

# **GEOSPATIAL AND TEMPORAL ANALYSIS OF PATTERNS AND TRENDS OF SALINITY IN FINEGAYAN BASIN**

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**TECHNICAL REPORT NO. 177**

**DECEMBER 2022**



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## **ABSTRACT**

Finegayan Basin is one of six groundwater basins in the Northern Guam Lens Aquifer (NGLA), which supplies 90% of Guam's drinking water. It comprises 7% of the NGLA but supplies about 15% of total production from 15 wells operated by Guam Waterworks Authority (GWA) and 3 wells operated by Naval Facilities Engineering Command Marianas (NFM). This project sought to characterize historical patterns and trends in chloride concentration to provide a baseline for managing saltwater contamination.

This study focuses on geospatial-temporal analysis of the patterns and trends of salinity in Finegayan Basin. Using statistics in Microsoft Excel and ArcGIS, spatial and temporal trends of salinity levels measured by chloride concentrations are observed and analyzed. In Finegayan Basin, data is available for sixteen individual wells. Among the wells, seven of which are basal wells, eight of which are parabasal wells, and one is in the supra-basal zone. The seven basal wells are F1, F02, F03, F04, F10, F11, and F13. The eight basal wells are D24, F08, F12, F15, F16, F17, F18 and HGC2. The one supra-basal well is D22A. Of all the wells analyzed in this basin, five of the wells exceed the MCL and of that five, two exceed the USEPA National Secondary Drinking Water Regulation Guideline.

Temporal analysis not only indicates the increasing, decreasing, or stable trends, but also demonstrates cyclical patterns. This may be due to El Nino to La Nina periods as the periods usually last up to 6 years. Spatial analysis is applied to determine whether adjacent wells affect each other, and to determine whether the groundwater in the coinciding area has a trend of increased levels of chloride so that appropriate inferences can be made.

# **1. INTRODUCTION**

## **1.1 Statement of Problem**

The NGLA produces 90% of Guam's drinking water and with new development underway, namely the development of Marine Corps Base Camp Blaz on top of the Finegayan Basin, the NGLA must be carefully monitored to minimize risk of saltwater contamination and to ensure our water remains fit for consumption. As the population of the island is projected to continue to increase, the demand for water will rise and make it important that future endeavors match the growing demands. Geospatial and temporal analysis of the patterns and trends of salinity in Finegayan Basin may assist in management of water resources and decision making for new development in the study area.

## **1.2 General Geology**

The island of Guam, located in the western Pacific Ocean, is the largest and southernmost island of the Marianas Island chain located at 13°30'N and 144°45'W. The island is around thirty miles long and is 4 to 12 miles wide with an area of about 212 square miles. The island is divided in half by the Pago-Adelup fault that runs from the northwest to the southeast. The northern half of the island is characterized by flat terrain surrounded by vertical coastal cliffs and contains a significant amount of groundwater in the Northern Guam Lens Aquifer that underlies.

## **1.3 General Hydrogeology**

The Northern Guam Lens Aquifer (NGLA) underlies the entirety of the northern half of the island. This karst aquifer recharges, transfers and discharges water through underground pathways. As a karst aquifer made of limestone—a soluble rock that is high in porosity, the water undergoes no filtering. The body of groundwater is lens-shaped and is thickest towards the center of the island and thinnest along the coastline. The water is stored in the crevices and caves formed by water passing through the limestone. The aquifer's freshwater is recharged through water permeating through the ground and becoming groundwater. Freshwater is naturally discharged from the aquifer through coastal springs and is also extracted by production wells for our consumption. The Barrigada Limestone and the Mariana Limestone are the two principal aquifer rocks of the NGLA. The Barrigada limestone is the main aquifer rock and is deposited in deep water, constituting most of the bedrock mass on northern Guam. The Mariana Limestone is an emerged reef and forms 75% of the exposed limestone of Guam.

Guam receives about one hundred inches of rain annually (Lander 1994). There are two seasons on Guam—wet and dry. The breakdown of rainfall per season is 69% from the wet season (July through December) and 31% from the dry season (January through June).

Saltwater contamination is important to monitor in terms of maintaining the health of the NGLA. This is measured by the quantity of chloride (Cl<sup>-</sup>) ions. Following the lens-shape of the aquifer, the level of salinity increases as the lens is thinner. Saltwater intrusion occurs when the extraction of freshwater drops the level of fresh groundwater in the aquifer reducing water pressure and allowing the contamination of saltwater. This can be avoided by not drilling wells too deep or too close together and by not over pumping. If there is volcanic rock underlying the freshwater and not saltwater, it is far less likely to develop problems of saltwater intrusion. In addition to saltwater contamination by means of saltwater intrusion, it is possible that

contamination can be caused by contaminants originating from the land surface and being carried by recharging water. Examples of what can transport potentially harmful substances into the groundwater include spills of sewage, sea salt spray, leaks from septic tanks, industrial spills, materials washed off the land and carried by storm water, and runoff from agricultural areas.

## **1.4 Previous Salinity Studies on Guam**

### ***1.4A Groundwater Resources on Guam (Mink 1976)***

John Mink evaluated the past, present, and future of groundwater development on Guam in his technical report (Mink, 1976). Before the use of vertical wells that began in the mid-1960s, potable water on Guam was sourced from springs or impounded surface water (Fena Reservoir). Many wells drilled before the 1960s were plagued with high salinity and eventually abandoned due to their being set deeper than necessary and over pumped.

Mink recommended that areas within 2,000 feet of the ocean be considered as a zone of mixture. This zone contained greater than 250 mg/L of chloride (USEPA secondary standard). Mink proposed these chloride concentration benchmarks as a guideline for future evaluation and management of groundwater quality in the NGLA:

- Background: 15 to 20 mg/L chloride
- Para-basal: less than 20 mg/L chloride
- Basal: 20 to 60 mg/L chloride

Mink also proposed production well guidelines depending on the bedrock type underlying the production well. He recommended that well bottom depth be twenty-five feet below sea level and that it could be extended to 35 to 50 feet below sea level (depending on where the pumping would occur) to achieve a two hundred gallon per minute (gpm) production rate.

### ***1.4B Northern Guam Lens Study (BHA 1982)***

The 1982 Northern Guam Lens Study (NGLS) was conducted by Barrett, Harris & Associates, Inc. (BHA). This study saw Mink's initial zone of mixture revised to become a 4,000-foot coastal buffer zone. The six basins of the aquifer were also divided into forty-seven management zones and saw the drilling of exploratory monitoring wells and noted that the lower the permeability area of the aquifer, the thicker the transition zones would be and vice versa. Mink's previous chloride concentration benchmarks also saw a revision in this study and 150 mg/L became the design standard maximum chloride concentration for wells in the basal zone:

- Para-basal: Less than 30 mg/L chloride
- Saltwater toe: 30 to 70 mg/L
- Basal: 70 to 150 mg/L
- Saltwater up-coning: Greater than 150 mg/L

The NGLS concluded that most wells in the NGLA had not experienced serious degradation of groundwater quality because of saltwater up-coning and that there was a direct correlation between aquifer permeability and production capacity. For example, the lower the aquifer permeability, the lower the production should be. The NGLS production well design guideline maximum pump rates (gpm) suggested by this study were:

- Basal: 200 to 350 gpm
- Para-basal – Southern Hagatña sub-basin: 200 to 350 gpm
- Para-basal – Upper Yigo sub-basin: 750 gpm
- Para-basal – Other para-basal areas: 500 gpm

These guidelines allowed for deeper wells with higher pumping rates to be present in the Upper Yigo-subbasin, but there were no specific boundaries stated. This study did not set the precedent for supra-basal production wells.

