Dissolved Organic Carbon in Lakes from the North Temperate Region

https://github.com/cwatson1013/Env_Data_Analysis_Final_Proj.git

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Abstract

Dissolved organic carbon (DOC) is a significant part of the carbon cycle. DOC can come from within the lake, such as from decaying organisms or plant matter, or from the catchment area of the lake. The catchment area soils can influence the amount of DOC that enters each lake. The purpose of this study is to see if there is a relationship between depth and DOC and if so, if there is a seasonal relationship. This study looked at lakes that were part of the North Temperate Region located in Wisconsin, USA. DOC was found to not be normally distributed, so a two-way ANOVA with an interaction test was conducted. The results found that depth and lake name were significant. A non-parametric test was run on Peter, Paul, and West Long lakes to determine trends and changepoints in the data. Peter and West Long lake had trends and changepoints, but Paul lake did not. Overall, it was found that the depth and DOC do not have a relationship and a seasonal relationship between change in depth and DOC could not be determined with the data.

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```r
knitr::opts_chunk$set(echo = TRUE, eval = TRUE,
                      cache = TRUE, fig.pos = "H", warning = FALSE, message = FALSE)

# Set your working directory
setwd("/Users/carolinewatson/Documents/Spring 2019/Environmental Data Analytics/Final_Pr

# Load your packages
suppressMessages(library(tidyverse))
library(ggplot2)
library(leaflet)
library(dplyr)
library(RColorBrewer)
library(viridis)
library(knitr)
library(kableExtra)
library(lubridate)
library(lme4)
library(nlme)
library(trend)
library(gridExtra)
library(multcomp)

# Set your ggplot theme
caroline_theme <- theme_classic(base_size = 16) +
  theme(axis.text = element_text(color = "black"),
        legend.position = "right")

theme_set(caroline_theme)
```

1 Research Question and Rationale

The rationale for this analysis is that there typically is a relationship between dissolved organic carbon and depth. There is also typically a relationship between land area surrounding lakes that have high amounts of organic soils usually deposit large amounts of dissolved organic carbon into lakes. Dissolved organic carbon is an important part of the carbon cycle and supplies nutrients for some organisms. Most DOC is natural, but high amounts can indicate human influence, such as land surrounding the lake that is high in organic amount.

This study aims to find out whether there is a relationship between dissolved organic carbon (DOC) and depth. If there is a relationship between these two variables, I want to see if this relationship varies seasonally. This dataset contains various parameter measurements for different lakes in the North Temperate Region in Wisconsin, USA that were part of the Long Term Ecological Research station. The measured parameters include temperature, depth, dissolved organic carbon, dissolved inorganic carbon, particulate organic matter and others.

2 Dataset Information

The data for this analysis were collected from June 3, 1984 - August 17, 2016. Dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate organic matter, partial pressure of CO2, and absorbance at 440nm were all parameters that were measured. Peter, Paul, West Long, East Long, Tuesday, and Crampton lakes were all sampled. The samples for dissolved organic carbon and absorbance were collected from the epilimnion, metalimnion, hypolimnion and PML (Pooled Mixed Layer). It is important to note that there were no numeric depths corresponding to DOC or absorbance. The samples for inorganic carbon were taken at 100%, 50%, 25%, 10%, 5%, and 1% of the surface irridance, with some samples being collected from the hypolimnion as well. Two types of samples for partial pressure of CO2 were obtained: one was from the air, the other from the lake. The air sample was taken at 2 meters above the lake, and the water sample was taken right below the surface of the lake. from 2 meters above the surface of the lake, Table 1 shows a summary of all the measurements in the carbon dataset. The frequency of the sampling varied.

```r
#reading in data file
carbon.data <- read.csv("../Raw/NTL-LTER_Lake_Carbon_Raw.csv")

#structure of data frame
carbon.data.summary <- summary(carbon.data)
```

Table 1: Summary of Carbon Data from NTL-LTER Lakes in Wisconsin

	lakeid	lakename	year4	daynum	sampledate	depth	depth_id	tpc	tpn	DIC_mg	DIC_uM	air_pco2	water_pco2	doc	absorbance
	R :3887	Peter Lake :3887	Min. :1984	Min. : 82.0	5/24/99: 18	0 :1719	Min. :-2.000	Min. : 0.100	Min. :0.000	Min. : 0.023	Min. : 1.917	Min. :197.7	Min. : 0.0	Min. : 2.710	Min. :0.011
	L :3852	Paul Lake :3852	1st Qu.:1993	1st Qu.:166.0	5/25/99: 18	Metalimnion:1297	1st Qu.: 1.000	1st Qu.: 0.580	1st Qu.:0.070	1st Qu.: 0.812	1st Qu.: 67.625	1st Qu.:343.4	1st Qu.: 478.0	1st Qu.: 4.570	1st Qu.:0.060
	T :1818	Tuesday Lake :1818	Median :1999	Median :192.0	5/26/99: 18	Hypolimnion:1020	Median : 3.000	Median : 0.890	Median :0.103	Median : 1.322	Median : 110.167	Median :362.9	Median : 838.5	Median : 5.603	Median :0.146
	W :1571	West Long Lake:1571	Mean :2000	Mean :192.4	5/31/99: 18	PML : 876	Mean : 2.775	Mean : 1.110	Mean :0.149	Mean : 2.310	Mean : 192.487	Mean :360.4	Mean :1012.3	Mean : 6.932	Mean :0.194
	E :1435	East Long Lake:1435	3rd Qu.:2007	3rd Qu.:218.0	6/1/99 : 18	Epilimnion : 570	3rd Qu.: 5.000	3rd Qu.: 1.305	3rd Qu.:0.180	3rd Qu.: 1.968	3rd Qu.: 164.000	3rd Qu.:379.0	3rd Qu.:1175.6	3rd Qu.: 8.370	3rd Qu.:0.265
	M : 456	Crampton Lake : 456	Max. :2016	Max. :310.0	6/14/99: 18	(Other) :7918	Max. : 7.000	Max. :11.860	Max. :2.170	Max. :48.599	Max. :4049.883	Max. :608.1	Max. :9348.2	Max. :44.080	Max. :1.213
	(Other): 538	(Other) : 538	NA	NA	(Other):13449	NA's : 157	NA's :170	NA's :11410	NA's :11409	NA's :3642	NA's :3642	NA's :12411	NA's :12411	NA's :9993	NA's :10658

3 Exploratory Data Analysis and Wrangling

```r
#class of sampledate column
class(carbon.data$sampledate)
```

```
## [1] "factor"
```

```r
#converting sampledate to a date in R
carbon.data$sampledate <- as.Date(carbon.data$sampledate, format = "%m/%d/%y")

#checking class of sampledate
class(carbon.data$sampledate)
```

```
## [1] "Date"
```

```r
#summary of the dataset
head(carbon.data)
```

```
##   lakeid   lakename year4 daynum sampledate depth depth_id tpc tpn DIC_mg
## 1      L  Paul Lake  1984    155 1984-06-03     0        1  NA  NA   1.45
## 2      L  Paul Lake  1984    155 1984-06-03     1        2  NA  NA   1.82
## 3      L  Paul Lake  1984    155 1984-06-03     2        3  NA  NA   1.51
## 4      L  Paul Lake  1984    155 1984-06-03   3.5        4  NA  NA   1.47
## 5      L  Paul Lake  1984    155 1984-06-03   5.5        5  NA  NA   2.69
## 6      R Peter Lake  1984    156 1984-06-04     0        1  NA  NA   2.85
##     DIC_uM air_pco2 water_pco2 doc absorbance
## 1 120.8333       NA         NA  NA         NA
## 2 151.6667       NA         NA  NA         NA
## 3 125.8333       NA         NA  NA         NA
## 4 122.5000       NA         NA  NA         NA
## 5 224.1667       NA         NA  NA         NA
## 6 237.5000       NA         NA  NA         NA
```

```r
summary(carbon.data)
```

```
##      lakeid                lakename        year4          daynum
##  R      :3887   Peter Lake     :3887   Min.   :1984   Min.   : 82.0
##  L      :3852   Paul Lake      :3852   1st Qu.:1993   1st Qu.:166.0
##  T      :1818   Tuesday Lake   :1818   Median :1999   Median :192.0
##  W      :1571   West Long Lake:1571   Mean   :2000   Mean   :192.4
##  E      :1435   East Long Lake:1435   3rd Qu.:2007   3rd Qu.:218.0
##  M      : 456   Crampton Lake : 456   Max.   :2016   Max.   :310.0
##  (Other): 538   (Other)       : 538
##    sampledate                 depth         depth_id           tpc
##  Min.   :1984-06-03   0           :1719   Min.   :-2.000   Min.   : 0.100
##  1st Qu.:1993-06-16   Metalimnion:1297   1st Qu.: 1.000   1st Qu.: 0.580
##  Median :1999-07-06   Hypolimnion:1020   Median : 3.000   Median : 0.890
```

