Chlorophyll A trends in Utah Lake from 1989 to 2019

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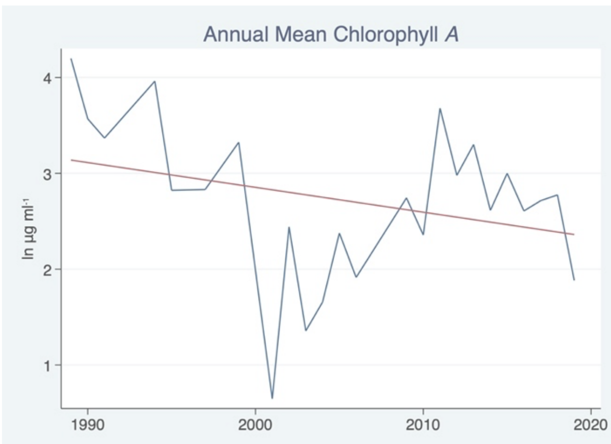
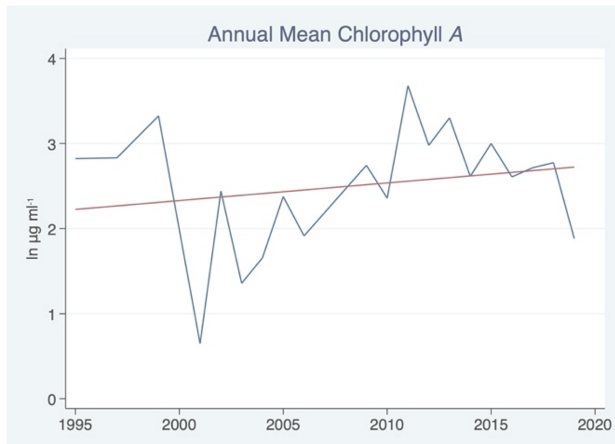
CHLOROPHYLL *A* TRENDS IN UTAH LAKE FROM 1989 TO 2019

Technical Memo





To
Wasatch Front Water Quality

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INTRODUCTION

Water column chlorophyll *A* (μg mL^{-1}) is an often-used surrogate for phytoplankton cell counts, biomass/biovolume, and estimating harmful algal (cyanobacteria) blooms including in Utah Lake. For several years DWQ has suggested that algal blooms were increasing in Utah Lake apparently based on chlorophyll *a* data and some citizen groups and professors, including those associated with Conserve Utah Valley suggest that algal blooms are decreasing in the lake inferring that the health of the lake is improving.

There are many problems associated with determining algal bloom trends in Utah Lake based on Chl *a* data including spatial and temporal factors that affect concentrations, different sampling and laboratory methods, changes in water chemistry, phytoplankton assemblage changes over time and space, and the assumption that Chl *a* is a suitable surrogate for cell counts and biovolume. In addition, the type of statistical models used to determine trends can have a strong effect in interpreting trends. In this report, I examine a readily available DWQ Utah Lake Chl *a* dataset from Utah Lake collected between 1989 and 2019 to evaluate trends.

METHODS

The Chl *a* datset analyzed was downloaded from DWQ website: https://udwq.shinyapps.io/UtahLakeDataExplorer/. Data in the set were collected from 1989 to 2019. I filtered the dataset by "Parameter=Chlorophyll a" and "depth = surface". There were four "Result Analytical Methods" used: GENERIC METHOD, 10200-H, 10200H(2), and HPLCMOD_CHL that I coded as a categorical factor. One Chl *a* value of 0.2 ug/ml collected on September 21, 2001, was removed because "Laboratory Name = NA". This value was also an outlier. All other samples in the dataset were analyzed at Utah DOH Division of Epidemilogy (sic) and Laboratory Services. All samples were collected by Utah Department of Environmental Quality. Sample locations were scattered across the lake (Figure 1). Samples other than Provo Bay samples were not modeled separately nor combined into superficial areas, although in future analyses Goshen Bay samples should be modeled separately and perhaps other area groupings can be defined and modeled separately, as most researchers acknowledge that Utah Lake is more heterogenous than often depicted.

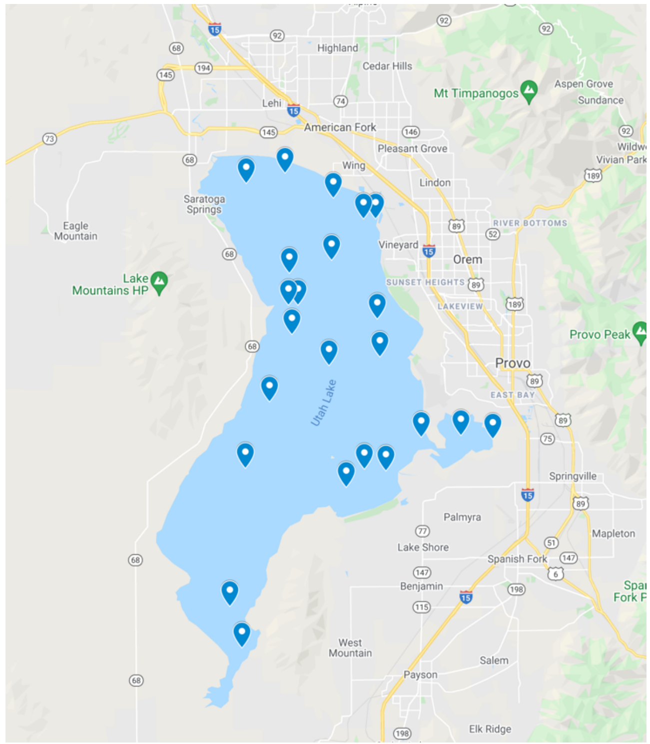

FIGURE 1. LOCATIONS OF CHL A SAMPLE COLLECTIONS IN UTAH LAKE FROM DWQ DATASET USED IN THESE ANALYSES.