#### ***1.4C Chloride History and Trends of Water Production Wells in the Northern Guam Lens Aquifer (McDonald and Jenson 2003)***

This technical report looked at the chloride contamination prevalent in 128 PUAG/GWA and Navy production wells between 1973 and 1999 and identified probable causes of the chloride contamination. This study also provided risk management guidelines to address the contamination. The study applied the USEPA Safe Drinking Water Guideline of 250 mg/L to locate wells with salinity problems. Linear regression was utilized to evaluate chloride concentrations over time and revealed that there were increasing trends in 50 % of the production wells. Other than solely using the chloride concentration benchmarks, McDonald and Jenson added three categories to assist in distinguishing production wells:

- Remained within the original benchmark category
- Increased sufficiently and crossed into another benchmark category
- Started and remained high

The study also saw an improvement of previous benchmark guidelines providing benchmark labels for every category:

McDonald and Jenson (2003) Chloride Benchmark	Proposed Chloride Benchmark Label	Chloride Concentration (mg/L)
Para-basal	Exceptional	Less than 30
Saltwater toe	Good	30 to 70
Basal	Standard	70 to 150
Saltwater Up-coning	Marginal	150 to 250
USEPA SDW Guideline	Out of Standard	More than 250

#### ***1.4D Salinity in the Northern Guam Lens Aquifer (Simard et. al 2015)***

This report evaluated the salinity trends from 1973 to 2010 and identified factors that might influence salinity and offered recommendations for aquifer management. Through linear regression analysis, it was revealed that there were significant temporal trends for 112 of the 153 wells studied. 107 production wells exhibited increasing trends and five showed significant decreasing trends. In addition to utilizing the proposed chloride benchmark labels from McDonald and Jenson 2003, the study reported that chloride concentrations were higher during the 2000-2010 decade compared to any of the previous decades in all production wells that had more than one decade of chloride data. Many production wells have been recorded to have unknown construction measurements. This study also showed the introduction of a new chloride benchmark, the supra-basal groundwater zone. In the supra-basal zone, seawater is not connected

with groundwater and is not the source of chloride. Sources of chloride in the supra-basal zone include airborne salt particles, industrial waste, septic system effluent or chlorine-treated potable water leaking from the distribution system. This study states that as the freshwater lens thinned out from 2005 to 2010, the excessive production well depths may have caused the increasing chloride concentrations.

Finegayan Basin is the smallest basin in NGLA, and 21 production wells were analyzed in this study. Eleven of the twenty-one production wells are situated in the basal groundwater zone, and all exhibit “standard” to “out of standard” chloride concentrations. Nine production wells are situated in the para-basal groundwater zone and exhibit “Exceptional” to “standard” chloride concentrations. The supra-basal groundwater zone has one well and this well exhibits “good” chloride concentrations.

## 2. METHODOLOGY

Data was given for sixteen individual wells from Guam Waterworks Authority (GWA) spanning January 1973 to June 2022. Seven of these wells are basal wells, eight are parabasal wells and one well is in the supra-basal zone. The seven basal wells include F1, F02, F03, F04, F10, F11, and F13. The eight basal wells are D24, F08, F12, F15, F16, F17, F18 and HGC2. The one supra-basal well is D22A.

To analyze the data, basic statistical methods were applied. The minimum, maximum, mean, and standard deviation were calculated for the chloride concentrations of every well. Decadal averages were also calculated using the time intervals of 1973-1979, 1980-1989, 1990-1999, 2000-2009, 2010-2019, and 2020 to present. The decadal averages were also color-coded based on the table below from Simard et al (2015) regarding chloride benchmark guidelines, their labels and assigned color.

McDonald and Jenson (2003) Chloride Benchmark	Proposed Chloride Benchmark Label	Chloride Concentration (mg/L)	Color Code
Para-basal	Exceptional	< 30	Light Blue
Saltwater toe	Good	30 – 70	Green
Basal	Standard	70 – 150	Yellow
Saltwater Up-coning	Marginal	150 – 250	Orange
SDW Guideline	Out of Standard	> 250	Red

Scatter plots were made for individual wells’ concentrations so that linear regression lines can be calculated. To determine the statistical significance of the linear regression lines, the correlation coefficient,  $r$ , was calculated from the scatter plot data. The  $r$  value was then compared to the critical values of the correlation coefficient,  $r_{crit}$ , which were calculated based on a two-tailed test with a 95% confidence level, or with an  $\alpha = 0.05$ . The  $r_{crit}$  values are found from Table B.17 of *Biostatistical Analysis* (Zar 1999). If the  $r$  values exceeded the critical values,  $r_{crit}$ , then the correlation values can be categorized as significant. Summaries of linear regression analysis and the linear regression scatter plots for chloride concentration are provided in the Appendix A and Appendix B, respectively.



The concentration data was also processed and displayed in bar graphs in ArcGIS Pro. This allowed for important guidelines to be marked out for easier visualization of when chloride concentrations passed the local benchmark Maximum Contaminant Level (MCL) at 150 mg/L and the USEPA National Secondary Drinking Water Regulation Guideline of 250 mg/L. Bar graphs displaying the chloride concentrations over the years for the individual wells are provided in the Appendix C.

Production was graphed separately in bar graphs with the Maximum Recommended Pump Rate from the NGLS study for visualization of whether wells were pumping their ideal rates. Production bar graphs can be found in Appendix D. Chloride concentration data was also plotted against the average production of the wells in the basin. These scatter plots also saw linear regression analysis and it is important to note that only the dates with both chloride concentration data and production data were graphed against each other. The linear regression summary for the relationship between chloride concentrations and well productions can be found in Appendix E, and the graphs for the relationship are listed in Appendix F.

To further analyze the changes in chloride concentration spatially, the wells were plotted in ArcGIS Pro and time properties were enabled. An animation was made to allow visualization of the changes in chloride concentration from the period of January 1973 to June 2022. This allows for inferences to be made about the relation of certain wells in proximity to each other, roads, or other external factors. For example, if multiple wells increase and decrease together as a group, it may be inferred that there is a relationship. The wells were again color coded using the same chloride benchmark guidelines from Simard above.

### **3. ANALYSIS AND RESULTS**

The chloride sampling frequencies were originally recorded monthly from 1973 to 1983. From 1984 to current day however, the chloride concentration collection was changed to occur quarterly. Few wells have gaps in their data from what we only assume as the well was out of order or taken offline, not use, or the collection of data was lost or taken. Below are the production and chloride statistics of the wells in the Finegayan Basin. The decadal means for chloride concentration were only marked if they surpassed the MCL or USEPA Guidelines in these charts. Regarding the status of the well section, the final year of production is given if the well is Out of Commission. Any well with the date and a GM means that currently the well is not operational due to a problem with the grounded motor as of the date given. For some of the values, an NA is input, meaning that the data is not available because the NGLS Recommended Pump Rate and Well Bottom Elevations were not given in previous reports.

