaction of parameters in question (Puestow et al. 2001; Hamoutene et al. 2007).

DTA was carried out using the procedure described by Breiman et al. (1984). At every level of the tree, stepwise splitting is performed by examining each of the predictor variables in turn and selecting the predictor resulting in the smallest within-group sum-of-squares for a binary split. The splitting criterion is expressed as proportional reduction in error (PRE), with a minimum PRE of 0.05 required for a split to result for any given predictor variable. The procedure supports both continuous and categorical variables. The risk of overfitting was by specifying a minimum number of cases, or stop size, for the creation of new nodes (Puestow et al. 2001). That is, if a given node contained fewer observations than the specified stop size it was not further partitioned. A stop size of five was selected for all tree models.

For each site, the following analysis was performed:

- Variability of individual variables, time series plots.
- Rank correlation analysis: the rank correlation coefficient was used in order to minimize the impact of serial correlation and non-normality on the analysis.
- Daily summaries of principal water quality parameters.

RESULTS

Although RTWQ used recorded a long list of water physical characteristics as shown in Table 1, only data of dissolved oxygen (DO, mg/L); temperature (T, °C); salinity (ppt) and pH are presented in this report.

GENERAL OBSERVATIONS AND HYPOXIC EVENTS

Monitoring Site (A) in 2007

Data ranges, means, medians and variability of DO, T, salinity and pH for measurements conducted at a nominal water depth of 2 and 14 m are presented in Table 2. No pH measurements were recorded at 14 m depth.

At 2 m, a total of 20 hypoxic events were recorded over the period of measurement (Fig. 1). Out of these, 12 were recorded for a single interval only of 20 minutes duration. However, the average duration of the hypoxic events during the total observation period was 47 minutes. Most of these events (19) occurred at night. A general cooling trend was apparent over the observation period as shown from the figure. At 14 m, no hypoxic event was detected over the month of September and October, 2007, however a similar decrease in water temperature over the same period was observed at that depth.

Monitoring Site (B) in 2007

The data shows a persistent state of hypoxia that was recorded in the water next to the Atlantic salmon cages in that site, both at 2 m and 14 m depth during the period from September 5 to October 10, 2007 (Fig. 2 and 3). Summary of the data measurements of dissolved oxygen, temperature and salinity are presented in Table 3. DO was persistently low at 14 m depth with concentrations ranged from 0.38 mg/L to 2.18 mg/L and a mean of 1.13 mg/L. However, at 2 m depth, only the first seven measurement intervals recorded levels higher than 6 mg/L where the DO decreased from an initial level of 8.89 mg/L to less than 6 mg/L in just 140 min.

Similarly to Site A, a general cooling trend is apparent over the entire period at both 2 m and 14 m with a sharp decrease in temperature on the night of September 13, 2007. That coincided with a sharp increase in DO at the same time as indicated in the graphs.

Monitoring Site (C) in 2006

Data collected in 2006 from Site C are summarized in Table 4. A total of 69 hypoxic events were detected over the observation period (Fig. 4). Forty three of these events (62%) lasted one or two measurement intervals (20-40 min). On August 26th and 28th, the duration of the hypoxic events extended 16 intervals (i.e. total of 320 min). The majority of events (88%) occurred in August. The average duration of hypoxic events over the observation period was 63 min. The data shows that those hypoxic events occurred any time during the day. On the other hand, water temperature decreased from around 17ºC in early August to an average of 11ºC by the end of the observation period in early October, 2006.

Monitoring Site (C) in 2007

Table 5 shows data ranges, means, medians and variability of DO, pH, salinity and water temperature measured at a nominal water depth of 5 and 8 m at Site C in 2007. The site was left to fallow during 2007. No hypoxic events were recorded at 5 or 8 m depth during the measurement period. At 5 m, the level of dissolved oxygen decreased from around 10 mg/L in July to a minimum of 6.19 mg/L in mid-August, before rising again to between 9 and 10 mg/L in mid-October. At 8 m, the level of dissolved oxygen decreased from more than 11 mg/L in July to a minimum of 7.47 mg/L in mid-August and inc0reased again to 9-9.5 mg/L in mid-October. Figure 5 shows mean daily dissolved oxygen concentrations (± SD) over the comparable dates in August of 2006 and 2007. It appears that DO at the same recorded point was generally less in 2006 than 2007.

At 5 m, water temperature increased from around 12°C in July to reach its maximum of 20.22°C in early August, before decreasing again to 10°C by the end of the observation period in mid-October. The average temperature observed over the entire period is 13.93°C. At 8 m, a similar trend was observed, with a temperature increase from around 9°C in July to a maximum of 18°C in mid-August, before decreasing again to 10°C by the end of the observation period. The average temperature observed over the entire period was 13.02°C. Sharp increases and decreases in temperature linked well with corresponding decreases and increases in dissolved oxygen concentration (e.g. early July, mid-September).