```
##  Mean   :2000-07-14   PML        : 876   Mean   : 2.775   Mean   : 1.110
##  3rd Qu.:2007-08-28   Epilimnion : 570   3rd Qu.: 5.000   3rd Qu.: 1.305
##  Max.   :2016-08-17   (Other)    :7918   Max.   : 7.000   Max.   :11.860
##                       NA's       : 157   NA's   :170      NA's   :11410
##       tpn            DIC_mg            DIC_uM            air_pco2
##  Min.   :0.000   Min.   : 0.023   Min.   :   1.917   Min.   :197.7
##  1st Qu.:0.070   1st Qu.: 0.812   1st Qu.:  67.625   1st Qu.:343.4
##  Median :0.103   Median : 1.322   Median : 110.167   Median :362.9
##  Mean   :0.149   Mean   : 2.310   Mean   : 192.487   Mean   :360.4
##  3rd Qu.:0.180   3rd Qu.: 1.968   3rd Qu.: 164.000   3rd Qu.:379.0
##  Max.   :2.170   Max.   :48.599   Max.   :4049.883   Max.   :608.1
##  NA's   :11409   NA's   :3642     NA's   :3642       NA's   :12411
##    water_pco2          doc           absorbance
##  Min.   :   0.0   Min.   : 2.710   Min.   :0.011
##  1st Qu.: 478.0   1st Qu.: 4.570   1st Qu.:0.060
##  Median : 838.5   Median : 5.603   Median :0.146
##  Mean   :1012.3   Mean   : 6.932   Mean   :0.194
##  3rd Qu.:1175.6   3rd Qu.: 8.370   3rd Qu.:0.265
##  Max.   :9348.2   Max.   :44.080   Max.   :1.213
##  NA's   :12411    NA's   :9993     NA's   :10658
```

```
colnames(carbon.data)
```

```
##  [1] "lakeid"     "lakename"   "year4"      "daynum"     "sampledate"
##  [6] "depth"      "depth_id"   "tpc"        "tpn"        "DIC_mg"
## [11] "DIC_uM"     "air_pco2"   "water_pco2" "doc"        "absorbance"
```

```
dim(carbon.data)
```

```
## [1] 13557    15
```

```
#renaming columns
colnames(carbon.data)[1:5] <- c("Lake.ID", "Lake.Name", "Year", "Day.Number", "Date")
```

The dataset was imported and the date column was formatted as a date in R. A summary of the dataset was run to understand what the dataset contained. The head of the dataset was viewed as well as the dimensions and column names. Some column names were changed to make it easier to identify them.

```
#wrangling dataset
carbon.data.skinny <- carbon.data %>%
  filter(depth_id == -2 | depth_id == -1 | depth_id == 7) %>%
  filter(depth == "Hypolimnion" | depth == "Epilimnion" | depth == "PML" |
           depth == "Metalimnion") %>%
  mutate(depth = factor(depth, levels = c("Epilimnion", "Metalimnion",
                                          "PML", "Hypolimnion"))) %>%
  filter(is.na(doc) == FALSE) %>%
  dplyr::select(Lake.ID:depth_id, doc)
```

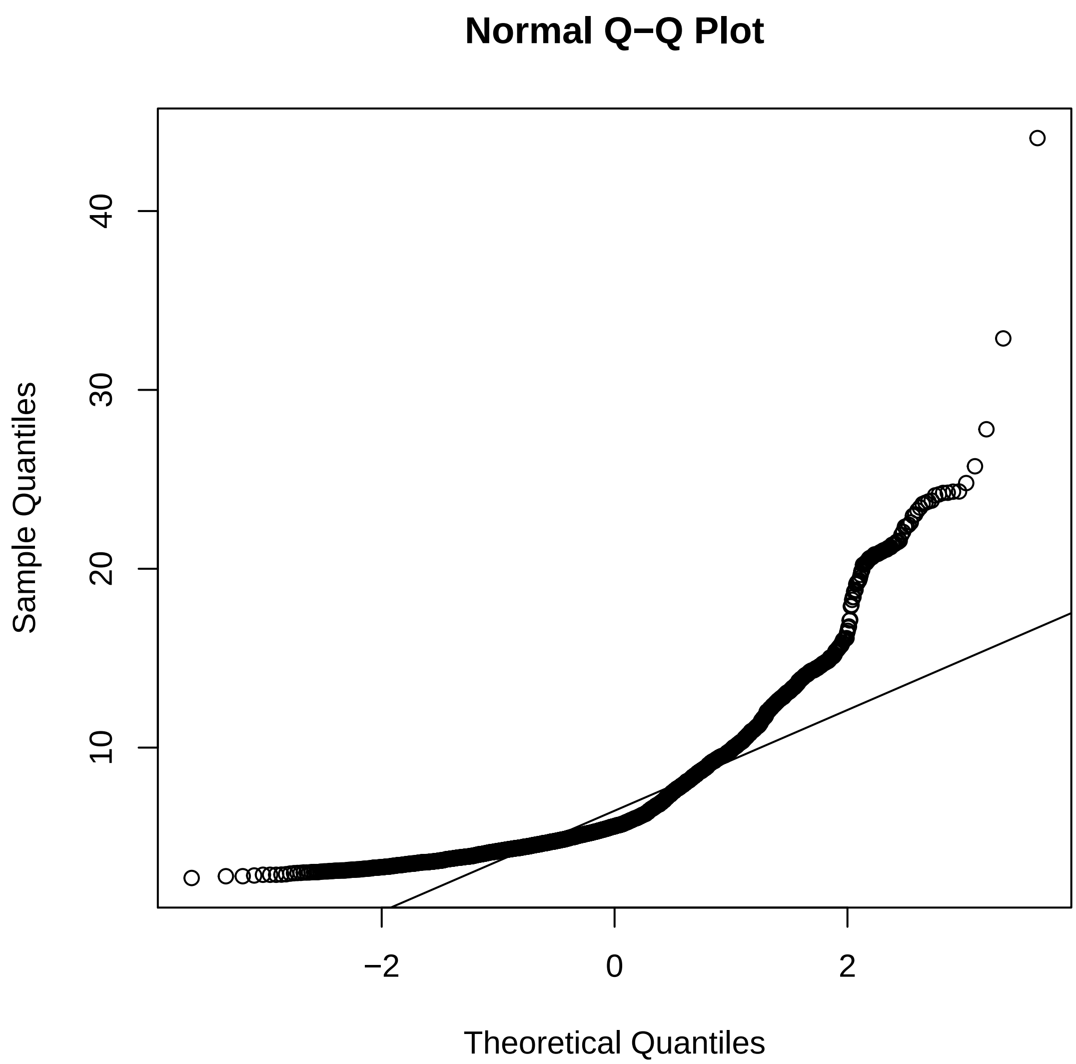

Figure 1: QQplot showing whether data for DOC is normally distributed.