Production Statistics		D22A	D24	F01	F02	F03	F04
Groundwater Zone		Supra-basal	Para-basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	5.91	-63.02	-35.74	-40.76	-55.77	-37.74
	Meters	1.80	-19.21	-10.89	-12.42	-17.00	-11.50
NGLS Max. Recommended Bottom Elevation (feet)		NA	-50	-40	-40	-40	-40
Well Screen Length (feet)		Unknown	Unknown	45	Unknown	40	40
Well Construction Year		1996	1995	1969	1971	1975	1975
Status/Final Year of Production		Operational	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		NA	500	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989			158.97	167.36	116.99	137.48
	1990-1999	117.08	116.48	141.25	119.50	146.59	132.10
	2000-2009	152.08	183.37	155.42	138.13	149.38	151.36
	2010-2019	92.80	188.07	112.39	133.67	182.23	129.12
	2020-Present	112.90	140.12	144.39	145.70	155.28	130.15
Chloride Statistics		D22A	D24	F01	F02	F03	F04
Total Number of Chloride Samples		50	78	255	246	234	233
Minimum Concentration (mg/L)		14.00	28.00	54.00	11.20	16.10	15.50
Maximum Concentration (mg/L)		218.90	205.90	233.90	237.50	184.20	364.40
Standard Deviation		36.78	30.96	41.62	26.51	24.83	75.08
Mean Chloride Concentration (mg/L)	1973-1979			72.64	102.94	92.23	82.47
	1980-1989			86.59	112.91	106.30	139.13
	1990-1999	30.73	42.53	99.32	117.50	107.30	167.27
	2000-2009	47.66	86.47	145.10	144.89	124.03	179.59
	2010-2019	26.08	84.71	152.84	143.60	123.59	212.37
	2020-Present	21.54	65.70	135.96	131.26	110.07	177.15

Continued:

Production Statistics		F08	F10	F11	F12	F13	F15
Groundwater Zone		Para-basal	Basal	Basal	Para-basal	Basal	Para-basal
Well Depth Elevation	Feet	-18.34	-47.29	-47.06	-41.33	-53.78	-51.47
	Meters	-5.59	-14.41	-14.34	-12.60	-16.39	-15.69
NGLS Max. Recommended Bottom Elevation (feet)		-50	-40	-40	-50	-40	-50
Well Screen Length (feet)		30	40	40	40	Unknown	Unknown
Well Construction Year		1976	1978	1978	1990	1992	1995
Status/Final Year of Production		Operational	GM - 1/5/2022	Operational	Operational	GM - 6/14/2020	MF - 1/17/2022
NGLS Max. Recommended Pump Rate (gpm)		500	200	200	500	200	500
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	134.74	165.38	154.92			
	1990-1999	146.88	146.95	146.93	142.16	228.07	356.97
	2000-2009	152.78	197.49	168.73	190.22	246.82	238.34
	2010-2019	166.43	160.37	141.83	189.48	234.48	239.15
	2020-Present	154.89	166.09	122.67	184.33	292.50	356.88
Chloride Statistics		F08	F10	F11	F12	F13	F15
Total Number of Chloride Samples		227	187	199	123	94	100
Minimum Concentration (mg/L)		12.10	24.00	71.80	12.00	22.00	22.00
Maximum Concentration (mg/L)		142.90	468.00	257.40	272.90	394.80	156.00
Standard Deviation		19.80	94.78	45.81	19.30	79.60	20.19
Mean Chloride Concentration (mg/L)	1973-1979	17.02	145.65	110.43			
	1980-1989	24.08	163.05	109.89			
	1990-1999	24.89	190.49	126.69	25.03	200.77	58.05
	2000-2009	54.87	280.47	170.52	49.73	257.46	62.10
	2010-2019	51.19	302.88	167.52	38.89	270.50	62.94
	2020-Present	35.49	202.32	134.56	25.64	333.37	86.30

Continued:

Production Statistics		F16	F17	F18	HGC2
Groundwater Zone		Para-basal	Para-basal	Para-basal	Para-basal
Well Depth Elevation	Feet	-50.14	-62.80	-62.93	-81.95
	Meters	-15.28	-19.14	-19.08	-24.98
NGLS Max. Recommended Bottom Elevation (feet)		-50	-50	-50	-50
Well Screen Length (feet)		Unknown	Unknown	Unknown	60
Well Construction Year		1995	1995	1995	1987
Status/Final Year of Production		Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		500	500	500	500
Mean Pump Rate (gpm) (Mgal/month)	1980-1989				
	1990-1999	159.57		200.44	394.41
	2000-2009	326.12		316.30	516.83
	2010-2019	211.12	243.04	269.86	539.60
	2020-Present	206.47	266.79	256.27	498.57
Chloride Statistics		F16	F17	F18	HGC2
Total Number of Chloride Samples		102	48	98	116
Minimum Concentration (mg/L)		6.00	19.50	10.00	11.00
Maximum Concentration (mg/L)		77.00	60.00	109.60	75.20
Standard Deviation		13.79	10.69	13.19	13.26
Mean Chloride Concentration (mg/L)	1973-1979				
	1980-1989				
	1990-1999	20.95		18.00	22.42
	2000-2009	39.38		33.85	36.51
	2010-2019	38.99	33.85	32.77	39.69
	2020-Present	32.55	26.59	25.94	33.04

Decadal mean averages of chloride concentration show that F01, F04, F10, F11, and F13 have decadal chloride benchmarks that pass the MCL with F10 and F13 also surpassing the USEPA Guideline. However, from graphing the chloride concentrations in bar graphs, conclusion can be made that more wells have passed the chloride concentration benchmarks although not listed in the decadal averages. Of the sixteen wells analyzed, eleven wells have had chloride concentration readings that exceeded the MCL, and they are D22A, D24, F01, F02, F03, F04, F10, F11, F12, F13 and F15. Of these eleven five exceeded the USEPA Guideline, being F04, F10, F11, F12 and F13. Five wells did not reach the MCL, and they are F08, F16, F17, F18 and HGC2. For many wells, the chloride concentration reading seems to be a one off, or not characteristic compared to previous readings, but they were still taken into consideration.

Through temporal analysis of the changes in chloride concentration, ten of the sixteen wells (62.5%) demonstrate a significant increasing trend, four of the sixteen (25%) demonstrate a non-significant increasing trend, one well (6.25%) demonstrates a non-significant decreasing trend. To determine the significance of the linear regression lines, a two-tailed test was performed at  $\alpha = 0.05$ . Through use of the scatter plots, cyclical trends were demonstrated shown in wave pattern. The cyclical patterns usually tend to increase in overall chloride concentration. The wavelengths tend to span around six years and may be correlated to the El Niño/La Niña cycles. Wells that exhibit these wave patterns include F01, F02, F04, F10, F11, and F13.

Through spatial analysis of the changes over time from the visualization in ArcGIS Pro, wells can be grouped by how they follow similar patterns. Wells F01, F10, F11, F02, F03, and F04 are all located along Pol Road and increase or decrease as a group. Another cluster of wells that demonstrate group increases and decreases are F15, F16, F17, and F18. Many of the wells in the basin located towards the center of the island show at least “standard” to even better ground water quality.

In terms of production, some wells have had the ability to surpass their NGLS recommended production rates while maintaining a “good” to “standard” chloride concentration. A notable well that has at least “standard” concentrations and surpasses the recommend pump rate is HGC2. Wells F08, F16, F17, and F18 have extremely low chloride concentrations and do not meet their NGLS recommended pumping rate. Wells D24, F12, and F15 can also be pumped more, however do have one or two readings of chloride concentrations that exceed the USEPA Guideline. The parabasal wells do not usually meet their normal NGLS recommended pump rate of 500 gpm. Well F03 passed its NGLS recommended pump rate a couple times, but overall has had high chloride concentrations. There is no NGLS recommended pump rate for D22A as supra-basal wells were not analyzed in the NGLS study. From the data provided there are some anomalies of extremely high pumping rates, as these were provided in the data.