SIGNIFICANT CORRELATIONS AND DECISION TREE ANALYSIS RESULTS

As stated in the description of the statistical analysis, rank correlation between water quality parameters was investigated as well as the relationship between dissolved oxygen and other parameters using decision tree analysis (DTA). DTA was applied on DO in mg/L to explore parameters influencing oxygen values at different sites and different depths. Four predictors were used: pH, temperature, salinity, and chlorophyll to summarize measurements performed (specific conductance being correlated to conductivity and temperature, salinity being the result of calculations with specific conductance, etc.). Figure 6 is an example of a decision tree applied on Site A at 2 m. Not all DTAs are presented in this report, but the results of important predictors for DO are summarized in Table 6. In most cases, results showed that temperature is the main predictor influencing DO.

Rank correlation revealed high correlation coefficients between salinity, specific conductivity, and TDS. Specific conductance is found to be a good measure for the concentration of TDS and salinity, these correlations are therefore expected. A negative correlation is found between temperature and DO only for data of Site A; 14 m depth, Site C; 5 and 8 m depth in 2007, and Site C 5 m depth in 2006. These first three sets of data showed no hypoxic events, while intermittent hypoxia was observed at Site C at 5 m in 2006.

Traditionally, a water mass is characterized by the most typical values or ranges of temperature and salinity defined by the joint analysis of temperature and salinity (Postnov et al. 2007). Table 7 summarizing coefficient correlations between temperature (T) and salinity (S), is presented below to help identify patterns of water circulation on the considered sites. Temperature and salinity are negatively correlated in all cases with low correlation for Site A (2 m) and Site C (5 m).

DISCUSSION

This study showed the presence of hypoxic conditions defined when the dissolved oxygen levels dropped below 6 mg/L in all monitored sites during summer and early fall 2006-07. Site B showed continuous hypoxic events at both measured depths (2 and 14 m). On the other hand, intermittent hypoxic events, with a mean duration of approximately 2 hours, were reported at Site A at 2 m and in Site C at 5 m depth, only when fish were present on the site. Oxygen conditions in a site can be influenced by fish themselves through factors such as oxygen consumption (Johansson et al. 2006), and attenuation or increasing of the current due to their presence or movements (Chacon-Torres et al. 1988). This may explain the situation at Site C that generally recorded lower DO when fish were present at the site in 2006 during comparable times of the year in 2007 at the same recording station.

At all sites, hypoxic events are more prominent in summer months confirming the reduced capacity of water to dissolve oxygen during periods of high temperature (Davis 1975). Continuous hypoxia reported at Site B raises a red flag on using this site for growing salmon during summer months. While salmon kept at low density on this site in 2007 with the 2007 year class (average weight about 500 gm at the time of monitoring), condition may vary when fish reach market size later in 2008. The industry has reoriented the cage structure at this site to alleviate those concerns and they will closely monitor the fish development in 2008. It is generally accepted that DO at levels lower than 5 mg/L in aquaculture facilities may cause chronic stress and is insufficient to support optimal fish growth, though not lethal unless it falls below 1 mg/L (Brett and Groves 1979; Neill and Bryan 1991).

In this study, sondes were deployed outside cages. Oxygen levels inside cages differ from reference points outside the cages and are dependent on the oxygen consumption of the fish (Oppedal et al. 2007). Nonetheless, it can be assumed that hypoxic conditions measured in points located outside cages are indicative of the lack of available oxygen for fish kept in close vicinity of these monitoring points.

DTA and rank correlations showed no interaction between chlorophyll and oxygen levels at all sites confirming the fact that photosynthesis capacity within a farm site is insufficient to supply the demand of the biomass of fish (Wildish et al. 1993). Oxygen requirements must be therefore met by physical transport with water currents being regarded as the most important factor for transporting oxygen to cage systems (Johansson et al. 2006). So, in future studies, water current measurements would be an essential complement to RTWQ use on aquaculture sites.

DTA revealed also that temperature was the most important predictor for DO in most sites. Johansson et al. (2007) found that regression tree analysis applied to water quality parameters at fjord sites identified current velocity as an important factor explaining the variability in oxygen levels. No evaluation of current direction or velocity was performed during this study but temperature changes could be indicative of the circulation of different water masses. Traditionally, a water mass is characterized by the most typical values or ranges of temperature and salinity defined by the joint analysis of these two parameters (Postnov et al. 2007). In a study on correlation between temperature (T) and salinity (S) in the North Atlantic, Postnov et al. (2007) found that analysis of the fields of correlation coefficient between T and S (multi-year data) showed that values superior to 0.6 are most typical of the North Atlantic in the upper 1000 m layer. According to the geographic location of the sites considered in this study, multi-year data characterizing the area as described by Postnov et al. (2007) should show low positive correlation ($0 < R < 0.6$) between temperature and salinity. In our study, 67% of the data had R values lower than -0.6; the remaining sites showed also weak negative relationships between T and S. This discrepancy between Postnov et al. (2007) observations and R values obtained in this study could be due to the fact that data considered here is seasonal and does not summarize a yearly trend. Whether the correlation is negative or positive, Postnov et al. (2007) concluded that regions with low correlation coefficients are regions of the formation of water masses. Our results suggest that Site A and Site C could be located in areas where mixing of surface water (5 m and 2 m) occurs making these sites more suitable for aquaculture. These statements remain of course speculative in nature without assessment of water circulation patterns in these areas.