```
#saving processed file to the processed folder
write.csv(carbon.data.skinny,
          file = "../Processed/NTL-LTER_Lake_Carbon_Processed.csv")
```

The dataset was wrangled by filtering for depth id and depth description. DOC measurements were only taken at the epilimnion, metalimnion, PML, and hypolimnion, so the dataset needed to be filtered by these options. This study focused mainly on DOC and depth, so columns such as total particulate carbon, or irridance, were not needed. Columns that were needed were selected when the data was wrangled. The depths were also mututated as factor levels so that future analyses would present the depths from shallowest to deepest (epilimnion to hypolimnion).

Figure 1 is a qqplot that shows whether the dissolved organic carbon data has a normal distribution. From Figure 1, it is clear that the dissolved organic carbon data do not follow a

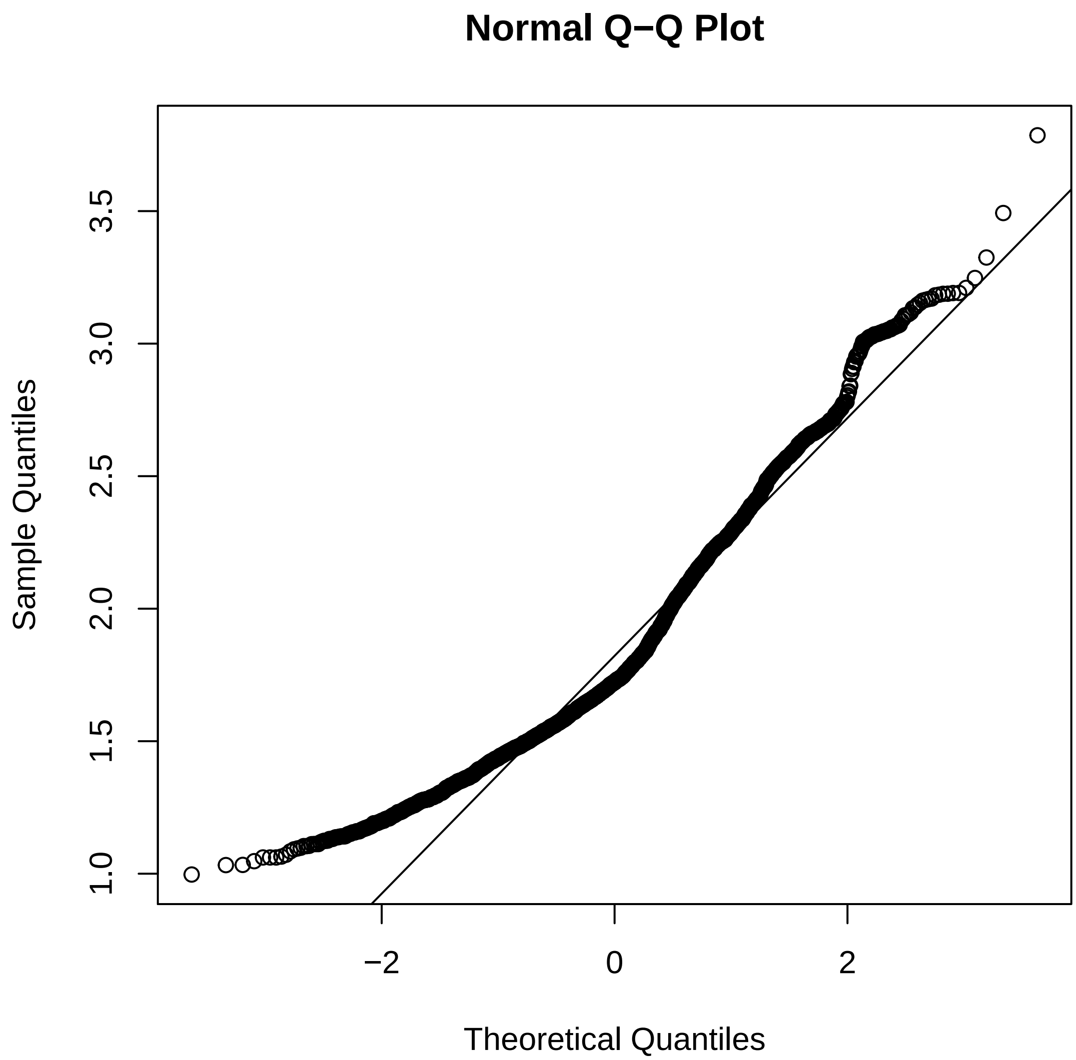

Figure 2: Log QQplot of dissolved organic carbon data.

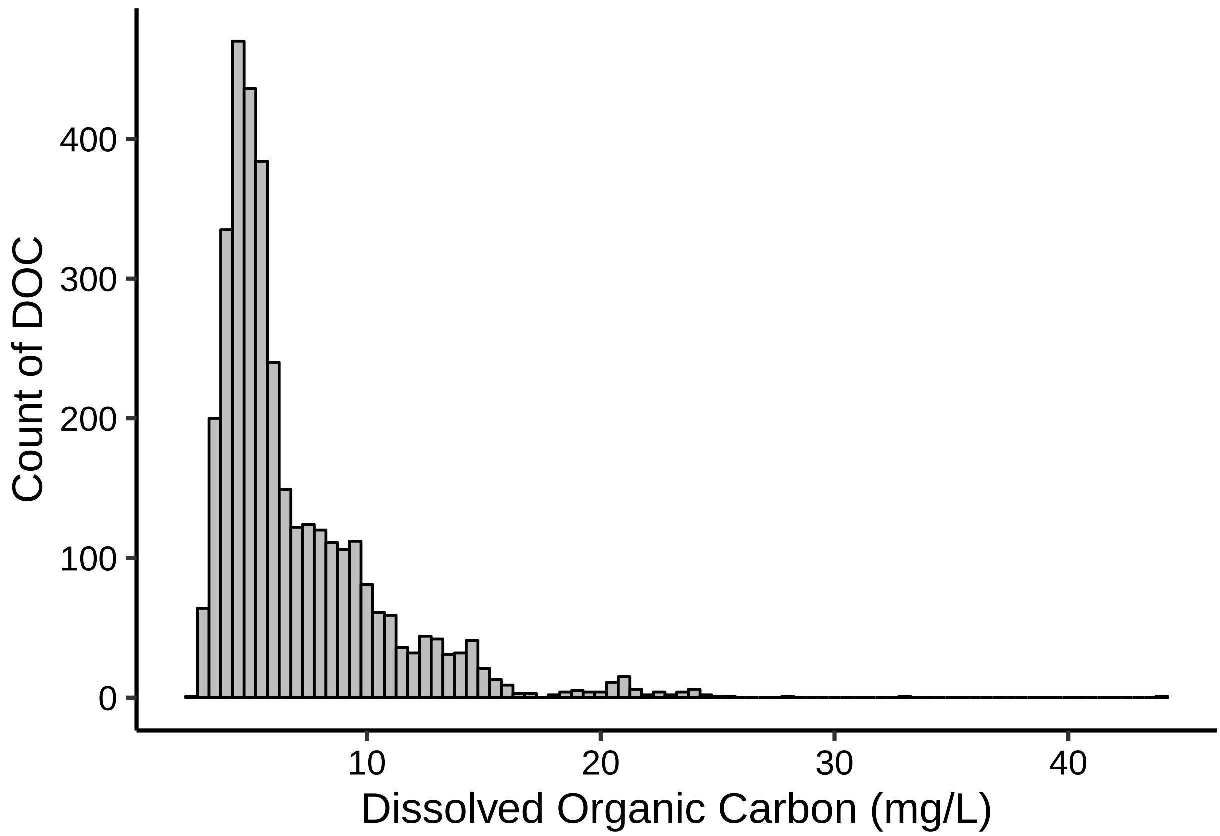

Figure 3: Histogram of dissolved organic carbon (mg/L).

normal distribution. Becuase the data are not normally distributed, a log qqplot was run to see if log transforming the data would help the data look more normally distributed. Figure 2 shows the dissolved organic carbon data log transformed. From Figure 2 it is clear that dissolved organic carbon is not normally distributed, but log transforming the data makes the data more normally distributed than not log transforming the data.