The chloride concentration of individual wells was graphed against the average production rates to see whether there is a linear relationship between the two factors. Seven wells (43.75%) showed a significant increasing relationship, five wells (31.25%) showed a not significant increasing relationship, four wells (25%) showed a not significant decreasing relationship, and no wells showed a significant decreasing relationship.

#### **4. DISCUSSION**

In comparison to the study done by Simard, chloride trends for 62.5% of the wells studied have shown increases as compared to the original 67%. The factors that could potentially contribute to this slight increase are sea spray, salinization of soils, leakage of septic tanks, and industrial waste. A probable cause of chloride concentrations to reach levels higher than 150 mg/L could be saltwater intrusion. Another cause of high chloride concentrations may be attributed to the construction or well design. Many of the newer wells in the basin have lesser chloride concentrations compared to the older wells.

Probable causes of the increase of contamination include production and this is evident in a few wells when looking at their production rates and the level of chloride concentration. Some wells are unable to produce “standard” quality water and should be monitored or remedied. Wells with extremely low chloride concentrations should be investigated and pumped in higher rates to make up for wells that should be remedied or undergone maintenance. The linear relationships between chloride concentration of individual wells show that while there may be significant relationships more analysis should be done. More external factors that could potentially contribute to the increase of chloride concentration are sea spray, salinization of soils, leakage of septic tanks, and industrial waste. More analysis should be done to determine whether saltwater intrusion is occurring in clusters of wells. Thorough investigations on well depth, construction and the respective groundwater zones’ max recommended pump rate should be conducted and

updated as these too may affect chloride concentrations. Many of the newer wells in the basin have lesser chloride concentrations suggesting that older wells need to receive more remedial treatment. As more production wells have been brought online and pumping rates increased to match our growing demand for drinking water, we may infer that these are also causes to chloride concentrations rising due to more fresh groundwater being extracted allowing for saltwater intrusion to occur.

The cyclical chloride trends or wave patterns may be due to the increase or decrease in rainfall due to the El Niño and La Niña cycles. With the increase of rainfall, the chloride levels should drop and with the decrease of rainfall the chloride levels should increase. This is another relationship that should be investigated. As stated in Simard's study, the thinning of the freshwater lens from 2005 to 2010 may be attributed to the below-average total annual rainfall which reduced the recharge to the aquifer allowing the chloride concentration to remain high. Further analysis on the lag between precipitation and recharge in the aquifer should be done.

As the aquifer does not filter any water, further monitoring of chloride concentrations and other contaminants must be continued. It may be beneficial for monitoring if the schedule to take chloride concentration readings go back to every month and that production rates also be recorded. The more data accrued; the more thorough analysis can be performed. It is important to update documentation regarding well bottom depths, overall well construction, and status of wells to effectively manage and maintain existing wells. It would also be beneficial to update the NGLS Max Recommended Pumping Rate Guidelines to include the wells in the supra-basal groundwater zone and Tumon Maui Wells.

## **5. ACKNOWLEDGEMENTS**

This work was funded by the U.S. Geological Survey 104b Program and Guam Hydrologic Survey via Water Environmental Research Institute of the Western Pacific, University of Guam. The Guam Waterworks Authority provided chloride concentrations and production rates with updated information compiled by Ms. Jennifer Cruz, Dr. Nathan Habana, and Mr. Jovic Caasi.

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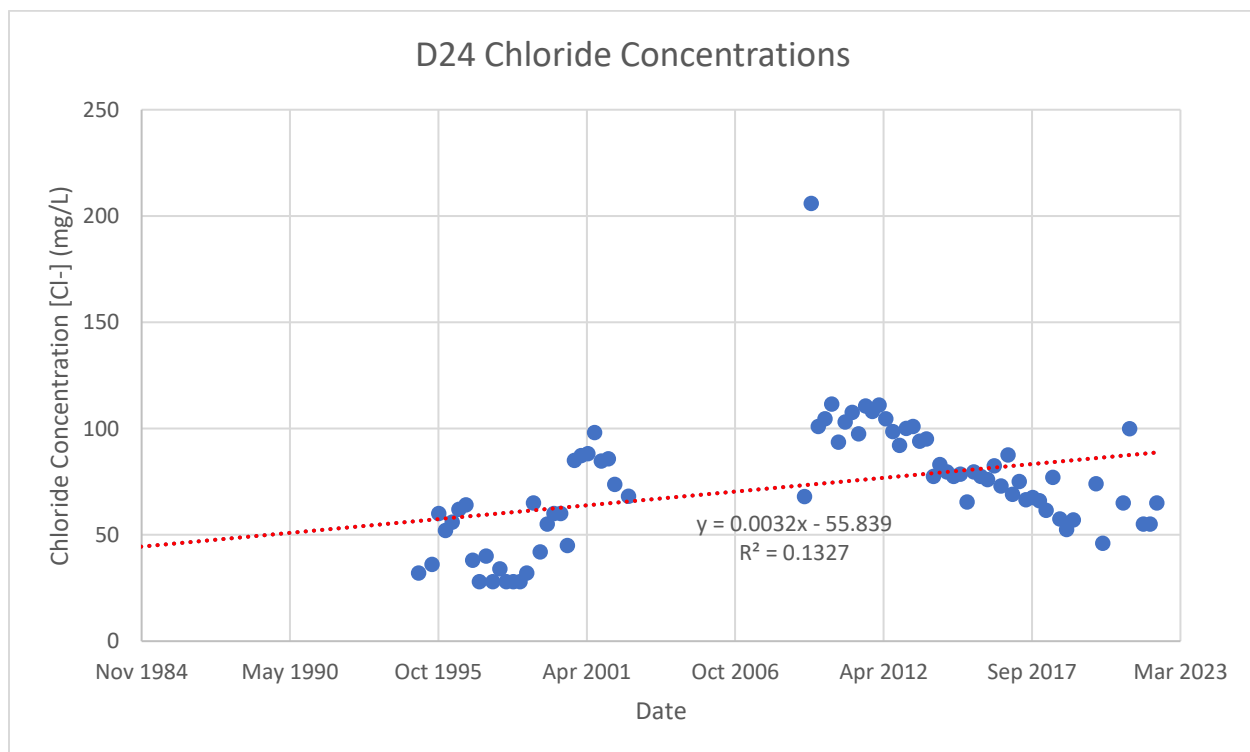
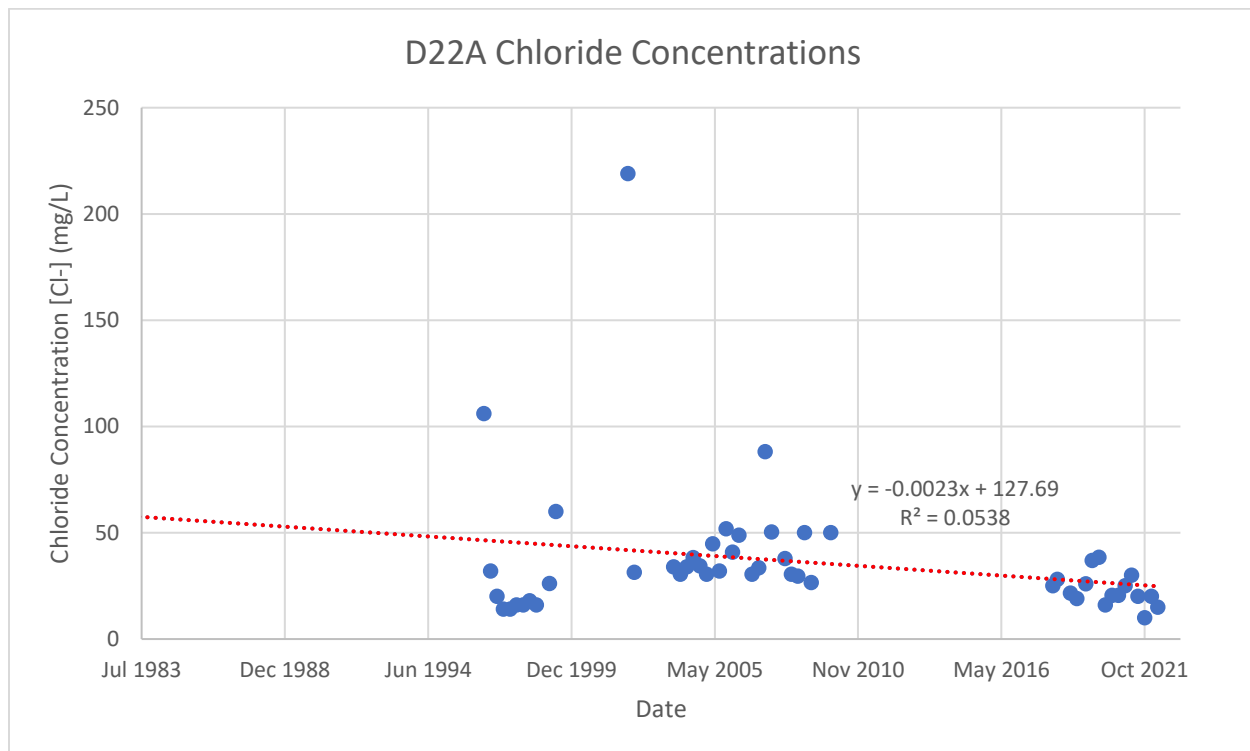
## APPENDIX