The results of this investigation confirm the utility of RTWQ technology to monitor aquaculture sites for the occurrence of hypoxic conditions. The continuous observation of water quality using RTWQ probes at critical sites should therefore be considered. In addition to providing early warning of impending hypoxic conditions (especially when real-time data communications are enabled), a continuous monitoring program would allow for the quantitative analysis of long-term trends, seasonal variations and cyclical phenomena. Given observed deterioration of linear relationships between dissolved oxygen concentration and other water quality parameters (e.g. temperature, salinity) at hypoxic conditions, the dedicated collection of continuous water quality data would also support the in-depth examination of complex mechanisms controlling hypoxia. Other relevant variables mainly water current measurements as well as fish behavior and movement should be studied further.

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Table 1. Overview of water quality measurements at three Atlantic salmon sites in Fortune Bay, Newfoundland.

	Site (A)		Site (B)		Site (C)		
Nominal depth of probe and monitoring year	2 m (2007)	14 m (2007)	2 m (2007)	14 m (2007)	5 m (2007) - No fish	8 m (2007)- No fish	5 m (2006)
Start Date	Sep. 6	Sep. 5	Sep. 5	Sep. 5	Jul. 5	Jul. 5	Aug. 10
Start Time	14:01	20:01	20:01	20:01	09:01	09:01	20:41
End Date	Oct. 18	Oct. 8	Oct. 10	Oct. 10	Oct. 18	Oct. 18	Oct. 11
End Time	09:41	19:01	19:41	19:41	09:41	09:21	22:41
Measurement Interval	20 min	20 min	20 min	20 min	20 min	20 min	20 min
Chlorophyll (CHL) [µg/L]	✓	n/a	n/a	n/a	✓	✓	✓
Conductivity [mS/cm]	✓	✓	✓	✓	✓	✓	✓
Depth [m]	✓	✓	✓	✓	✓	✓	✓
Dissolved Oxygen (DO) [mg/L]	✓	✓	✓	✓	✓	✓	✓
Dissolved Oxygen (DO) [%]	✓	✓	✓	✓	✓	✓	✓
pH	✓	N/A	N/A	N/A	✓	✓	✓
Salinity [ppt]	✓	✓	✓	✓	✓	✓	✓
Specific Conductance [mS/cm]	✓	✓	✓	✓	✓	✓	✓
TDS [g/L]	✓	✓	✓	✓	✓	✓	✓
Temperature [°C]	✓	✓	✓	✓	✓	✓	✓

Table 2. Water quality parameter measurements at 2 M (N = 2868), and 14 M (N = 2375) at Cage Site (A) (September-October, 2007).

Water quality parameter	Min.	Max.	Median	Mean	Standard deviation
DO [mg/L]- 2m	5.06	9.44	8.06	8.21	0.76
pH- 2m	3.42	9.92	7.87	7.90	0.22
Salinity [ppt]- 2m	25.38	30.81	29.30	29.54	0.83
Temperature [°C]-2m	8.65	16.68	12.72	12.80	1.69
DO [mg/L]- 14m	9.83	16.89	12.68	12.69	1.12
Salinity [ppt]- 14m	30.05	32.47	31.21	31.21	0.32
Temperature [°C]- 14m	1.35	15.93	11.55	11.81	2.00

Table 3: Water quality parameter measurements at 2 m (n = 2520), and 14 m (n=2520) at Site (B) (September-October).

Water quality parameter	Min.	Max.	Median	Mean	Standard deviation
DO [mg/l]- 2m	3.65	8.89	5.22	5.28	0.39
Salinity [ppt]- 2m	26.50	33.29	30.81	31.19	1.10
Temperature [°C]-2m	5.85	16.58	13.24	13.01	1.52
DO [mg/l]- 14m	0.38	2.18	1.18	1.13	0.13
Salinity [ppt]- 14m	29.48	31.83	30.82	30.78	0.36
Temperature [°C]- 14m	1.23	16.08	11.19	11.57	2.31

Table 4. Water quality parameter measurements at 5 m (n = 4470) at Site (C) in 2006 (August-October).

Water quality parameter	Min.	Max.	Median	Mean	Standard deviation
DO [mg/l]	4.75	10.45	7.88	8.06	0.96
Salinity [ppt]	26.96	32.36	30.20	30.35	0.75
Temperature [°C]	2.06	18.09	13.57	13.63	2.78

Table 5. Water quality parameter measurements at 5 m (n = 7394) and 8 m (n=7331) at cage site (C) in 2007 (July-October).