Figure 3 shows a histogram of the distribution of dissolved organic carbon (mg/L). From Figure 3 it is apparent that the distribution of dissolved organic carbon is not noramlly distributed. This information will factor into the statistical analyses conducted since the data is not normally distributed.

Figure 4 shows the cumulative frequency of dissolved organice carbon in each lake. From Figure 4, it is apparent that Paul lake has the highest cumulative frequency of dissolved organic carbon, followed by Peter lake. Figure 4 also shows that Peter and Paul lake mainly have dissolved organic carbon amounts between 0 mg/L and 10 mg/L, which is why there are two high spikes. The other lakes have dissolved orgnic carbon amounts that are more spread out, as shown in Figure 4.

Figure 5 shows a box plot of each depth category of the lake against the doc measurements. From Figure 5 it looks like there is no relationship between depth and dissolved organic carbon (mg/L). Figure 5 indicates that the Epilimnion (water closest to the surface) and Hypolimnion

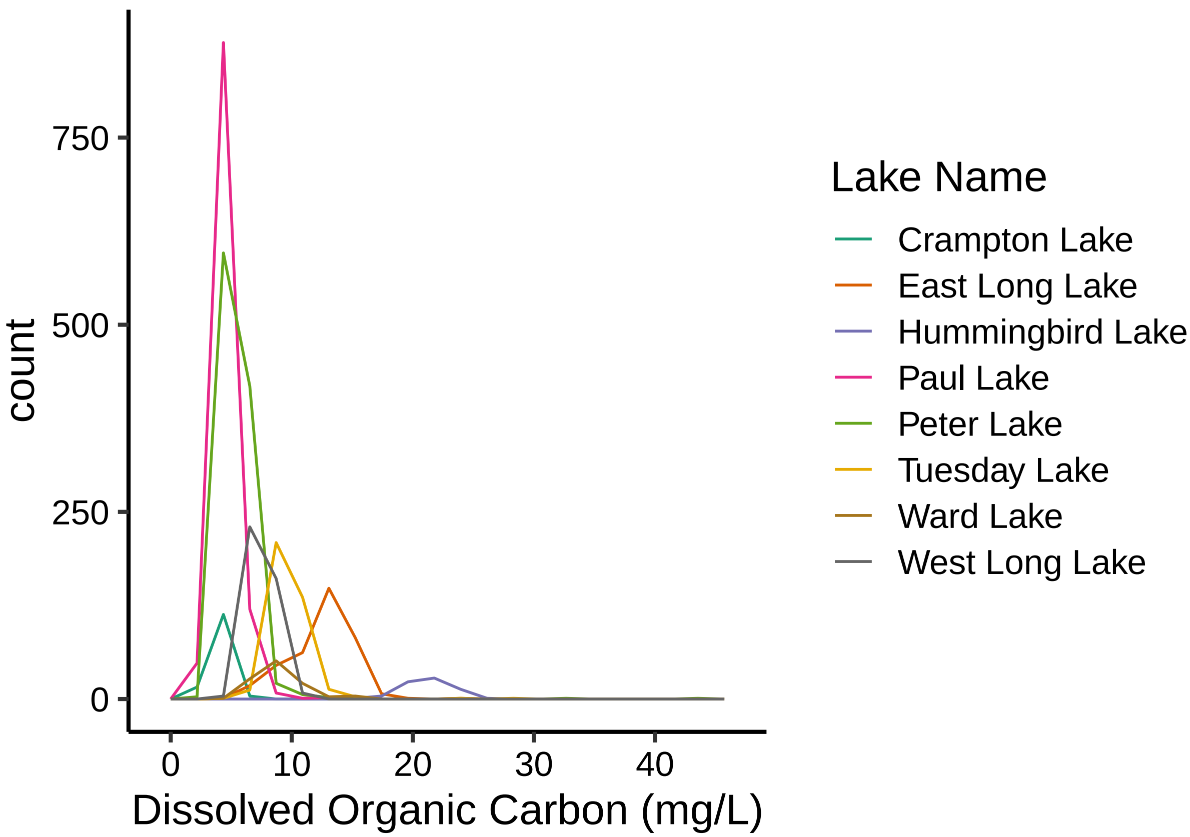

Figure 4: Frequency Polygon showing the count of DOC (mg/L) amounts in each Lake

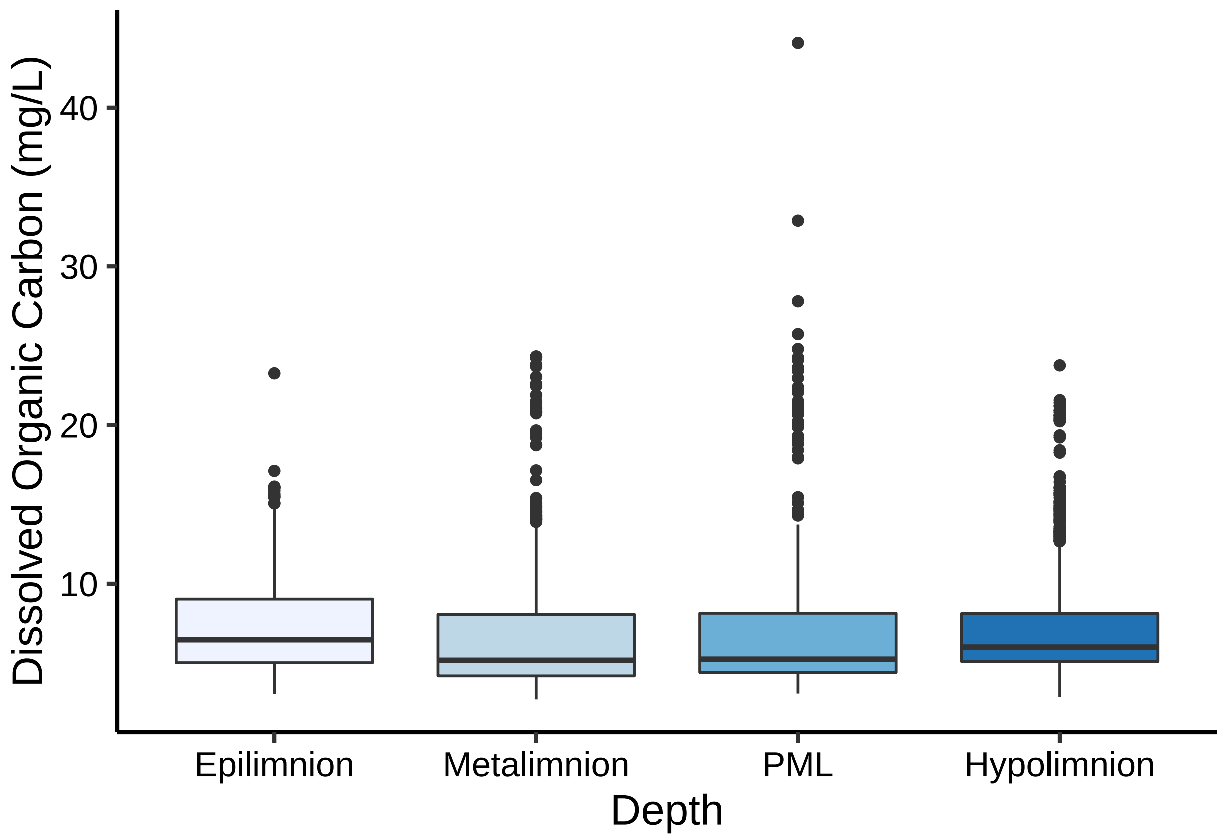

Figure 5: Dissolved Organic Carbon varying with depth. Depth increases from left to right, with Epilimnion being the surface of the lake.

(water from deepest part of the lake) have greater medians than the Metalimnion or the pooled mixed layer (PML). However, the PML has the greatest distribution of dissolved organic carbon, with one sample that might be considered an outlier as seen in Figure 5.