### Appendix A: Linear Regression Summary of Chloride Concentrations For Individual Wells Over Time

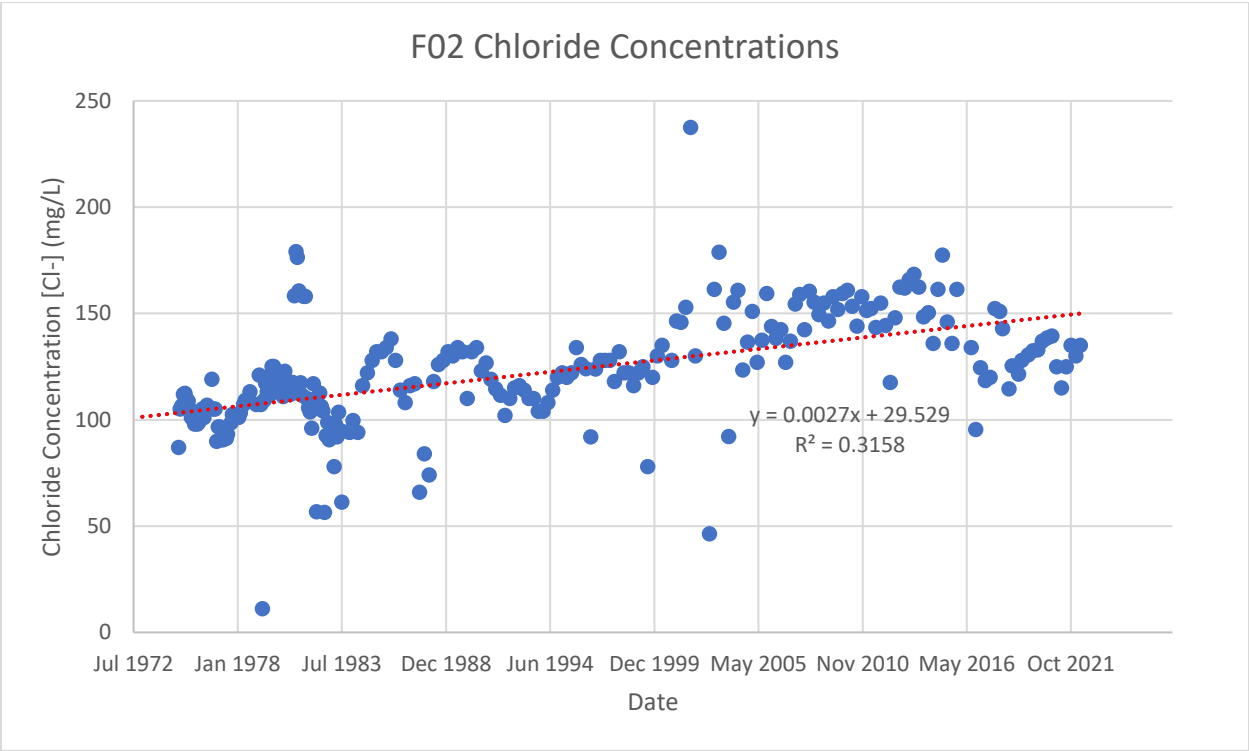
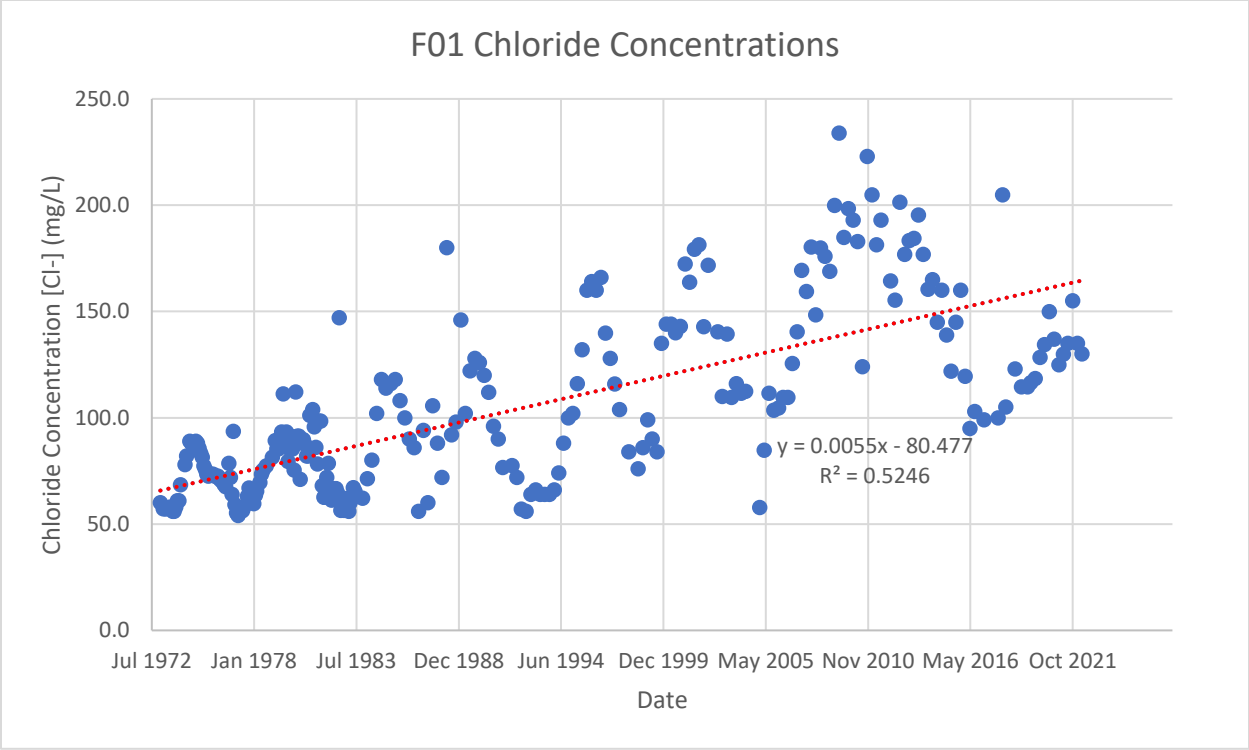
Chloride Concentration Linear Regression Analysis								
Well ID	Regression Equation	$r^2$	r	$r_{crit}$	n	df = n - 2	Significant if $r > r_{crit}$	Trend
D22A	$y = -0.0023x + 127.69$	0.0538	0.231948	0.279	50	48	Not Significant	Decrease
D24	$y = 0.0032x - 55.839$	0.1327	0.36428	0.223	78	76	Significant	Increase
F01	$y = 0.0055x - 80.477$	0.5246	0.724293	0.123	255	253	Significant	Increase
F02	$y = 0.0027x + 29.529$	0.3158	0.561961	0.125	246	244	Significant	Increase
F03	$y = 0.0017x + 51.343$	0.1362	0.369053	0.128	234	232	Significant	Increase
F04	$y = 0.007x - 89.99$	0.2692	0.518845	0.129	233	231	Significant	Increase
F08	$y = 0.0023x - 45.68$	0.4026	0.634508	0.13	227	225	Significant	Increase
F10	$y = 0.0109x - 167.92$	0.3292	0.57376	0.144	187	185	Significant	Increase
F11	$y = 0.0042x - 14.52$	0.2267	0.47613	0.139	199	197	Significant	Increase
F12	$y = 0.0011x - 5.4652$	0.0202	0.142127	0.177	123	121	Not Significant	Increase
F13	$y = 0.0035x + 116.1$	0.0148	0.121655	0.203	94	92	Not Significant	Increase
F15	$y = 0.0011x + 19.095$	0.0231	0.151987	0.197	100	98	Not Significant	Increase
F16	$y = 0.0013x - 17.368$	0.0866	0.294279	0.195	102	100	Significant	Increase
F17	$y = -0.0043x + 215.89$	0.3005	0.548179	0.285	48	46	Significant	Decrease
F18	$y = 0.0004x + 13.712$	0.0091	0.095394	0.99	98	96	Not Significant	Increase
HGC2	$y = 0.0017x - 32.422$	0.1895	0.435316	0.182	116	114	Significant	Increase