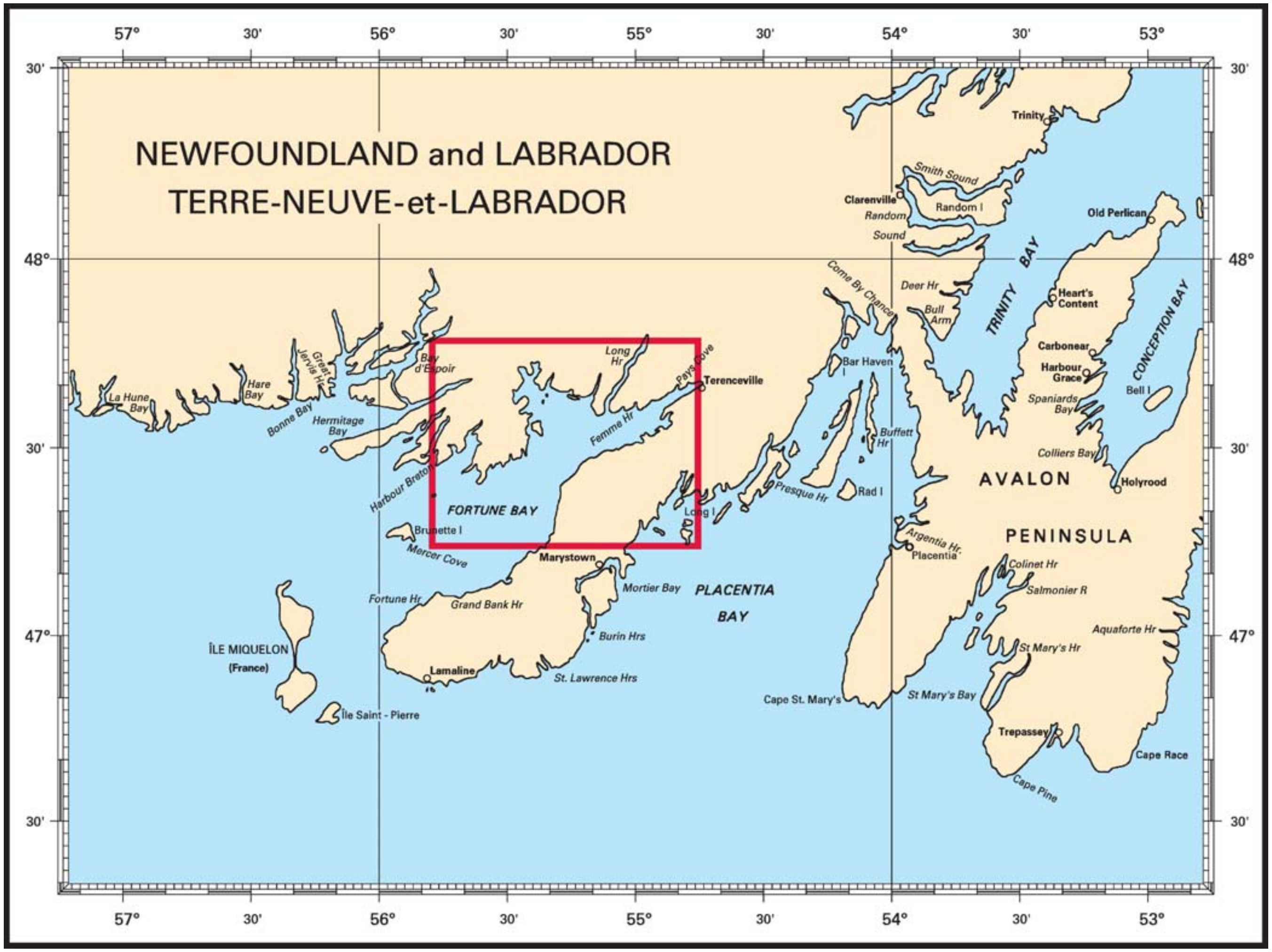
Water quality parameter	Min.	Max.	Median	Mean	Standard deviation
DO [mg/l]- 5m	6.19	9.84	8.23	8.32	0.94
pH- 5m	8.13	8.30	8.23	8.23	0.02
Salinity [ppt]- 5m	24.00	32.66	30.28	30.37	1.34
Temperature [°C]- 5m	7.91	20.22	14.25	13.93	2.29
DO [mg/l]- 8m	7.47	11.50	8.97	8.83	0.78
pH- 8m	7.86	8.37	8.17	8.28	0.18
Salinity [ppt]- 8m	24.93	32.84	30.44	30.57	0.75
Temperature [°C]- 8m	2.51	19.35	13.23	13.02	2.55

Table 6. First Level and Second Level Predictors of DO after Application of DTA with Four Predictors: pH, Temperature (Temp), Salinity, and Chlorophyll.