I used numerous statistical methods to evaluate trends in Chl *a* in the lake including linear regression, mixed effects regression models, ARIMA time series, correlograms and partial correlograms, and simple boxplots on raw and transformed data. All statistical analyses were conducted using Stata 16.1 for Mac.

RESULTS

INITIAL ANALYSES

Chlorophyll *A* concentration data were not normal (Gaussian) distributed and followed a negative binomial distribution truncated at zero (Figure 2). Data were consequently natural log (ln) transformed to approximate a more normal distribution for parametric regression and times series analyses (Figure 2).

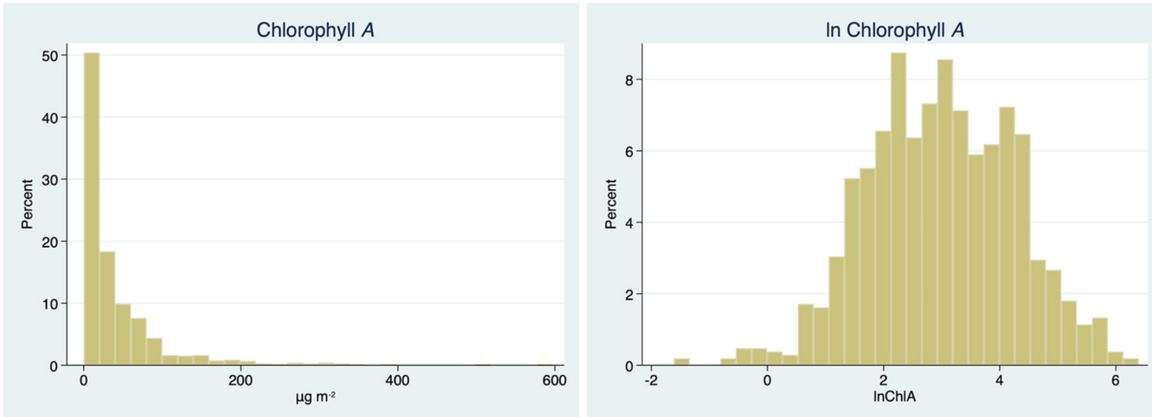

FIGURE 2. HISTOGRAMS OF CHL A RAW (LEFT) AND LN TRANSFORMED (RIGHT).

Linear fit trend lines with 95% CIs on raw data and transformed data suggested a slight decrease in Chl *a* concentration over time when modeled starting in 1989.

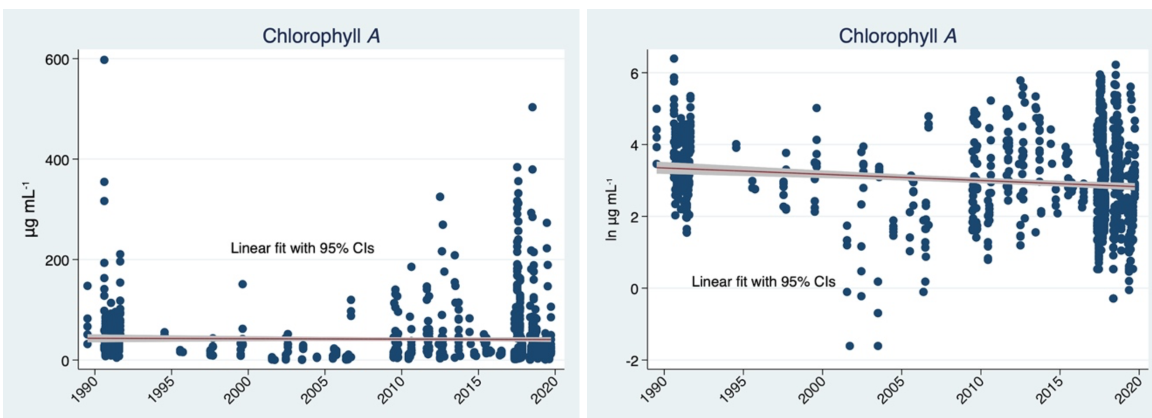

FIGURE 3. SCATTER PLOTS AND LINEAR FIT LINES WITH 95% CIS USING RAW CHL A AND LN TRANSFORMED CHL A DATA.

Linear regression on transformed data using date collected and no other predictors suggested that there was strong evidence for a very slight decrease in Chl *a* from 1989 to 2019 in Utah Lake outside of Provo Bay but there was no evidence for a trend in Provo Bay (Table 1). However, regression and time series models are strongly influenced by starting date values, for example starting values collected pre-1995 (Figure 3 and Figure 5). We do not have data pre 1989 and subsequently cannot tell what Chl *a* values were prior to 1989. As an example of the effects of starting date, regression of data post 1994 suggested that there was no evidence for an increasing or decreasing trend in Utah Lake outside of Provo Bay or in Provo Bay (Table 2 and Figure 4).