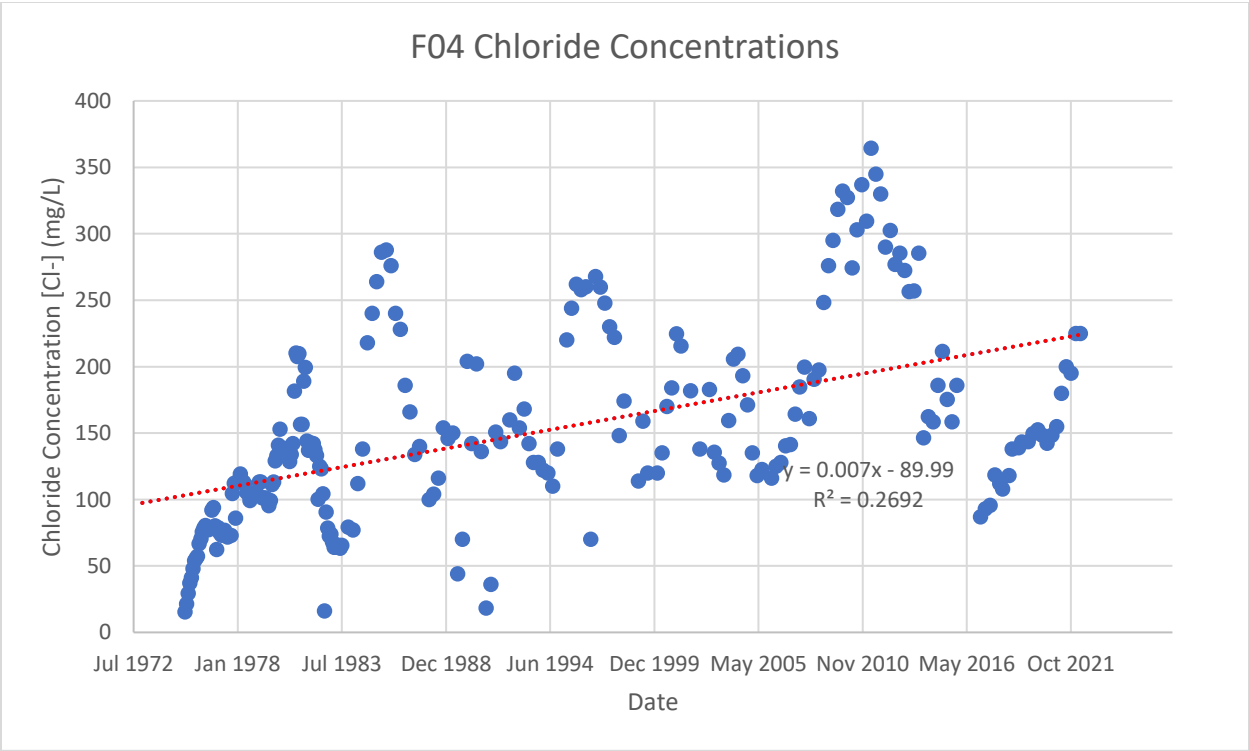
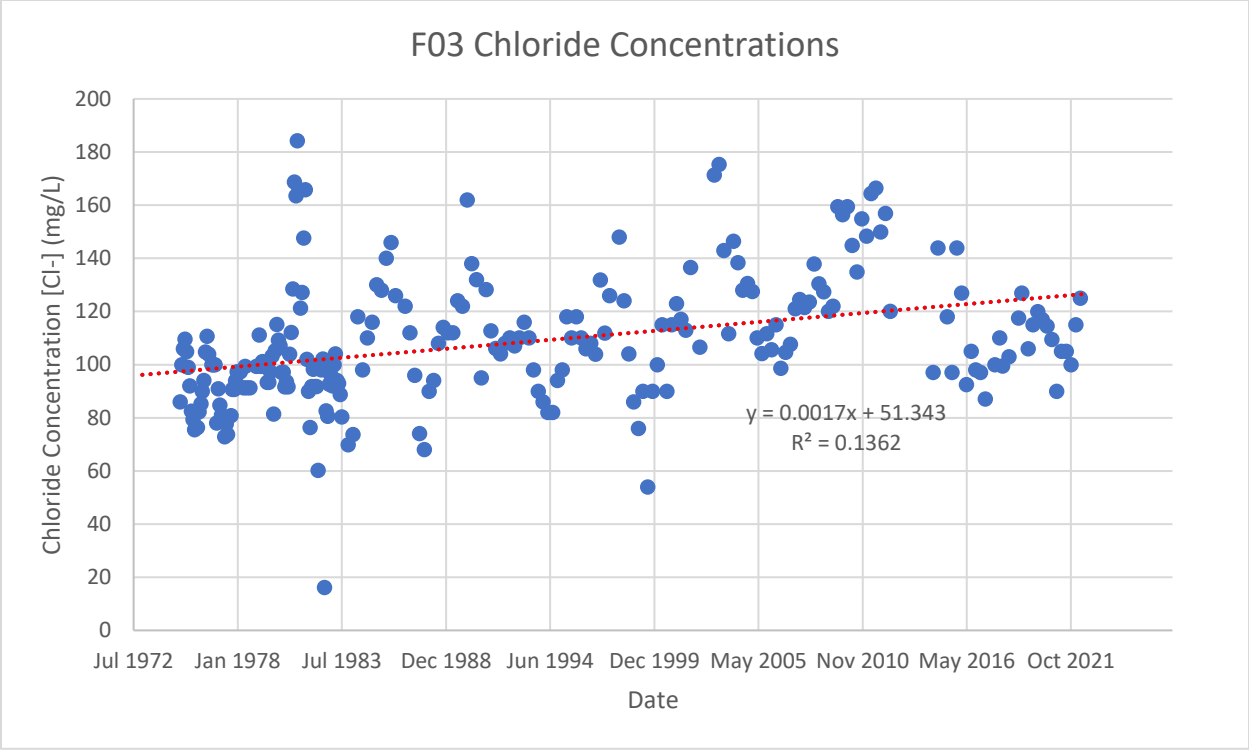
## Appendix B: Scatter Plots for Individual Wells' Chloride Concentrations Over Time