Figure 6 shows the distribution of dissolved organic carbon (mg/L) in each depth layer faceted by each lake. From Figure 6, the PML of Peter lake has the greatest distribution of dissolved organic carbon (mg/L). Further, the distribution of dissolved organic carbon (mg/L) in each lake does not vary with depth.

Figure 7 shows dissolved organic carbon over the years. Figure 1 was created to determine if there was a pattern of dissolved organic carbon in lakes over the years. From Figure 7 only Peter, Paul, and West long lake were continuously sampled very year. Other lakes, such as Hummingbird lake, were only sampled between the late 1990s to the early 2000s.

Figure 8 shows the day number of the year plotted against dissolved organic carbon (mg/L) with different colors for each lake. From Figure 8 it is apparent that sampling was done mainly between days 140 and 250 of the year, which is during spring and summer months. Since samples were taken during the spring and summer months, it will not be possible to analyze whether DOC varies with depth seasonally.

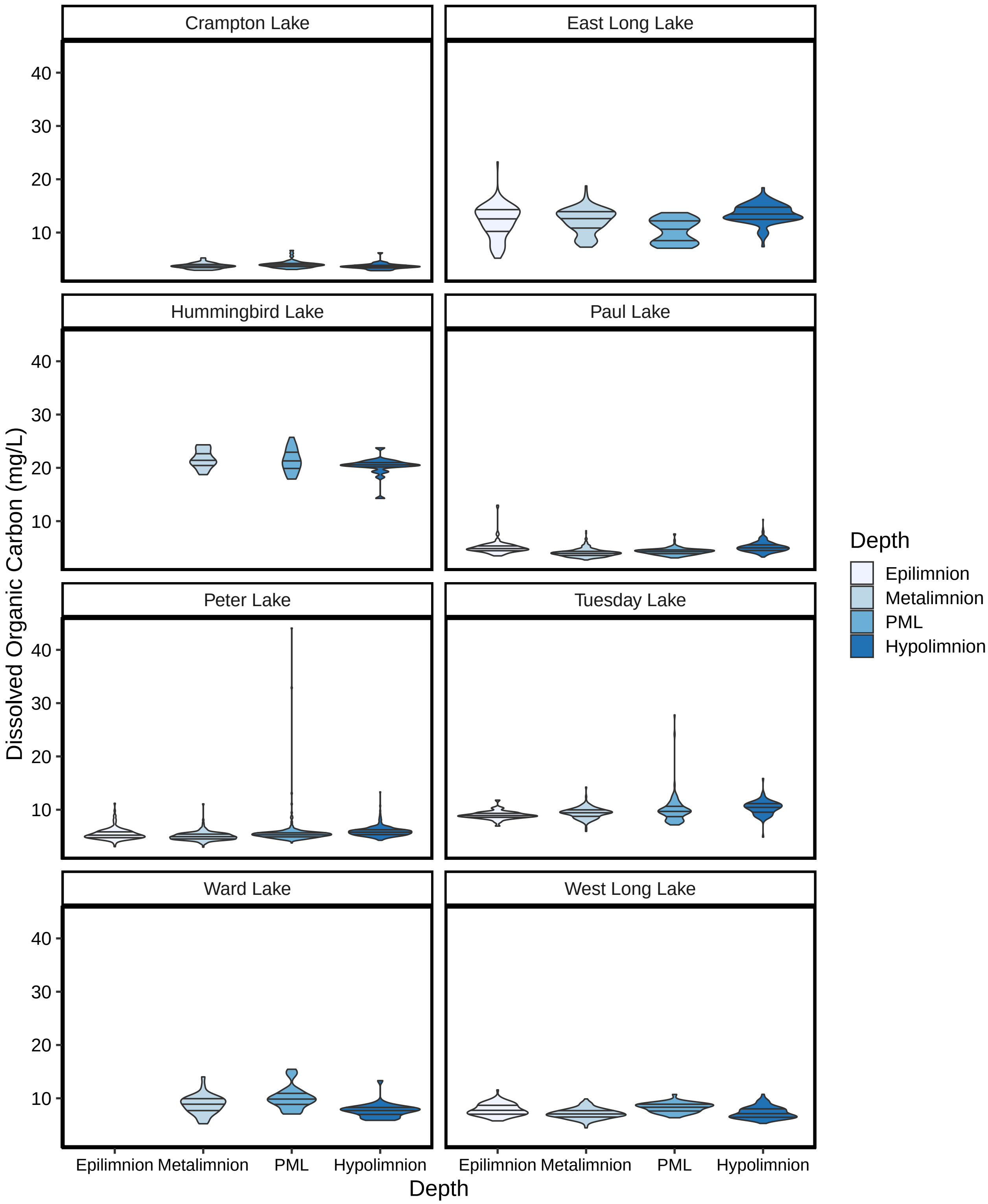

Figure 6: Distribution of dissolved organic carbon (mg/L) in each depth faceted by lake.

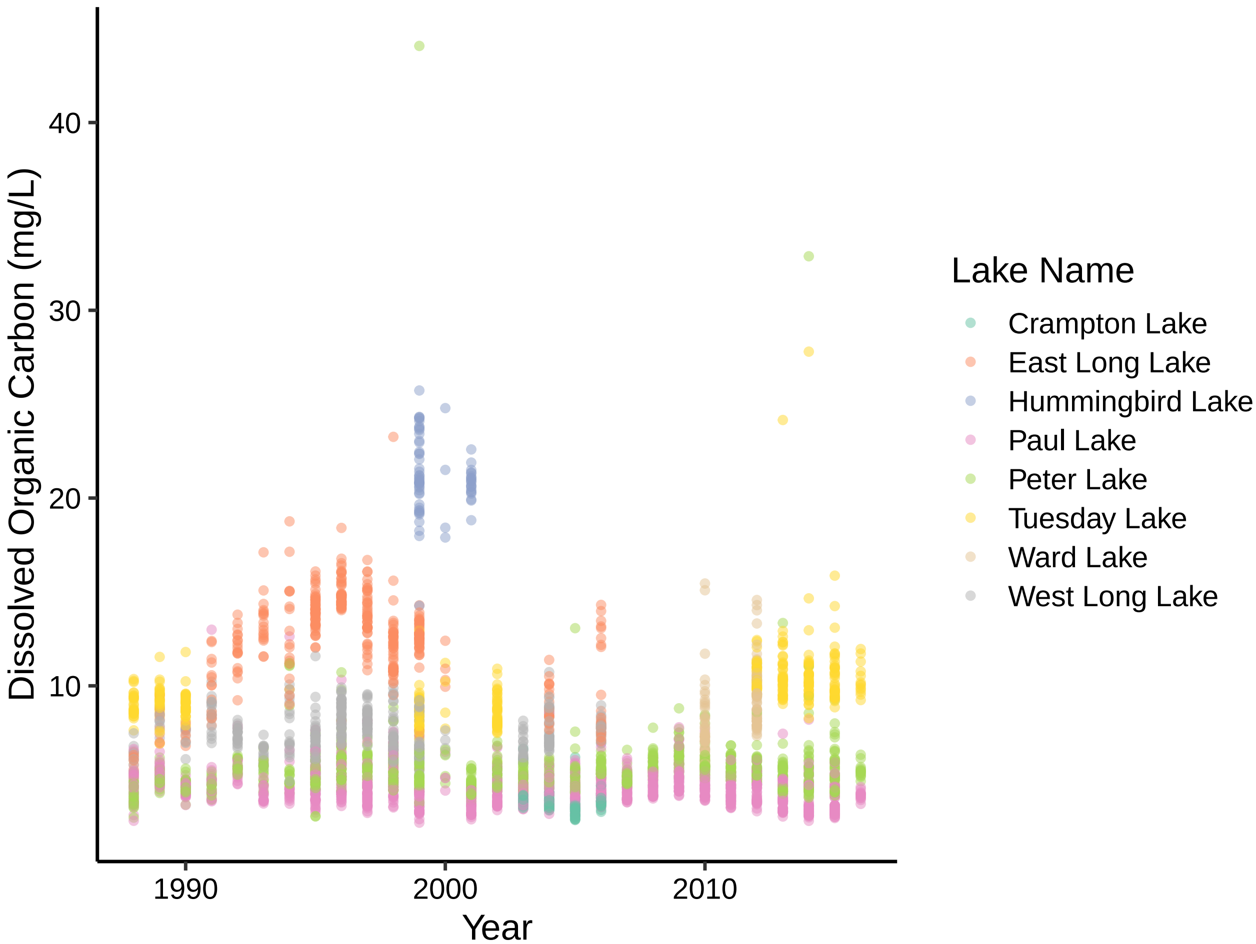

Figure 7: Dissolved organic carbon (mg/L) over time in each lake.

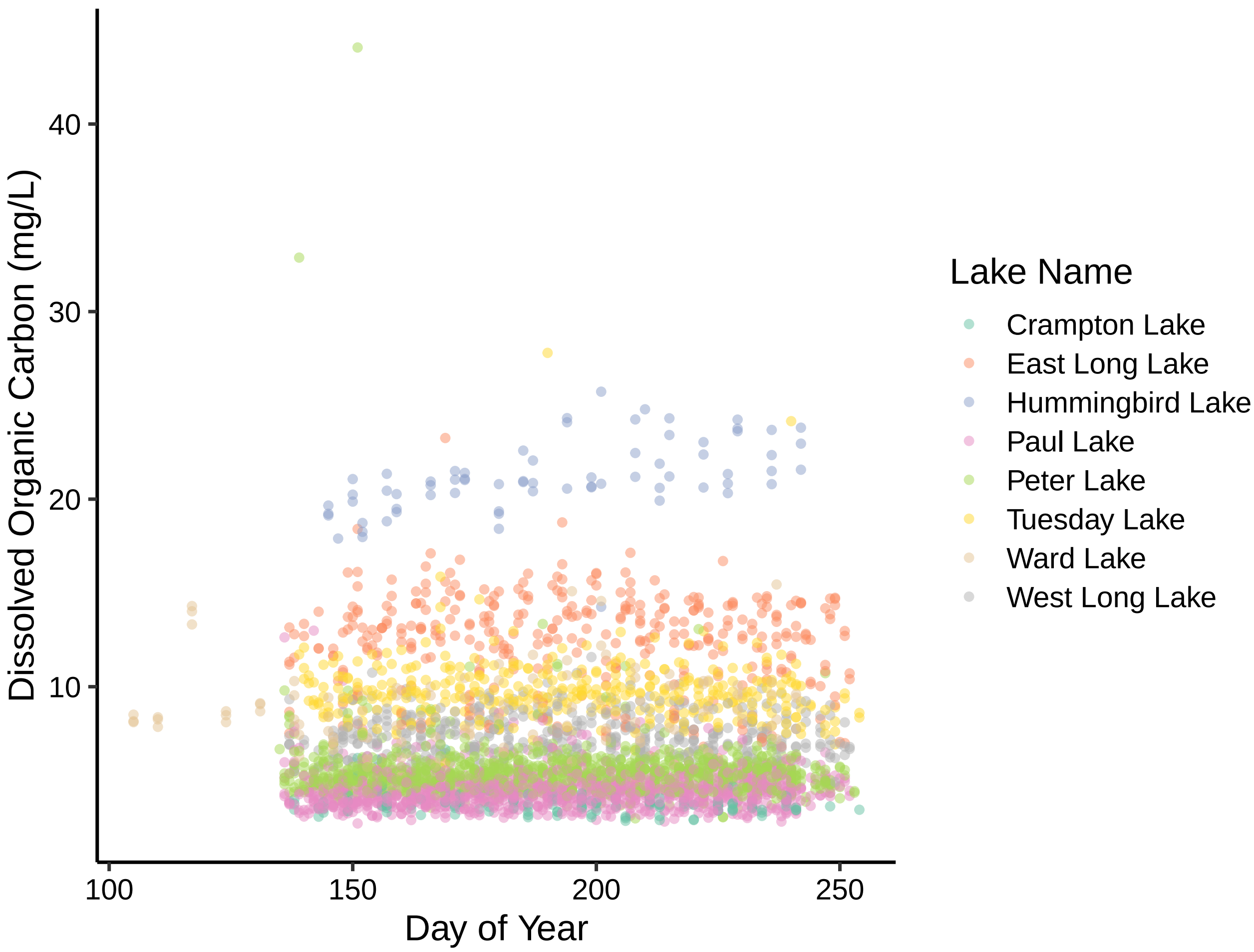

Figure 8: Dissolved organic carbon (mg/L) by day of the year.

4 Analysis