TABLE 1. REGRESSION WITH ALL YEARS UL AND PB

-> provo = Utah Lake

Source	SS	df	MS		
Model	86.4694019	1	86.4694019	Number of obs =	925
Residual	1183.82565	923	1.28258467	F(1, 923) =	67.42
				Prob > F =	0.0000
Total	1270.29505	924	1.37477819	R-squared =	0.0681
				Adj R-squared =	0.0671
				Root MSE =	1.1325

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	-.0000759	9.25e-06	-8.21	0.000	-.0000941	-.0000578
_cons	4.19209	.1725572	24.29	0.000	3.85344	4.53074

-> provo = Provo Bay

Source	SS	df	MS		
Model	1.0562235	1	1.0562235	Number of obs =	127
Residual	162.054628	125	1.29643702	F(1, 125) =	0.81
				Prob > F =	0.3685
Total	163.110851	126	1.29453057	R-squared =	0.0065
				Adj R-squared =	-0.0015
				Root MSE =	1.1386

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	-.00009	.0000998	-0.90	0.368	-.0002875	.0001074
_cons	6.137433	2.06093	2.98	0.003	2.058597	10.21627

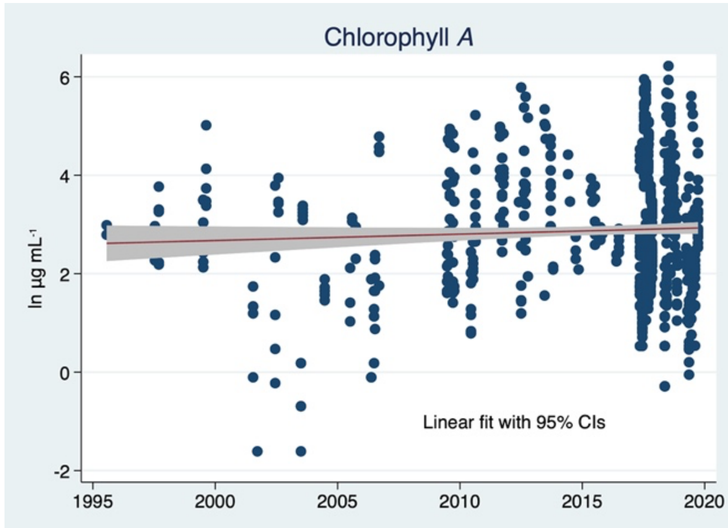

FIGURE 4. SCATTER PLOT AND LINEAR FIT WITH 95% CIS OF CHL A FROM 1995 TO 2019, UTAH LAKE AND PB COMBINED.

TABLE 2. LINEAR REGRESSION MODEL OF CHL A VS. DATE FOR UTAH LAKE OUTSIDE OF PROVO BAY AND FOR PROVO BAY FROM 1995 TO 2019.

-> provo = Utah Lake

Source	SS	df	MS			
				Number of obs	=	721
				F(1, 719)	=	0.22
Model	.321110122	1	.321110122	Prob > F	=	0.6359
Residual	1028.95225	719	1.43108797	R-squared	=	0.0003
				Adj R-squared	=	-0.0011
Total	1029.27336	720	1.42954634	Root MSE	=	1.1963

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	.0000108	.0000228	0.47	0.636	-.0000339	.0000555
_cons	2.406917	.4612106	5.22	0.000	1.501436	3.312397

-> provo = Provo Bay

Source	SS	df	MS			
				Number of obs	=	127
				F(1, 125)	=	0.81
Model	1.0562235	1	1.0562235	Prob > F	=	0.3685
Residual	162.054628	125	1.29643702	R-squared	=	0.0065
				Adj R-squared	=	-0.0015
Total	163.110851	126	1.29453057	Root MSE	=	1.1386

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	-.00009	.0000998	-0.90	0.368	-.0002875	.0001074
_cons	6.137433	2.06093	2.98	0.003	2.058597	10.21627

Boxplots showing medians, 25th, 75th, and ranges of Chl *a* did not show an obvious trend over time and similarly to the previous regression analyses. However, the year that the model was initiated can lead the viewer to imagine a trend (Figure 5). Humans have an uncanny ability to see trends where they don't exist.

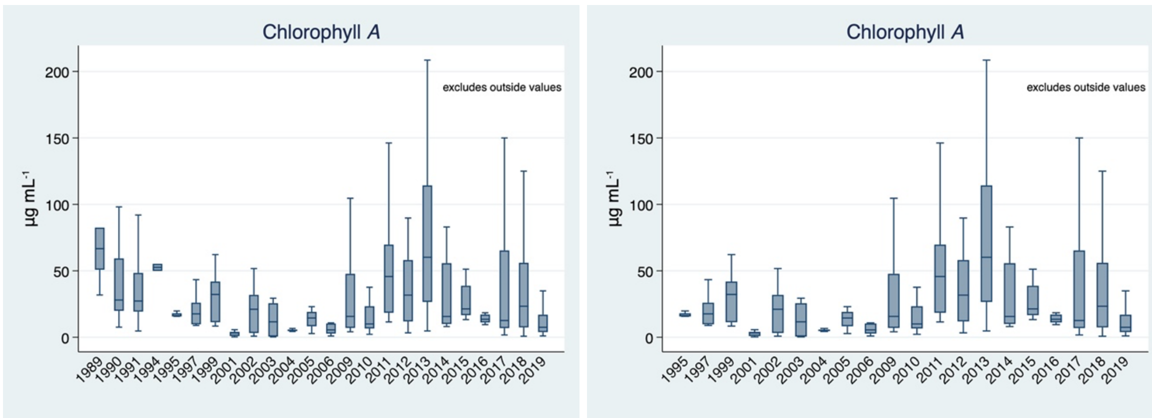

FIGURE 5. BOXPLOTS INCLUDING YEARS PRE 1995 AND POST 1994. APPARENT CYCLIC TREND AND POSSIBLY YEARLY TREND (SEE TIME SERIES SECTION THAT FOLLOWS).

As further examples, other regressions modeled at different starting dates (2001, 2006 for example) provided strong evidence for very slight increasing trends in Chl *a* (data not presented).

FULL REGRESSION ANALYSES

Many factors (covariates) reported in the database could have affected model results including month, hour samples were collected location, sampling methods, and laboratory methods, as well as unmeasured/unreported factors. I modeled measured covariables as fixed or random effects in the following regressions. Provo Bay is well known to be ecologically much different than other areas of Utah Lake and subsequently was modeled separately.