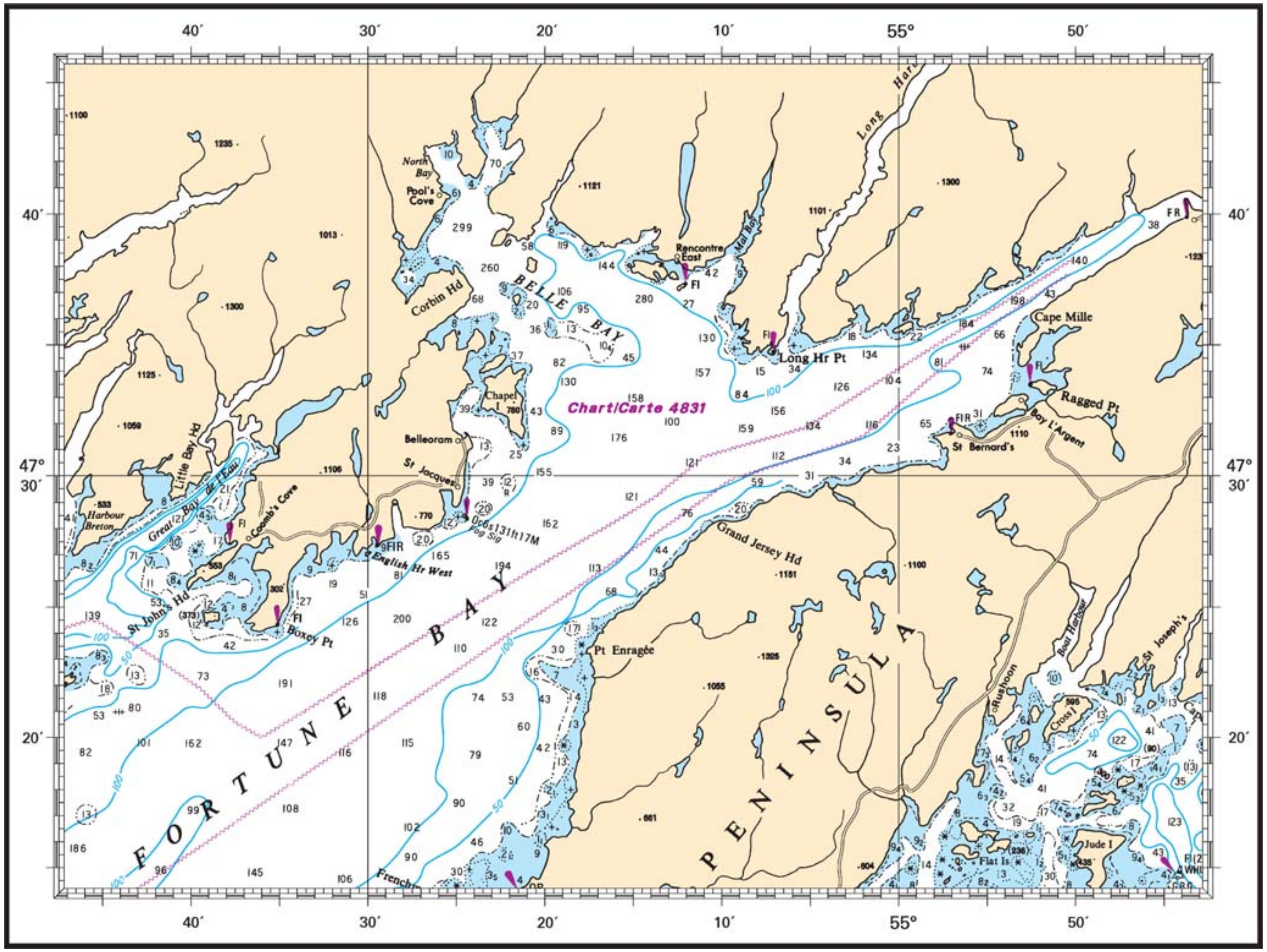
Sites	Site (A)		Site (B)		Site (C)		
Depth	2 m	14 m	2 m	14 m	5 m (2006)	5 m (2007)	8 m (2007)
Predictor 1	pH	Temp	Temp	Temp	Temp	Temp	Temp
Predictor 2	pH	Temp	Temp	Temp	Salinity	Temp + Salinity	Temp + pH

Table 7: Rank Coefficient Correlations between Temperature (T) and Salinity (S) at All Sites

	Site (A)		Site (B)		Site (C)		
Nominal Depth of Probe	2 m	14 m	2 m	14 m	5 m (2007)- No fish	8 m (2007)- No fish	5 m (2006)
Correlation Coefficient between T and S	-0.21	-0.88	-0.63	-0.87	-0.17	-0.85	-0.71



Map 1. Fortune Bay, Newfoundland (Province of Newfoundland and Labrador, Canada). (Reproduced with permission of the Canadian Hydrographic Service.)



Map 2. Bottom topography of Fortune Bay. (Reproduced with permission of the Canadian Hydrographic Service.)