```r
#Shapiro-Wilkes test for normality
shapiro.test(carbon.data.skinny$doc)
```

```
##
##  Shapiro-Wilk normality test
##
## data:  carbon.data.skinny$doc
## W = 0.79256, p-value < 2.2e-16
```

```r
#Bartlett test for equal variance
bartlett.test(carbon.data.skinny$doc, carbon.data.skinny$depth,
              carbon.data.skinny$Lake.Name)
```

```
##
##  Bartlett test of homogeneity of variances
##
## data:  carbon.data.skinny$doc and carbon.data.skinny$depth
## Bartlett's K-squared = 53.202, df = 3, p-value = 1.66e-11
```

```r
#Interaction effects with two-way ANOVA
carbon_aov <- aov(data = carbon.data.skinny, doc ~ depth*Lake.Name)
summary(carbon_aov)
```

```
##                   Df Sum Sq Mean Sq F value Pr(>F)
## depth              3    501     167   72.95 <2e-16 ***
## Lake.Name          7  37637    5377 2346.86 <2e-16 ***
## depth:Lake.Name   18    612      34   14.84 <2e-16 ***
## Residuals       3529   8085       2
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
#Interaction effects with two-way ANOVA with log of DOC
carbon_aov_log <- aov(data = carbon.data.skinny, log(doc) ~ depth*Lake.Name)
summary(carbon_aov_log)
```

```
##                   Df Sum Sq Mean Sq F value Pr(>F)
## depth              3   16.0    5.34  193.33 <2e-16 ***
## Lake.Name          7  528.5   75.50 2735.83 <2e-16 ***
## depth:Lake.Name   18   10.9    0.61   21.93 <2e-16 ***
## Residuals       3529   97.4    0.03
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
#post-hoc Tukey test using the glht function
K <- diag(length(coef(carbon_aov)))[-1,]
```

```r
rownames(K) <- names(coef(carbon_aov))[-1]

carbon.data.skinny$dl <- with(carbon.data.skinny, interaction(depth, Lake.Name))
cell <- aov(doc ~ dl - 1, data = carbon.data.skinny)
carbon.tukey <- summary(glht(cell, linfct = K))
carbon.tukey
```

```
##
##   Simultaneous Tests for General Linear Hypotheses
##
## Fit: aov(formula = doc ~ dl - 1, data = carbon.data.skinny)
##
## Linear Hypotheses:
##                                                    Estimate Std. Error
## depthMetalimnion == 0                                4.01891    0.22317
## depthPML == 0                                        3.65628    0.23082
## depthHypolimnion == 0                               12.09644    0.13934
## Lake.NameEast Long Lake == 0                        12.20887    0.13593
## Lake.NameHummingbird Lake == 0                      10.30667    0.26349
## Lake.NamePaul Lake == 0                             13.52778    0.15955
## Lake.NamePeter Lake == 0                            21.67227    0.32270
## Lake.NameTuesday Lake == 0                          21.33154    0.29684
## Lake.NameWard Lake == 0                             20.33227    0.32270
## Lake.NameWest Long Lake == 0                         5.02601    0.12658
## depthMetalimnion:Lake.NameEast Long Lake == 0        4.03800    0.07837
## depthPML:Lake.NameEast Long Lake == 0                4.28410    0.09592
## depthHypolimnion:Lake.NameEast Long Lake == 0        5.11462    0.08873
## depthMetalimnion:Lake.NameHummingbird Lake == 0      5.42785    0.12613
## depthPML:Lake.NameHummingbird Lake == 0              5.04127    0.07869
## depthMetalimnion:Lake.NamePaul Lake == 0             5.70222    0.09670
## depthPML:Lake.NamePaul Lake == 0                     5.89853    0.08904
## depthHypolimnion:Lake.NamePaul Lake == 0             8.97809    0.22078
## depthMetalimnion:Lake.NamePeter Lake == 0            9.40004    0.13027
## depthPML:Lake.NamePeter Lake == 0                    9.99247    0.14771
## depthHypolimnion:Lake.NamePeter Lake == 0           10.37263    0.16044
## depthMetalimnion:Lake.NameTuesday Lake == 0          8.81972    0.25227
## depthPML:Lake.NameTuesday Lake == 0                 10.08417    0.25227
## depthHypolimnion:Lake.NameTuesday Lake == 0          7.67629    0.25585
## depthMetalimnion:Lake.NameWard Lake == 0             7.84966    0.13934
## depthPML:Lake.NameWard Lake == 0                     7.12182    0.12932
## depthMetalimnion:Lake.NameWest Long Lake == 0        8.25478    0.22317
## depthPML:Lake.NameWest Long Lake == 0                7.30373    0.14987
##                                                    t value Pr(>|t|)
## depthMetalimnion == 0                                18.01   <2e-16 ***
```

```
## depthPML == 0                                      15.84   <2e-16 ***
## depthHypolimnion == 0                              86.81   <2e-16 ***
## Lake.NameEast Long Lake == 0                       89.82   <2e-16 ***
## Lake.NameHummingbird Lake == 0                     39.12   <2e-16 ***
## Lake.NamePaul Lake == 0                            84.79   <2e-16 ***
## Lake.NamePeter Lake == 0                           67.16   <2e-16 ***
## Lake.NameTuesday Lake == 0                         71.86   <2e-16 ***
## Lake.NameWard Lake == 0                            63.01   <2e-16 ***
## Lake.NameWest Long Lake == 0                       39.71   <2e-16 ***
## depthMetalimnion:Lake.NameEast Long Lake == 0      51.52   <2e-16 ***
## depthPML:Lake.NameEast Long Lake == 0              44.66   <2e-16 ***
## depthHypolimnion:Lake.NameEast Long Lake == 0      57.64   <2e-16 ***
## depthMetalimnion:Lake.NameHummingbird Lake == 0    43.03   <2e-16 ***
## depthPML:Lake.NameHummingbird Lake == 0            64.07   <2e-16 ***
## depthMetalimnion:Lake.NamePaul Lake == 0           58.97   <2e-16 ***
## depthPML:Lake.NamePaul Lake == 0                   66.25   <2e-16 ***
## depthHypolimnion:Lake.NamePaul Lake == 0           40.66   <2e-16 ***
## depthMetalimnion:Lake.NamePeter Lake == 0          72.16   <2e-16 ***
## depthPML:Lake.NamePeter Lake == 0                  67.65   <2e-16 ***
## depthHypolimnion:Lake.NamePeter Lake == 0          64.65   <2e-16 ***
## depthMetalimnion:Lake.NameTuesday Lake == 0        34.96   <2e-16 ***
## depthPML:Lake.NameTuesday Lake == 0                39.97   <2e-16 ***
## depthHypolimnion:Lake.NameTuesday Lake == 0        30.00   <2e-16 ***
## depthMetalimnion:Lake.NameWard Lake == 0           56.34   <2e-16 ***
## depthPML:Lake.NameWard Lake == 0                   55.07   <2e-16 ***
## depthMetalimnion:Lake.NameWest Long Lake == 0      36.99   <2e-16 ***
## depthPML:Lake.NameWest Long Lake == 0              48.73   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## (Adjusted p values reported -- single-step method)
```

An interaction effects two-way anova test was run to determine if the interaction among lake name and depth is significant. The assumptions are that each variable had been taken independently of the other, that the data was taken from a normally distributed population, and that the variances in each group are equal. From Figure 1, the data shown is not normally distributed, which thus violates the assumption of normality. Further, a Shapiro-Wilkes test was run to evaluate whether the dissolved organic carbon data is well approximated by a normal distribution. The Shapiro-Wilkes test showed that the data is not well approximated by a normal distribution ($p < 2.2e-16$). A Bartlett test was run on dissolved organic carbon, lake name, and depth to see if the variances were equal or different. The Bartlett test had a p-value less than 0.05, thus the null hypothesis is rejected and the alternate hypothesis that at least two of the variances are not equal.

From the results, the p-value for depth:Lake.Name is less than 0.05 (p-value = <2.e16), thus indicating that the interaction between these terms is siginifcant. Additionally the main effect, dissolved organic carbon, is significant.

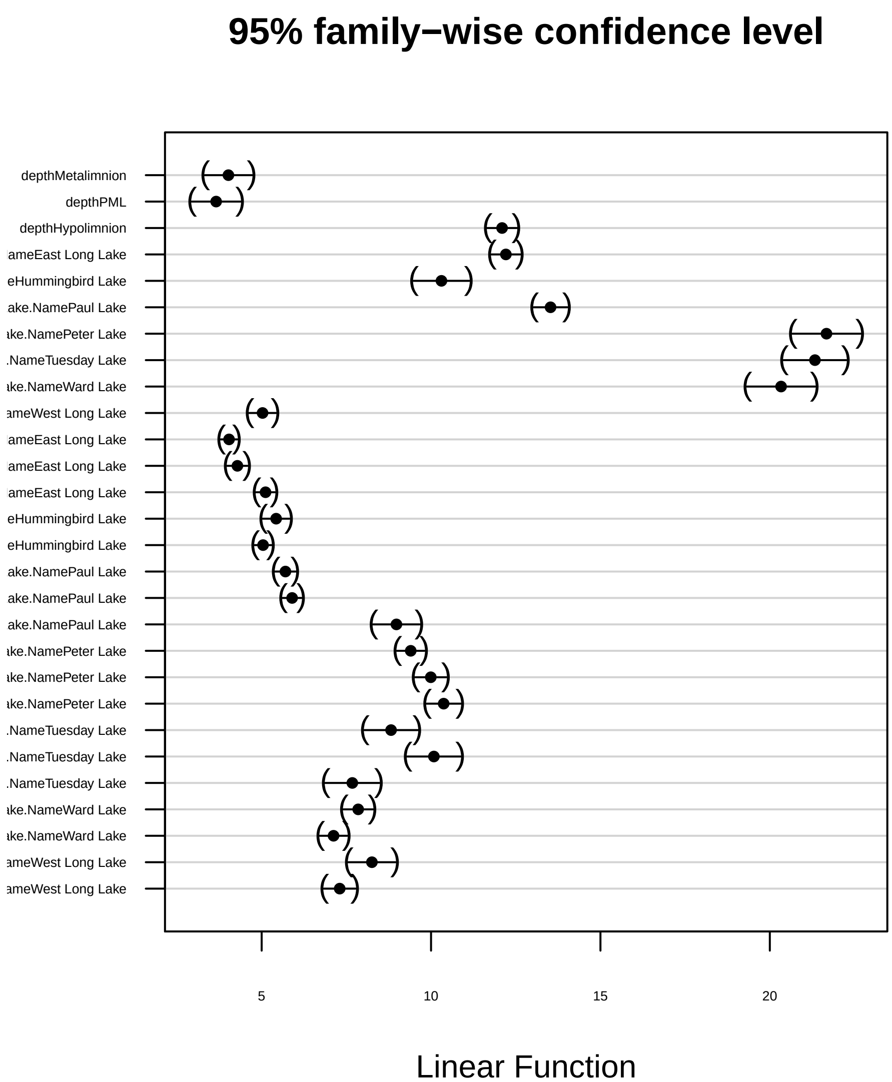

Figure 9: Plot of Post-Hoc Tukey test showing which pairwise differences are significant.

A non-parametric Post-Hoc Tukey test was run to determine the pairwise differences for the interaction since the interaction was significant. Pairs are in the same group if the p-value is greater than 0.05. From the Tukey test, the depths and lake names are all significantlly different. This is further evidenced in Figure 9.