The best fit regression model (lowest AIC, BIC) for Utah Lake outside of Provo Bay was natural log transformed Chl *a* as a function of date modeled as a continuous variable and month and hour modeled as categorical variables. Regression results showed that there was strong evidence that Chl *a* in Utah Lake outside of Provo Bay slightly decreased from 1989 to 2019 (Table 3). However, again, regression results were dependent on starting date. When modeled starting in 1995, there was strong evidence that Chl *a* in Utah Lake outside of Provo Bay slightly increased until 2019 (Table 4).

TABLE 3. BEST FIT LINEAR REGRESSION OF LN CHL A VS. DATE, MONTH, AND HOUR USING DATA FROM 1989 TO 2019.

Source	SS	df	MS			
				Number of obs	=	**925**
				F(19, 905)	=	**22.84**
Model	**411.675154**	**19**	**21.6671134**	Prob > F	=	**0.0000**
Residual	**858.619896**	**905**	**.948751266**	R-squared	=	**0.3241**
				Adj R-squared	=	**0.3099**
Total	**1270.29505**	**924**	**1.37477819**	Root MSE	=	**.97404**

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	**-.0000825**	**8.84e-06**	**-9.33**	**0.000**	**-.0000998**	**-.0000651**
month						
Apr	**-.4440515**	**.318956**	**-1.39**	**0.164**	**-1.070031**	**.1819279**
May	**-1.167838**	**.2801722**	**-4.17**	**0.000**	**-1.717701**	**-.6179755**
June	**-1.220752**	**.2752351**	**-4.44**	**0.000**	**-1.760925**	**-.6805786**
July	**.0398743**	**.2703972**	**0.15**	**0.883**	**-.4908041**	**.5705527**
Aug	**.4243634**	**.2746761**	**1.54**	**0.123**	**-.1147129**	**.9634397**
Sept	**.1994005**	**.2756404**	**0.72**	**0.470**	**-.3415682**	**.7403691**
Oct	**-.1744016**	**.2798513**	**-0.62**	**0.533**	**-.7236346**	**.3748315**
Nov	**-.3283903**	**.2876792**	**-1.14**	**0.254**	**-.8929862**	**.2362057**
hour						
9	**.251551**	**.2028779**	**1.24**	**0.215**	**-.1466148**	**.6497168**
10	**-.1185473**	**.1942107**	**-0.61**	**0.542**	**-.4997029**	**.2626084**
11	**-.0876245**	**.1923749**	**-0.46**	**0.649**	**-.4651774**	**.2899283**
12	**-.1310348**	**.1940575**	**-0.68**	**0.500**	**-.5118899**	**.2498203**
13	**.2177472**	**.2058992**	**1.06**	**0.291**	**-.1863482**	**.6218427**
14	**.3935765**	**.2176146**	**1.81**	**0.071**	**-.0335114**	**.8206645**
15	**.1066443**	**.2251231**	**0.47**	**0.636**	**-.3351797**	**.5484684**
16	**-.1215389**	**.3084242**	**-0.39**	**0.694**	**-.7268486**	**.4837709**
17	**.3927165**	**.2919152**	**1.35**	**0.179**	**-.180193**	**.9656261**
18	**.4195601**	**.3170669**	**1.32**	**0.186**	**-.2027117**	**1.041832**
_cons	**4.502413**	**.3106895**	**14.49**	**0.000**	**3.892657**	**5.112169**

TABLE 4. BEST FIT LINEAR REGRESSION OF LN CHL A VS. DATE, MONTH, AND HOUR USING DATA FROM 1995 TO 2019.

Source	SS	df	MS			
				Number of obs	=	**721**
				F(18, 702)	=	**22.50**
Model	**376.520777**	**18**	**20.917821**	Prob > F	=	**0.0000**
Residual	**652.752585**	**702**	**.929846987**	R-squared	=	**0.3658**
				Adj R-squared	=	**0.3496**
Total	**1029.27336**	**720**	**1.42954634**	Root MSE	=	**.96429**

lnChlA	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Date	.000084	.0000203	4.14	0.000	.0000441	.0001239
month						
May	-.7871414	.3068563	-2.57	0.011	-1.389607	-.1846753
June	-.4400469	.2993734	-1.47	0.142	-1.027821	.1477275
July	1.181183	.2960626	3.99	0.000	.5999089	1.762458
Aug	1.244584	.2950276	4.22	0.000	.6653418	1.823826
Sept	1.247809	.2955883	4.22	0.000	.6674656	1.828152
Oct	.6795451	.3010695	2.26	0.024	.0884405	1.27065
Nov	.513058	.309194	1.66	0.097	-.0939978	1.120114
hour						
9	-.6782567	.4456477	-1.52	0.128	-1.553219	.1967052
10	-1.115745	.4427574	-2.52	0.012	-1.985033	-.246458
11	-1.1907	.4430942	-2.69	0.007	-2.060648	-.3207512
12	-1.224001	.4449131	-2.75	0.006	-2.097521	-.3504812
13	-.9268793	.4517165	-2.05	0.041	-1.813756	-.0400022
14	-.8000373	.4552981	-1.76	0.079	-1.693946	.0938719
15	-1.165245	.4570041	-2.55	0.011	-2.062504	-.2679866
16	-1.748927	.5183885	-3.37	0.001	-2.766705	-.7311499
17	-.9944819	.4946784	-2.01	0.045	-1.965708	-.0232556
18	-.8718859	.5039223	-1.73	0.084	-1.861261	.1174895
_cons	1.300811	.6711631	1.94	0.053	-.0169159	2.618539

Chl *a* concentrations were consistently higher in Provo Bay than Utah Lake outside of the Bay except in April and November (Figure 6).