The x-axis is the date of the data taken in form of MM/YYYY. The y-axis is the chloride concentration measured in (mg/L).

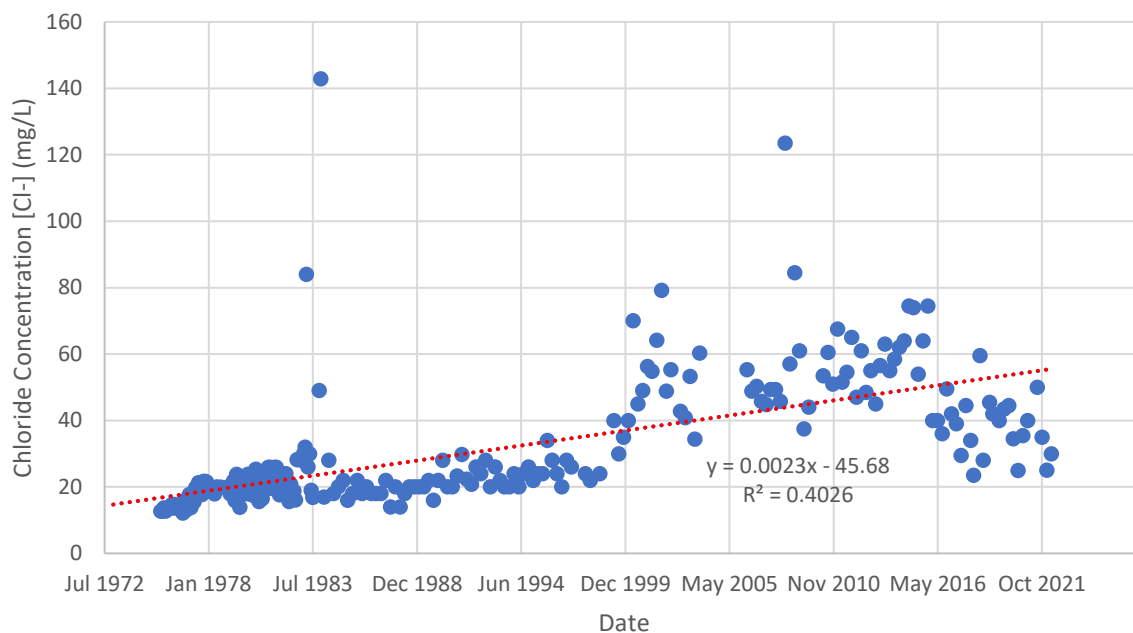