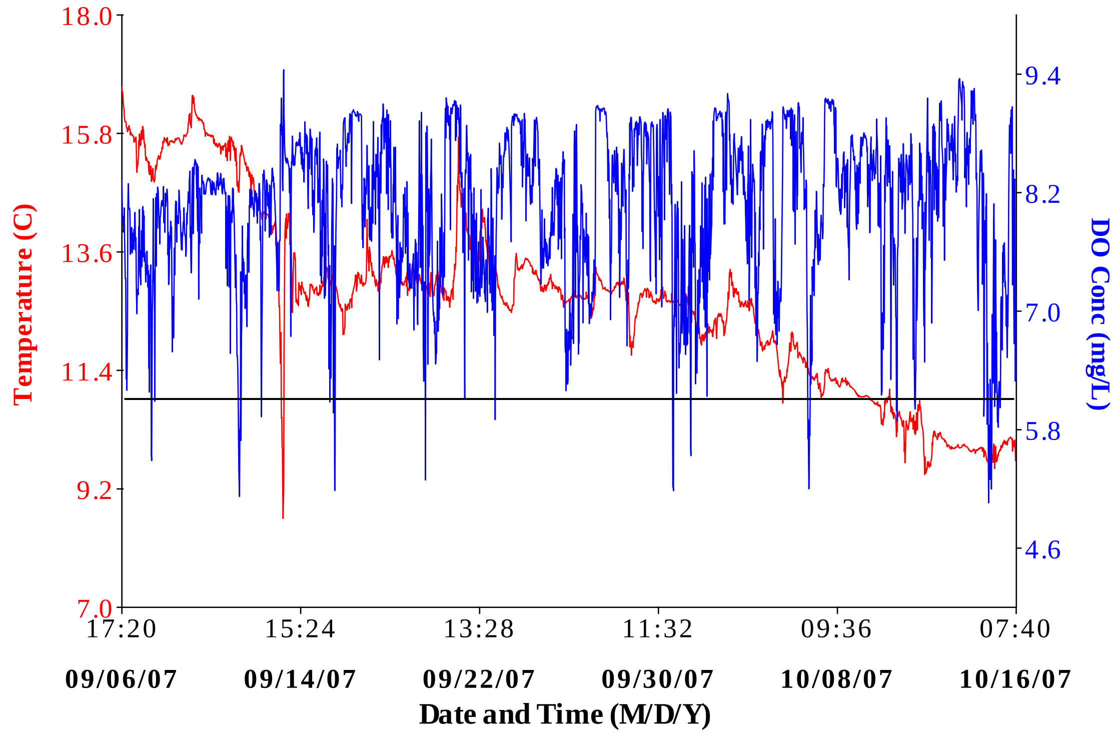


Figure 1. Site (A) at 2 m depth, dissolved oxygen concentration and temperature.

Note: Horizontal line indicates DO critical level of 6 mg/L.

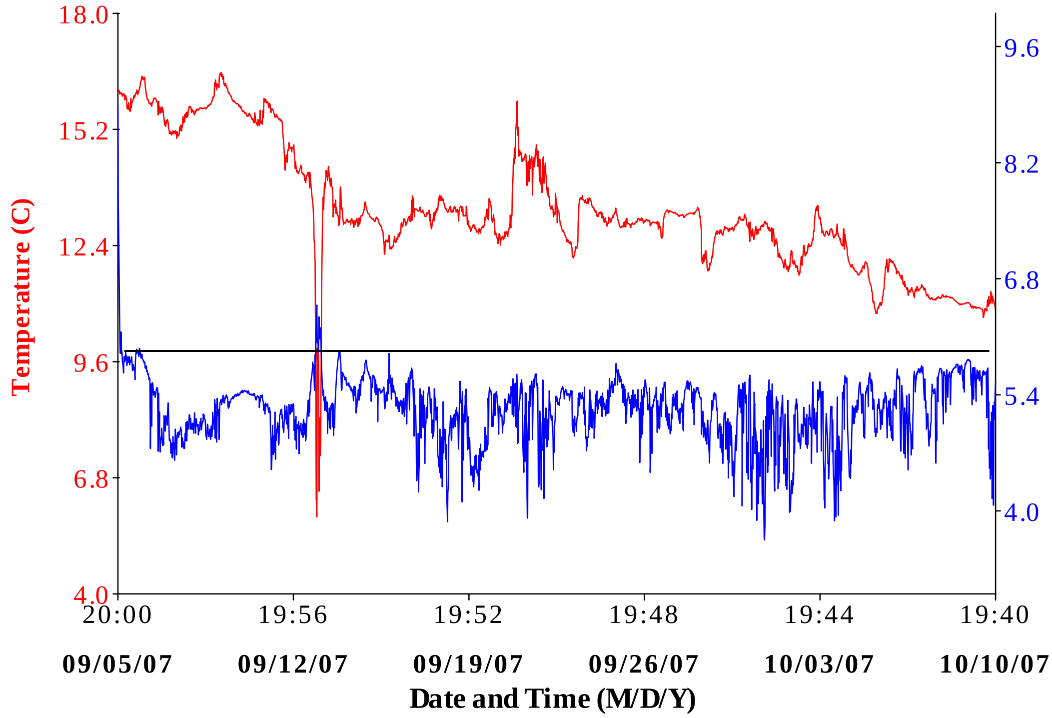


Figure 2. Site (B) at 2 m depth, dissolved oxygen concentration and temperature.

Note: Horizontal line indicates DO critical level of 6 mg/L.