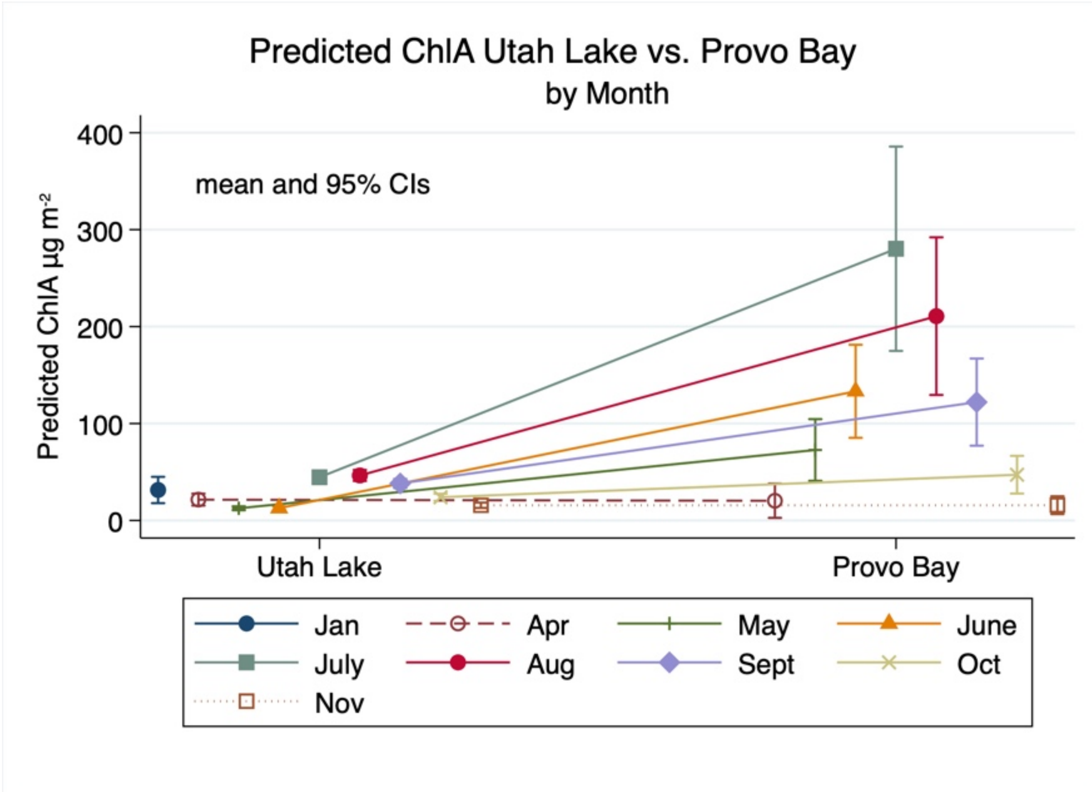

FIGURE 6. MONTHLY PREDICTED CHL A CONCENTRATIONS IN UTAH LAKE OUTSIDE OF PROVO BAY AND PROVO BAY. PREDICTIONS ARE BASED ON REGRESSION MODEL IN TABLE 4.

Mean annual Chl *a* was graphed vs. year starting in 1989 and then in 1995. Annual mean Chl *a* appeared to decrease over time when starting in 1989 but increased over time when started in 1995 (Figure 7). Year-to-year fluctuations and to a lesser extent two year- to- year fluctuations are visible as is an approximate (possible) seven-year cycle (Figure 7) (see Time Series section).

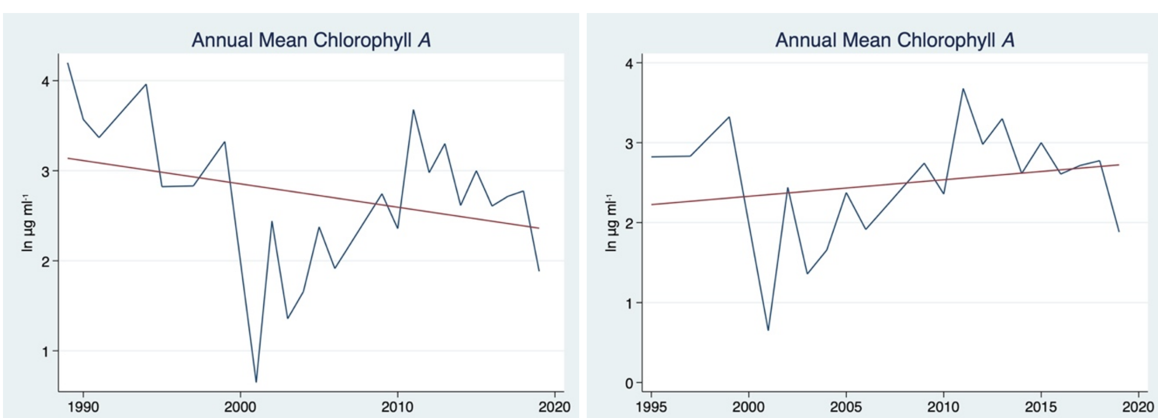

FIGURE 7. LEFT: MEAN ANNUAL CHL A FROM 1989 TO 2019. RIGHT: MEAN ANNUAL CHL A FROM 1995 TO 2019.

TIME SERIES TRENDS

A cursory ARIMA time series model was fit to mean ln Chl *a* as the response variable and year as the time series variable. The best fit ARIMA model (lowest AIC, BIC) was developed using Autoregressive order (p) = 2, Integrated (difference) order (d) = 1, and Moving-average order (q) = 0. Partial autocorrelation correlogram showed lags of 1 and 2 years (Figure 8, Table 6). Detrending (D = 1) data resulted in removal of any non-autocorrelated trend (t = 0.35, p = 0.73) allowing for testing of autocorrelated lags (Table 5).