```
#wrangling dataset down to just the three lakes
Carbon.three.lakes <-
  carbon.data.skinny %>%
  filter(depth == "Hypolimnion") %>%
  filter(Lake.Name == "Peter Lake" | Lake.Name == "Paul Lake" |
           Lake.Name == "West Long Lake")

#splitting data sets up into each lake data
carbon.peter2 <- filter(Carbon.three.lakes, Lake.Name == "Peter Lake")

carbon.paul2 <- filter(Carbon.three.lakes, Lake.Name == "Paul Lake")

carbon.west2 <- filter(Carbon.three.lakes, Lake.Name == "West Long Lake")
```

A Mann-Kendall test, which is a non-parametric trend test, was run to determine if there is a monotonic trend in dissolved organic carbon in Peter, Paul, and West Long lakes over time. This test was chosen because there is not a linear trend in DOC over time. These lakes were chosen based off of the Figure 7 which shows which lakes were monitored continuously over time. The hypolimnion was chosen because organic carbon can come from decomposed animals and plants in a lake which could settle at the bottom of the lake. Assumptions of a Mann-Kendall test include that methods for collecting data are unbiased, if there is no trend, the data are independently and identically distributed, and the measurements represent the true states of the observations when they were taken. In addition to a Mann-Kendall test, Pettitt's test were run. Pettitt test is a non-parametric test that can help determine if there is a change in tendancy and if so, where that change occurs (known as the changepoint).

```
#Mann-Kendall test for dissolved organic carbon in each lake

#mk.test in Paul Lake
mk.test(carbon.paul2$doc) #high p-value so we accept the null that
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.paul2$doc
## z = -1.4088, n = 291, p-value = 0.1589
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##             S          varS           tau
## -2.338000e+03  2.751939e+06 -5.547057e-02
```

```r
#there is no trend in data
```

The Mann-Kendall test from Paul Lake shows that there is no trend in the data since the p-value is greater than 0.05 (p-value = 0.1589).

```r
#peter lake
mk.test(carbon.peter2$doc) #low p-value so reject the null and accept that there is a t
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc
## z = 4.1173, n = 289, p-value = 3.833e-05
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##            S         varS          tau
## 6.761000e+03 2.695648e+06 1.626943e-01
```

```r
#pettitt test to see where changepoint is
pettitt.test(carbon.peter2$doc) #changepoint is at 167
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.peter2$doc
## U* = 9629, p-value = 2.119e-10
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                             167
```

```r
#mk.test before and after changepoint point
mk.test(carbon.peter2$doc[1:166]) #0.06 is greater than 0.05,
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[1:166]
## z = -1.8351, n = 166, p-value = 0.0665
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##             S          varS           tau
## -1.315000e+03  5.127363e+05 -9.621737e-02
```

```r
#so accept that there is no trend in this part of the data
mk.test(carbon.peter2$doc[167:289]) #small p-value so could see a trend here
```

```
##
```

```
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[167:289]
## z = -3.1, n = 123, p-value = 0.001935
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##             S          varS           tau
##  -1419.000000 209236.333333     -0.189301
```

```r
#pettitt test to see if there is a change point between 167 and 289
pettitt.test(carbon.peter2$doc[167:289]) #changepoint at 167+34 = 201
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.peter2$doc[167:289]
## U* = 1578, p-value = 0.0006955
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                              34
```

```r
#mk.test between 167 and 200 and 201 and 289
mk.test(carbon.peter2$doc[167:200]) #p-value less than 0.05,
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[167:200]
## z = 3.7815, n = 34, p-value = 0.0001559
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##           S        varS         tau
##  256.000000 4547.333333    0.457553
```

```r
#so might be another trend point in this area
mk.test(carbon.peter2$doc[201:289]) #p-value greater than 0.05,
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[201:289]
## z = -0.34022, n = 89, p-value = 0.7337
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##            S         varS          tau
##   -97.000000 79620.333333    -0.024786
```

```r
#so no trend point in this area

#pettitt test between 167 and 200
pettitt.test(carbon.peter2$doc[167:200]) #changepoint at 18+167 = 185
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.peter2$doc[167:200]
## U* = 238, p-value = 0.0004497
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                                18
```

```r
#mk.test between 167:184 and 185:200
mk.test(carbon.peter2$doc[167:184]) #p-value is equal to 1,
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[167:184]
## z = 0, n = 18, p-value = 1
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##    S varS  tau
##    0  696    0
```

```r
#so accept the null that there are no more trend points
mk.test(carbon.peter2$doc[185:200]) #p-value is greater than 0.05,
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.peter2$doc[185:200]
## z = 0.76538, n = 16, p-value = 0.444
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##        S     varS      tau
##  18.0000 493.3333   0.1500
```

```r
#so accept the null that there are no more trends
```

The Mann-Kendall test for Peter Lake detected several trends in the data and the pettitt tets detected several change points. The changepoints are visible on Figure 10.