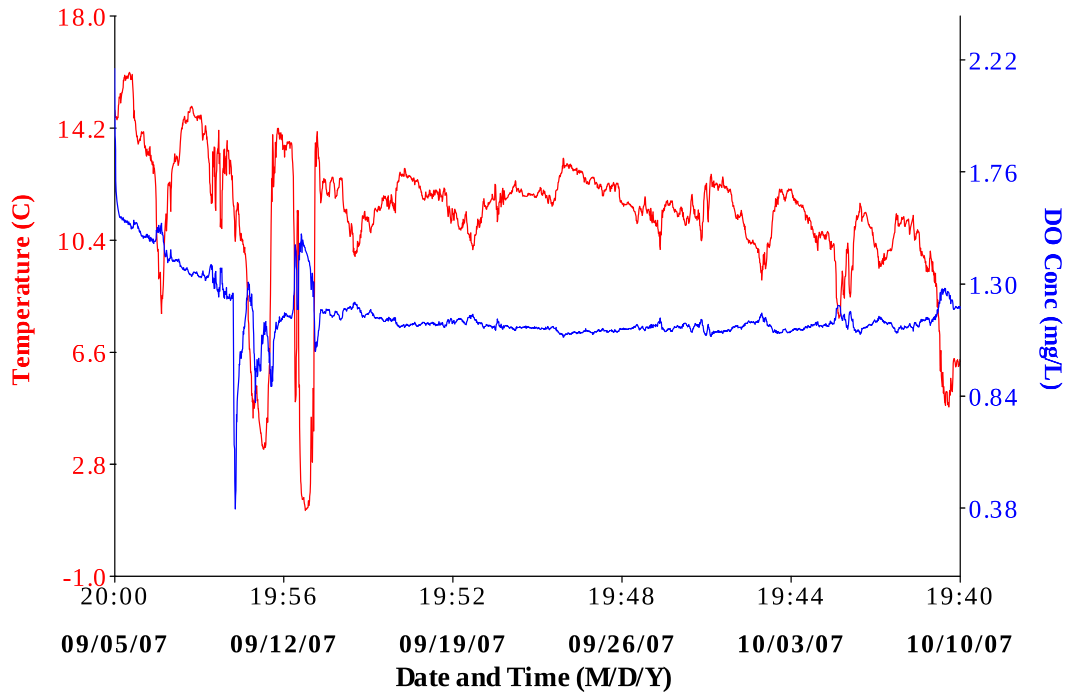


Figure 3. Site (B) at 14 m depth, dissolved oxygen concentration and temperature.

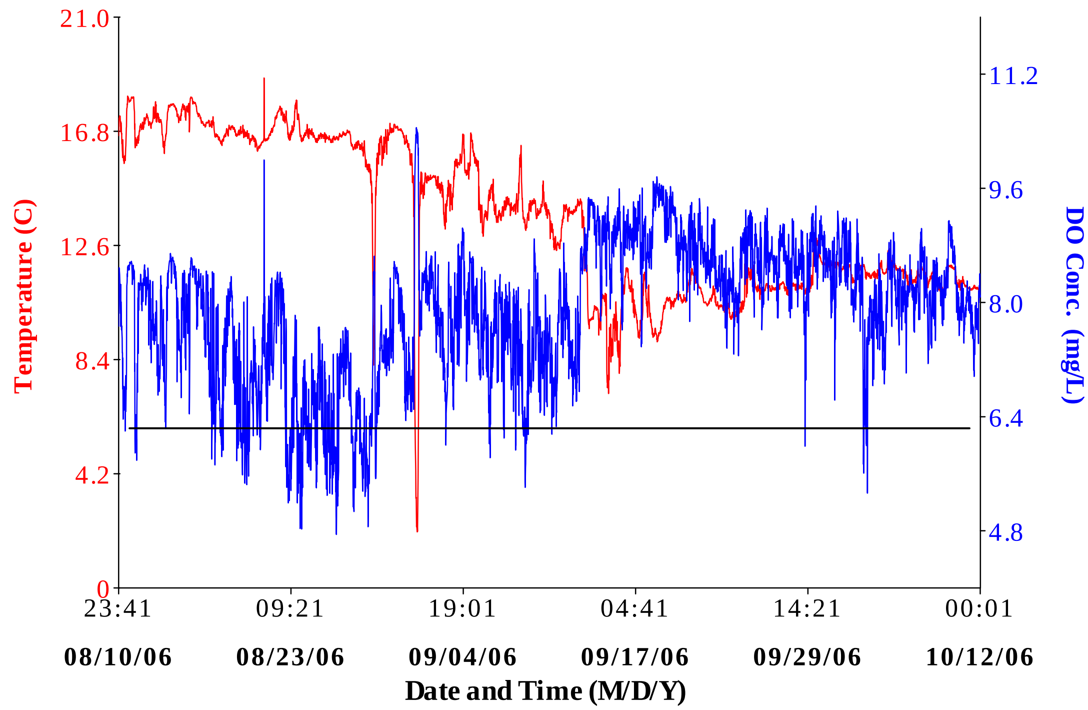


Figure 4. Site (C) in 2006 at 5 m depth, dissolved oxygen concentration and temperature.

Note: Horizontal line indicates DO critical level of 6 mg/L.