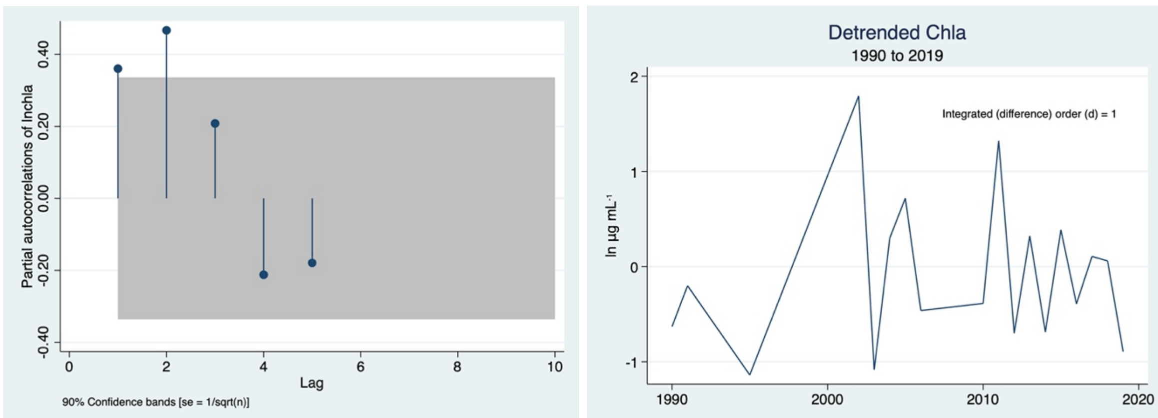

FIGURE 8. LEFT: PARTIAL AUTOCORRRELATION (P) OF LN CHL A SHOWING SIGNIFICANT LAGS OF 1 AND 2 YEARS. SHADED AREA IS 90% CIS. RIGHT: DETRENDED (D = 1) LN CHL A FROM 1990 TO 2019.

TABLE 5. LINEAR REGRESSION OF DETRENDED, ONE ORDER OF DIFFERENCING (D = 1) OF CHL A VS. YEAR 1990 TO 2019. THESE RESULTS SHOWED REMOVAL OF ANY TRENDS THAT COULD HAVE IMPEEDED AUTOCORRELATION FINDINGS.

Source	SS	df	MS	Number of obs	=	18
		F(1, 16)	=	0.12		
Model	.083581147	1	.083581147	Prob > F	=	0.7295
Residual	10.8002264	16	.675014147	R-squared	=	0.0077
		Adj R-squared	=	-0.0543		
Total	10.8838075	17	.64022397	Root MSE	=	.82159

D.lnchla	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
year	.0077923	.0221446	0.35	0.730	-.0391522	.0547368
_cons	-15.73264	44.46314	-0.35	0.728	-109.9903	78.525

The ARIMA time series model showed that there was strong evidence for a year-to-year autocorrelation (lag = 1, z = -3.60, p < 0.001) and a two year to year (lag = 2, z = -2.69, p = 0.007) of Chl *a* (Table 6).

TABLE 6. ARIMA TIME SERIES REGRESSION OF CHL A AS A FUNCTION OF YEAR USING P = 2, D = 1, AND Q = 0.

Sample: 1990 - 2019, but with gaps	Number of obs = 18
Wald chi2(2) = 13.64	
Log likelihood = -16.36919	Prob > chi2 = 0.0011

D.lnchla	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
lnchla						
_cons	-.0113498	.0738794	-0.15	0.878	-.1561508	.1334511
ARMA						
ar						
Lag 1	-1.060287	.2949232	-3.60	0.000	-1.638326	-.4822483
Lag 2	-.5922256	.22041	-2.69	0.007	-1.024221	-.16023
/sigma	.5223887	.1757504	2.97	0.001	.1779243	.8668531

EFFECTS OF NUMBER OF SAMPLE EVENTS, MONTHS, AND HOURS SAMPLED ON CHLOROPHYLL *A*

The number of samples collected in during each hour, month, and year obviously had an effect on Chl *a* concentrations. The number of sampling events differed widely as shown in Appendix 1. Subsequently, analysis of monthly and hourly interaction effects on ln Chl *a* concentrations were made on data with January, April, and November and hours 8, 16, 17 and 18 removed. The best fit linear mixed effect model was with ln Chl *a* as a function of month and hour modeled as categorical fixed effects with interactions and year as a random variable. Results are in Appendix 2. Marginal predictions were then made of ln Chl *a* based on this model shown in Appendix 3 and Appendix 4.

DISCUSSION AND CONCLUSION

Determining long-term trends of Chl *a* in Utah Lake is not straight forward and is strongly dependent on years that analyses are initiated. Consequently, no conclusion can be made from the DWQ data set used. However, there was strong evidence for year-to-year, and two-year-to-year autocorrelation trends and there was possibly an approximately seven-year trend. Reasons for these cycles were not examined but could be related to weather patterns, temperature, lake levels, changes in chemistry (e.g., salinity), direct and indirect biological interactions including intra and interspecific phytoplankton competition, changes in zooplankton grazer assemblages, changes in fish assemblages, or even possibly chironomid larvae densities (Richards et al. all years).

Problems with determining long-term trends were numerous and added to uncertainty and variability as presented in the introduction and throughout these results, including the effects on year, month, and hour sampled and their interactions (see Appendices). Other Chl *a* data sources need to be identified and incorporated into a meta-analysis.