```r
#Mann-Kendall tests and pettitt tests on West Long Lake to detect trends
mk.test(carbon.west2$doc)
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc
## z = -0.31518, n = 102, p-value = 0.7526
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##             S          varS           tau
## -1.100000e+02  1.196027e+05 -2.138624e-02
```

```r
pettitt.test(carbon.west2$doc) #changepoint at 60
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc
## U* = 1013, p-value = 0.006394
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                               60
```

```r
mk.test(carbon.west2$doc[1:59]) #trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[1:59]
## z = 2.4917, n = 59, p-value = 0.01271
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##            S         varS          tau
## 3.820000e+02 2.338067e+04 2.234572e-01
```

```r
mk.test(carbon.west2$doc[60:102]) #trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[60:102]
## z = 4.8254, n = 43, p-value = 1.398e-06
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##            S         varS          tau
```

```
##  462.0000000 9127.3333333    0.5124799
```

```r
#pettitt test
pettitt.test(carbon.west2$doc[1:59]) #changepoint at 16 + 1 = 17
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc[1:59]
## U* = 587, p-value = 0.0001005
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                               16
```

```r
pettitt.test(carbon.west2$doc[60:102]) #changepoint at 23+60 = 83
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc[60:102]
## U* = 417, p-value = 5.389e-06
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                               23
```

```r
#mk.test on carbon west
mk.test(carbon.west2$doc[1:16]) #no trend
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[1:16]
## z = 0.22511, n = 16, p-value = 0.8219
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##         S     varS      tau
##    6.0000 493.3333   0.0500
```

```r
mk.test(carbon.west2$doc[17:59]) #trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[17:59]
## z = -2.198, n = 43, p-value = 0.02795
## alternative hypothesis: true S is not equal to 0
```

```
## sample estimates:
##             S          varS           tau
## -211.0000000 9128.3333333   -0.2339248
```

```r
mk.test(carbon.west2$doc[60:82]) #no trend
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[60:82]
## z = -0.55481, n = 23, p-value = 0.579
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##              S           varS            tau
##  -22.00000000 1432.66666667   -0.08712888
```

```r
mk.test(carbon.west2$doc[83:102])#trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[83:102]
## z = 2.1425, n = 20, p-value = 0.03216
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##            S         varS         tau
##  67.0000000 949.0000000   0.3535632
```

```r
#pettitt test on carbon west
pettitt.test(carbon.west2$doc[17:59]) #changepoint at 32 + 17 = 49
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc[17:59]
## U* = 212, p-value = 0.0727
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                               32
```

```r
pettitt.test(carbon.west2$doc[83:102]) #changepoint at 7 + 83 = 90
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc[83:102]
## U* = 75, p-value = 0.03598
```

```
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                                7
```

```r
#mk.test on West Long Lake
mk.test(carbon.west2$doc[17:48]) #no trend
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[17:48]
## z = -0.30819, n = 32, p-value = 0.7579
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##             S          varS           tau
##  -20.00000000 3800.66666667   -0.04040412
```

```r
mk.test(carbon.west2$doc[49:59]) #no trend
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[49:59]
## z = 1.557, n = 11, p-value = 0.1195
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##           S        varS          tau
##  21.0000000 165.0000000   0.3818182
```

```r
mk.test(carbon.west2$doc[83:89]) #trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[83:89]
## z = -2.2787, n = 7, p-value = 0.02269
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##           S        varS          tau
## -16.0000000  43.3333333  -0.7807201
```

```r
mk.test(carbon.west2$doc[90:102]) #no trend detected
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[90:102]
```

```
## z = 0.42706, n = 13, p-value = 0.6693
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##           S        varS         tau
##   8.0000000 268.6666667   0.1025641
```

```r
#pettitt test on West Long lake
pettitt.test(carbon.west2$doc[83:89]) #changepoint at 2+83 = 85
```

```
##
##  Pettitt's test for single change-point detection
##
## data:  carbon.west2$doc[83:89]
## U* = 10, p-value = 0.4328
## alternative hypothesis: two.sided
## sample estimates:
## probable change point at time K
##                               2
```

```r
#mk.test on West Long Lake
#mk.test(carbon.west2$doc[83:84]) #this cannot be run because
#there must be at least 3 elements
mk.test(carbon.west2$doc[83:89])
```

```
##
##  Mann-Kendall trend test
##
## data:  carbon.west2$doc[83:89]
## z = -2.2787, n = 7, p-value = 0.02269
## alternative hypothesis: true S is not equal to 0
## sample estimates:
##           S        varS         tau
## -16.0000000  43.3333333  -0.7807201
```

The Mann-Kendall test for West Long Lake detected several trends in the data and the pettitt tets detected several change points. The changepoints are visible on Figure 10.

```r
grid.arrange(carbon.three.lakes.plot, peter, west.long, paul.lake,
            nrow = 2)
```

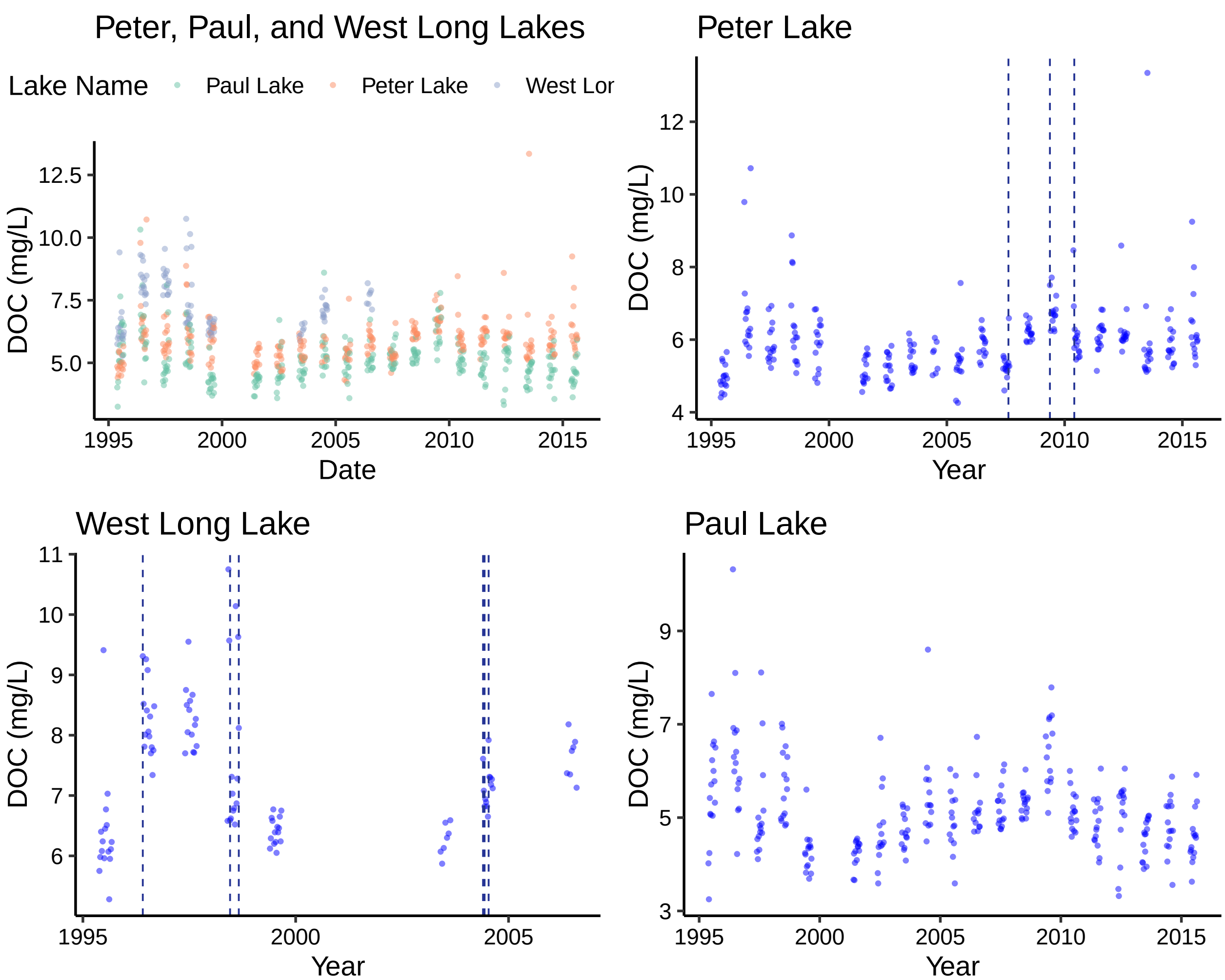

Figure 10: DOC (mg/L) over time for Peter, Paul, and West Long Lakes. Changepoints in the data are represented by vertical lines.

5 Summary and Conclusions

The significant findings from this analysis show that dissolved organic carbon does not vary by depth, as shown in Figure 5. Instead, DOC was found to vary by lake, likely because each lake has a different depth and catchment area, which can greatly contribute to the amount of dissolved organic carbon found in the lake. Additionally, seasonal trends were not able to be determined between depth and DOC because DOC was measured primarily during the spring and summer months.

The two-way ANOVA with interactions test shows that the interaction between depth and lake name is significant. The post-hoc Tukey test indicates that the interaction between all of the lakes and depths are significant. A non-parametric Mann-Kendall test was conducted to see how DOC varies over time. From the Mann-Kendall test on dissolved organic carbon in the hypolimnion, Paul lake had no changepoints. This might have to do with the fact that Paul lake has the smallest range of dissolved organic carbon (mg/L) compared to Peter and West Long lakes. Figure 10 shows that Peter lake had three change points, where as West Long lake had six change points. West Long Lake had the most change points and this could be because it is 27m deep at its deepest, which is significantly deeper than Peter and Paul lakes, with 19.3m and 12.2m, respectively. Paul lake does not have any detected changepoints, which is likely because it was used as a control during an experiment on nutrients. Since nutrients were not added to Paul lake, the main source of DOC would be from the catchment area. However, nutrients were added to Peter lake which resulted in algal blooms. Algae can lead to an increase in DOC in lakes, which is likely why Peter lake has three changepoints.