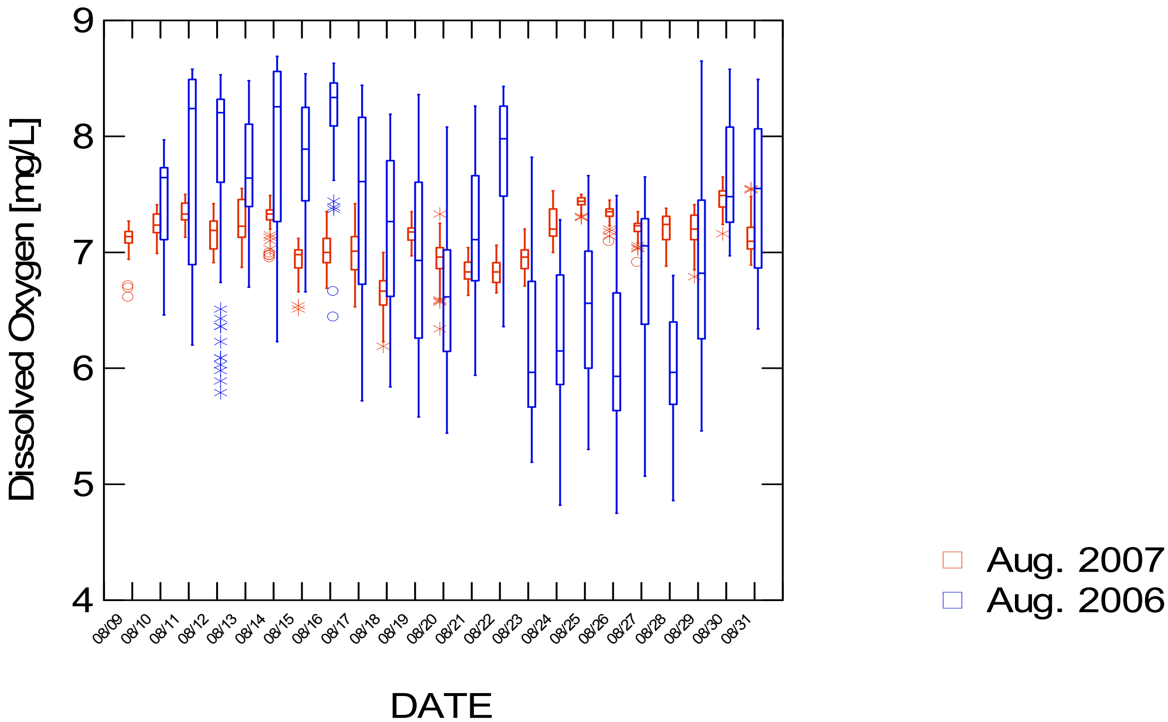


Figure 5. Dissolved Oxygen Concentration in Site (C) During Aug. 2006 and 2007

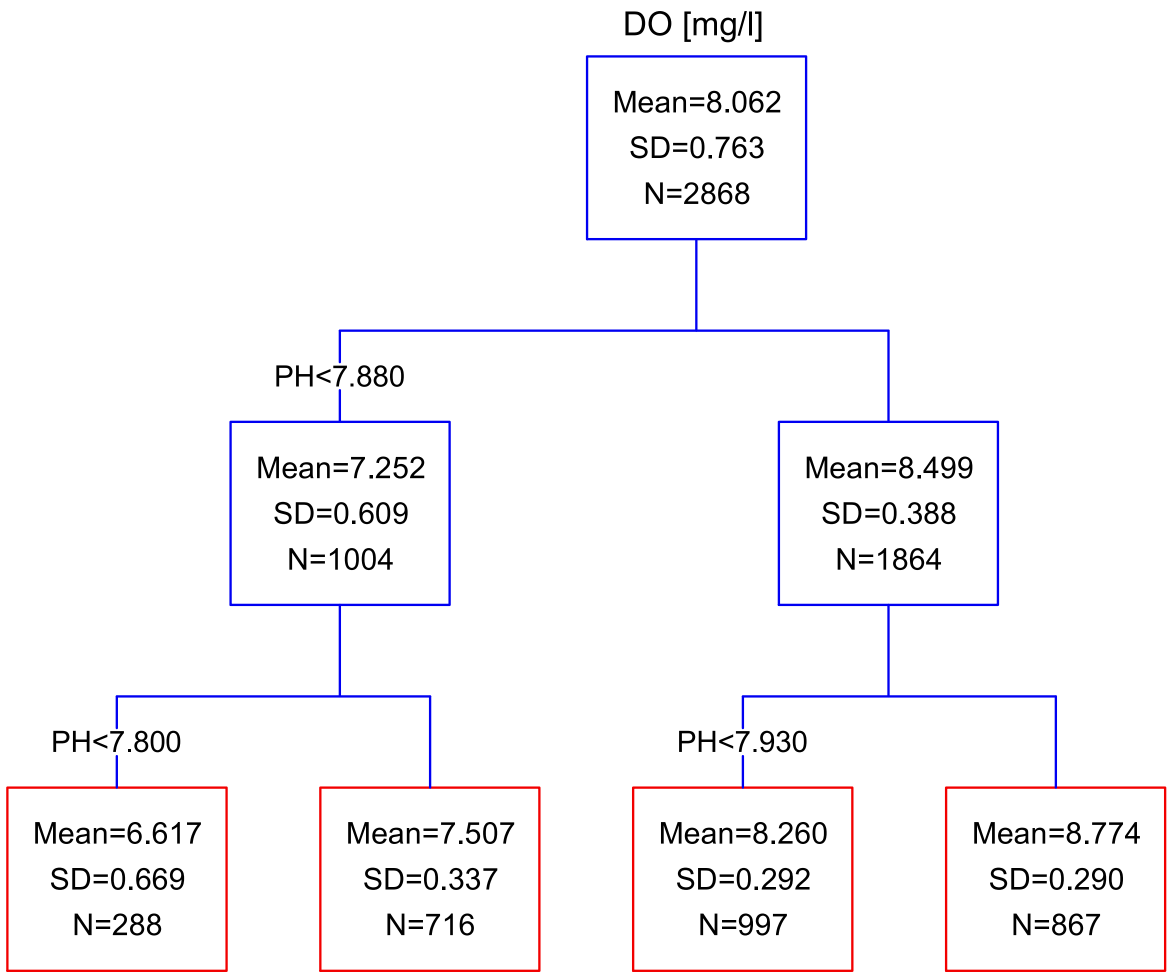


Figure 6. DTA of DO for Site (A) at 2 m with all four predictors (pH, temperature, salinity and Chlorophyll).