It is well known that Chl *a* is a modest surrogate for algal biovolume and harmful algal bloom (cyanobacteria) estimates. Given the uncertainty shown in determining long-term Chl *a* trends in Utah Lake from this analysis; it is strongly recommended **not** to infer trends in phytoplankton biovolumes, cell counts, or algal blooms. No long-term, consistent, robust cell counts or biovolume of phytoplankton assemblage data are available for Utah Lake to determine trends (but see Richards 2021).

As shown throughout this report, starting date has a strong influence on trend interpretation. I am not sure why 1989 to 1994 Chl *a* concentrations were substantially higher years. Were they unusually high Chl *a* years? Or were they following past trends? Additional research and more detailed analyses are needed.

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Appendices

APPENDIX 1. SAMPLE TOTALS AND COUNT TOTALS BY YEAR AND MONTH

Year	Jan	April	May	June	July	Aug	Sept	Oct	Nov	**Sample Total**	**Count Total**
1989					5					***5***	***1***
1990						15	17	20	15	***67***	***4***
1991	15	15	30	25	30	15				***130***	***6***
1994					2					***2***	***1***
1995					2		2			***4***	***2***
1997					5		5			***10***	***2***
1999					6	5				***11***	***2***
2001					5		1			***6***	***2***
2002				5		5				***10***	***2***
2003					10					***10***	***1***
2004				5						***5***	***1***
2005					3	2	4			***9***	***3***
2006			3	4	5		4			***16***	***4***
2009				7	7	7	7	7		***35***	***5***
2010				7	9	9				***25***	***3***
2011						12	12	12		***36***	***3***
2012			2		11	12	12	2		***39***	***5***
2013				3	2		10	2		***17***	***4***

2014				2	1		3		1	*7*	***4***
2015			2	2	5		3	1		***13***	***5***
2016			2	6						***8***	***2***
2017			29	45	61	52	55	55	53	***350***	***7***
2018			21	21	21	21	21	21	15	***141***	***7***
2019		16	16	16	16	16	16			***96***	***6***
Sample Total	**15**	**31**	**105**	**148**	**206**	**171**	**172**	**120**	**84**	**1052**	
Count Total	**1**	**2**	**8**	**13**	**19**	**12**	**15**	**8**	**4**		

APPENDIX 2. LINEAR MIXED EFFECTS OF LN CHL A AS A FUNCTION OF MONTH AND HOUR AS CATEGORICAL FIXED EFFECTS WITH INTERATCTIONS AND YEAR AS A RANDOM VARIABLE. AUGUST AND HOUR 13 WERE USED BASELINE VARIABLES FOR COMPARISONS.

```
Mixed-effects ML regression                     Number of obs     =        732
Group variable: _all                            Number of groups  =          1

                                                Obs per group:
                                                              min =        732
                                                              avg =      732.0
                                                              max =        732

                                                Wald chi2(40)     =     367.97
Log likelihood = -1027.9317                     Prob > chi2       =     0.0000
```

lnChlA	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
month						
May	-2.53898	.5100171	-4.98	0.000	-3.538595	-1.539364
June	-3.02704	.4619845	-6.55	0.000	-3.932513	-2.121567
July	-1.932289	.4389528	-4.40	0.000	-2.792621	-1.071958
Aug	0	(base)				
Sept	-1.221653	.5267434	-2.32	0.020	-2.254051	-.1892549
Oct	-2.241987	.4357064	-5.15	0.000	-3.095956	-1.388018
hour						
9	-1.534642	.4327639	-3.55	0.000	-2.382843	-.6864399
10	-2.026279	.4053205	-5.00	0.000	-2.820693	-1.231865
11	-1.392536	.4100692	-3.40	0.001	-2.196257	-.5888149
12	-1.71668	.4149888	-4.14	0.000	-2.530043	-.9033167
13	0	(base)				
14	.4442961	.4953098	0.90	0.370	-.5264933	1.415086
15	-1.187228	.4764573	-2.49	0.013	-2.121067	-.2533884
month#hour						
May# 9	1.353617	.6191713	2.19	0.029	.1400633	2.56717
May#10	1.174131	.5958502	1.97	0.049	.0062863	2.341976
May#11	1.006669	.5952186	1.69	0.091	-.1599381	2.173276
May#12	1.255619	.5765831	2.18	0.029	.1255366	2.385701
May#13	0	(base)				
May#14	-1.205787	.6889271	-1.75	0.080	-2.556059	.1444855
May#15	-.23139	.736628	-0.31	0.753	-1.675154	1.212374
June# 9	1.751042	.5572614	3.14	0.002	.6588298	2.843254
June#10	1.829994	.5474296	3.34	0.001	.7570514	2.902936
June#11	1.288831	.5398263	2.39	0.017	.2307912	2.346871
June#12	1.612297	.5546261	2.91	0.004	.52525	2.699345
June#13	0	(base)				
June#14	-.6934934	.6092151	-1.14	0.255	-1.887533	.5005462
June#15	1.054281	.631524	1.67	0.095	-.1834829	2.292045
July# 9	1.582173	.529225	2.99	0.003	.5449114	2.619435
July#10	1.991388	.4995608	3.99	0.000	1.012266	2.970509
July#11	1.194337	.4998529	2.39	0.017	.214643	2.17403
July#12	1.766164	.5119891	3.45	0.001	.7626838	2.769644
July#13	0	(base)				
July#14	.5059386	.6115411	0.83	0.408	-.6926599	1.704537
July#15	2.105471	.5963743	3.53	0.000	.9365994	3.274344
Aug# 9	0	(base)				
Aug#10	0	(base)				
Aug#11	0	(base)				
Aug#12	0	(base)				
Aug#13	0	(base)				
Aug#14	0	(empty)				
Aug#15	0	(base)				
Sept# 9	1.218059	.6287913	1.94	0.053	-.014349	2.450468
Sept#10	1.825383	.5875679	3.11	0.002	.6737713	2.976995
Sept#11	.4252194	.5807177	0.73	0.464	-.7129665	1.563405
Sept#12	.8387658	.5889922	1.42	0.154	-.3156378	1.993169
Sept#13	0	(base)				
Sept#14	-.4558179	.6668997	-0.68	0.494	-1.762917	.8512815
Sept#15	-.5805939	.6979463	-0.83	0.405	-1.948544	.7873557
Oct# 9	2.432644	.5792287	4.20	0.000	1.297377	3.567911
Oct#10	1.871792	.5058243	3.70	0.000	.8803945	2.863189
Oct#11	1.624675	.5199792	3.12	0.002	.6055348	2.643816
Oct#12	1.828977	.5295756	3.45	0.001	.7910277	2.866926
Oct#13	0	(base)				
Oct#14	0	(omitted)				
Oct#15	.7535597	.6320685	1.19	0.233	-.4852717	1.992391
_cons	4.942522	.3724638	13.27	0.000	4.212506	5.672537

Random-effects Parameters	Estimate	Std. Err.	[95% Conf. Interval]	
_all: Independent				
var(year)	**1.22e-24**	.	.	.
var(_cons)	**4.47e-18**	.	.	.
var(Residual)	**.9711052**	.	.	.

LR test vs. linear model: chi2(**2**) = **0.00** Prob > chi2 = **1.0000**

APPENDIX 3. MARGINAL ESTIMATES OF LNCHLA BY HOUR AND MONTH AND THEIR INTERACTIONS BASED ON BEST FIT LINEAR MIXED EFFECTS MODEL IN APPENDIX 2.

```
. margins i.hour#i.month

Adjusted predictions                          Number of obs     =        732

Expression   : Linear prediction, fixed portion, predict()
```

Continued next page:

	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
hour#month						
9#May	2.222517	.2733137	8.13	0.000	1.686832	2.758202
9#June	2.131882	.2203526	9.67	0.000	1.699999	2.563765
9#July	3.057764	.1970893	15.51	0.000	2.671476	3.444052
9#Aug	3.40788	.2203526	15.47	0.000	2.975997	3.839763
9#Sept	3.404286	.2633717	12.93	0.000	2.888087	3.920485
9#Oct	3.598537	.3116256	11.55	0.000	2.987762	4.209312
10#May	1.551394	.2633717	5.89	0.000	1.035195	2.067593
10#June	1.719196	.2463617	6.98	0.000	1.236336	2.202056
10#July	2.975341	.1769914	16.81	0.000	2.628444	3.322238
10#Aug	2.916243	.1598606	18.24	0.000	2.602922	3.229564
10#Sept	3.519973	.2054798	17.13	0.000	3.11724	3.922706
10#Oct	2.546047	.2011535	12.66	0.000	2.151794	2.940301
11#May	2.017675	.2544412	7.93	0.000	1.51898	2.516371
11#June	1.811777	.2203526	8.22	0.000	1.379894	2.24366
11#July	2.812033	.1665709	16.88	0.000	2.48556	3.138506
11#Aug	3.549986	.1715442	20.69	0.000	3.213765	3.886206
11#Sept	2.753552	.174204	15.81	0.000	2.412119	3.094986
11#Oct	2.932674	.226077	12.97	0.000	2.489571	3.375777
12#May	1.942481	.1970893	9.86	0.000	1.556193	2.328769
12#June	1.811099	.2463617	7.35	0.000	1.328239	2.293959
12#July	3.059716	.1896493	16.13	0.000	2.688011	3.431422
12#Aug	3.225842	.1829929	17.63	0.000	2.867182	3.584501
12#Sept	2.842955	.1896493	14.99	0.000	2.471249	3.21466
12#Oct	2.812832	.2390059	11.77	0.000	2.344389	3.281275
13#May	2.403542	.348408	6.90	0.000	1.720675	3.086409
13#June	1.915481	.2733137	7.01	0.000	1.379796	2.451166
13#July	3.010232	.232272	12.96	0.000	2.554987	3.465477
13#Aug	4.942522	.3724638	13.27	0.000	4.212506	5.672537
13#Sept	3.720869	.3724638	9.99	0.000	2.990853	4.450884
13#Oct	2.700535	.226077	11.95	0.000	2.257432	3.143637
14#May	1.642051	.3284822	5.00	0.000	.998238	2.285865
14#June	1.666284	.226077	7.37	0.000	1.223181	2.109387
14#July	3.960467	.2733137	14.49	0.000	3.424782	4.496152
14#Aug	.	(not estimable)				
14#Sept	3.709347	.2463617	15.06	0.000	3.226487	4.192207
14#Oct	3.144831	.4407052	7.14	0.000	2.281064	4.008597
15#May	.9849244	.4407052	2.23	0.025	.1211582	1.848691
15#June	1.782535	.3116256	5.72	0.000	1.17176	2.39331
15#July	3.928476	.2733137	14.37	0.000	3.392791	4.464161
15#Aug	3.755294	.2971234	12.64	0.000	3.172943	4.337645
15#Sept	1.953047	.348408	5.61	0.000	1.27018	2.635914
15#Oct	2.266867	.348408	6.51	0.000	1.583999	2.949734

APPENDIX 4. MEAN AND 95% CIS OF PREDICTED CHLOROPHYLL A (LN UG ML-1) BASED ON BEST FIT LINEAR MIXED EFFECTS MODEL IN APPENDIX 2 AND MARGINAL ESTIMATES IN APPENDIX 3.