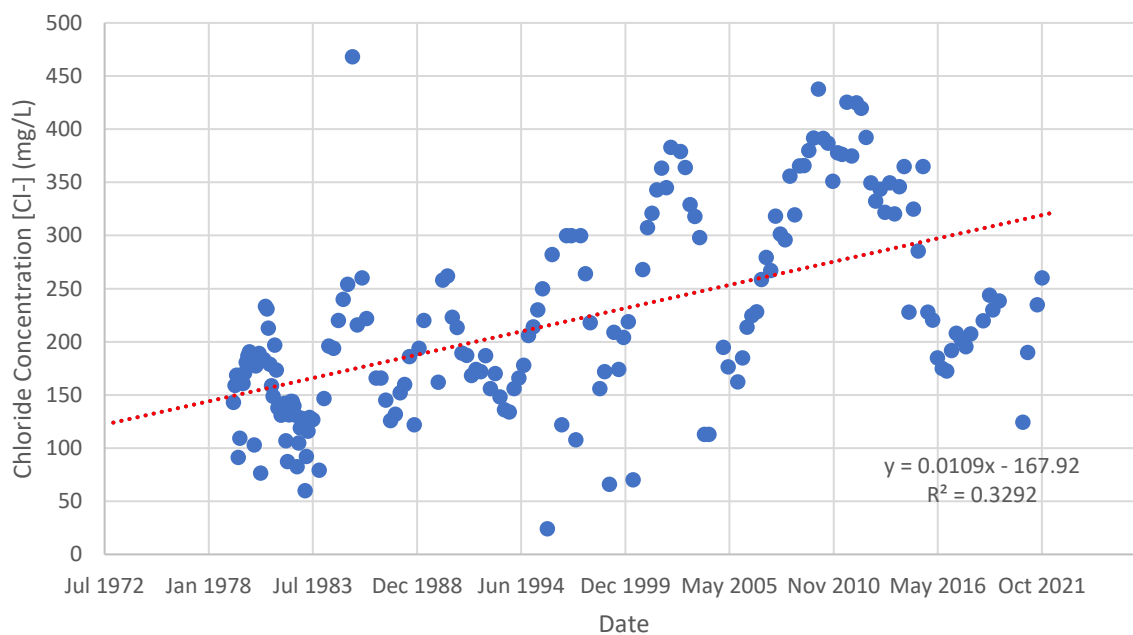


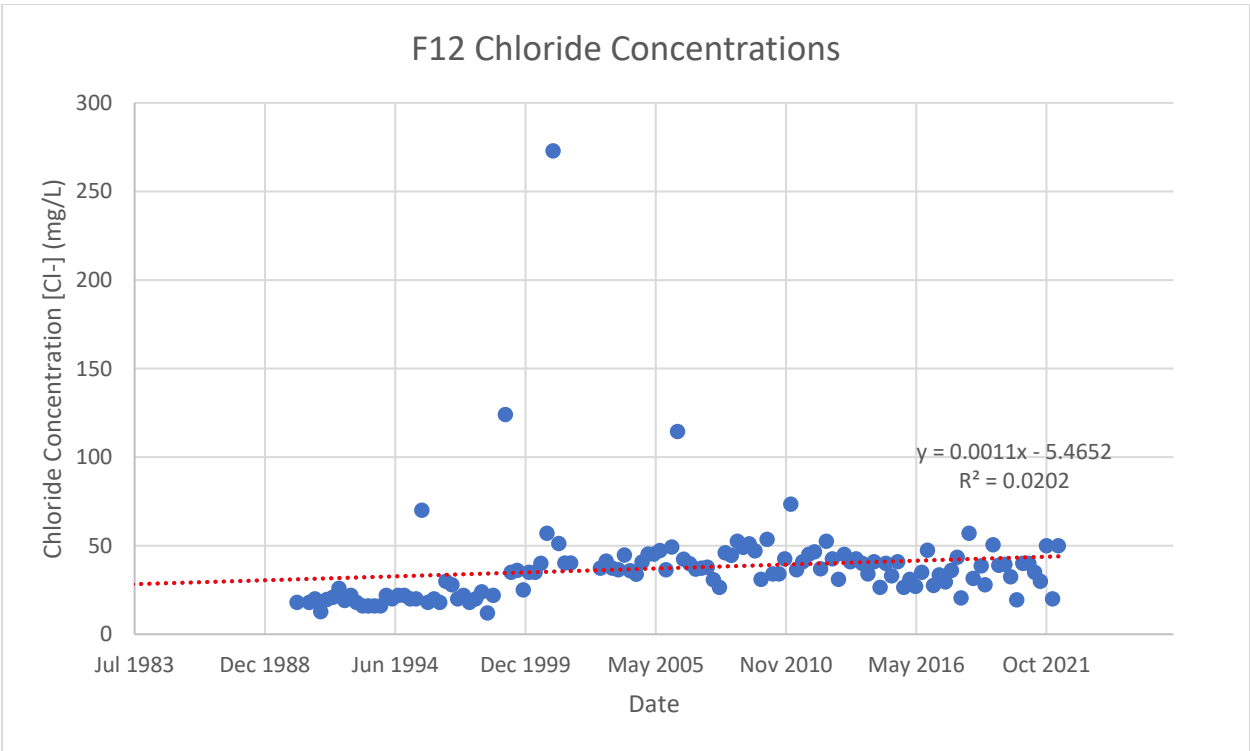
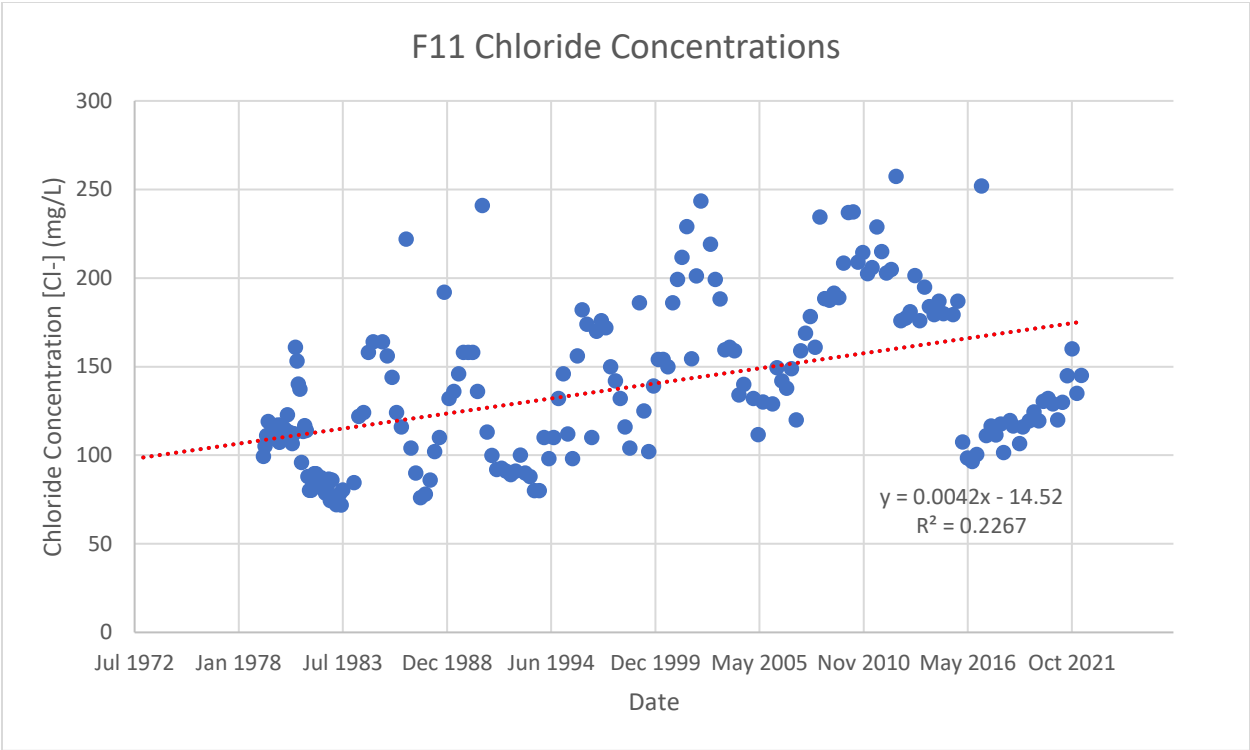


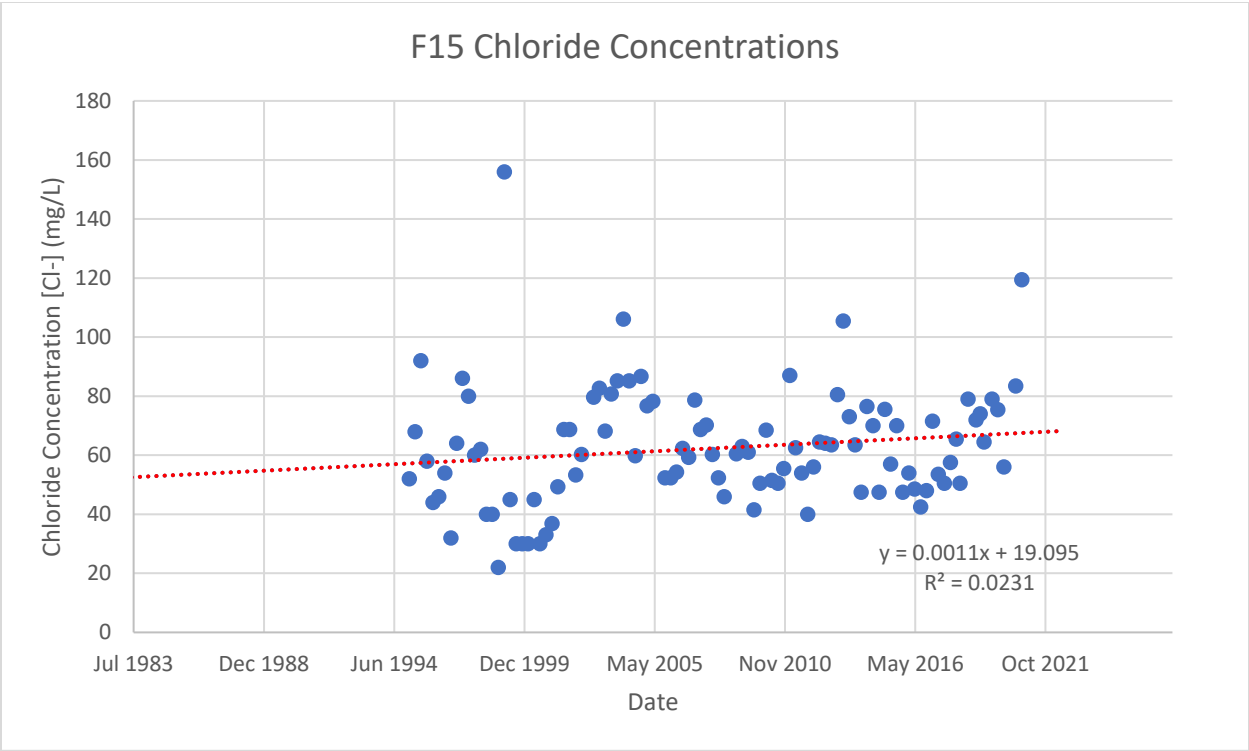
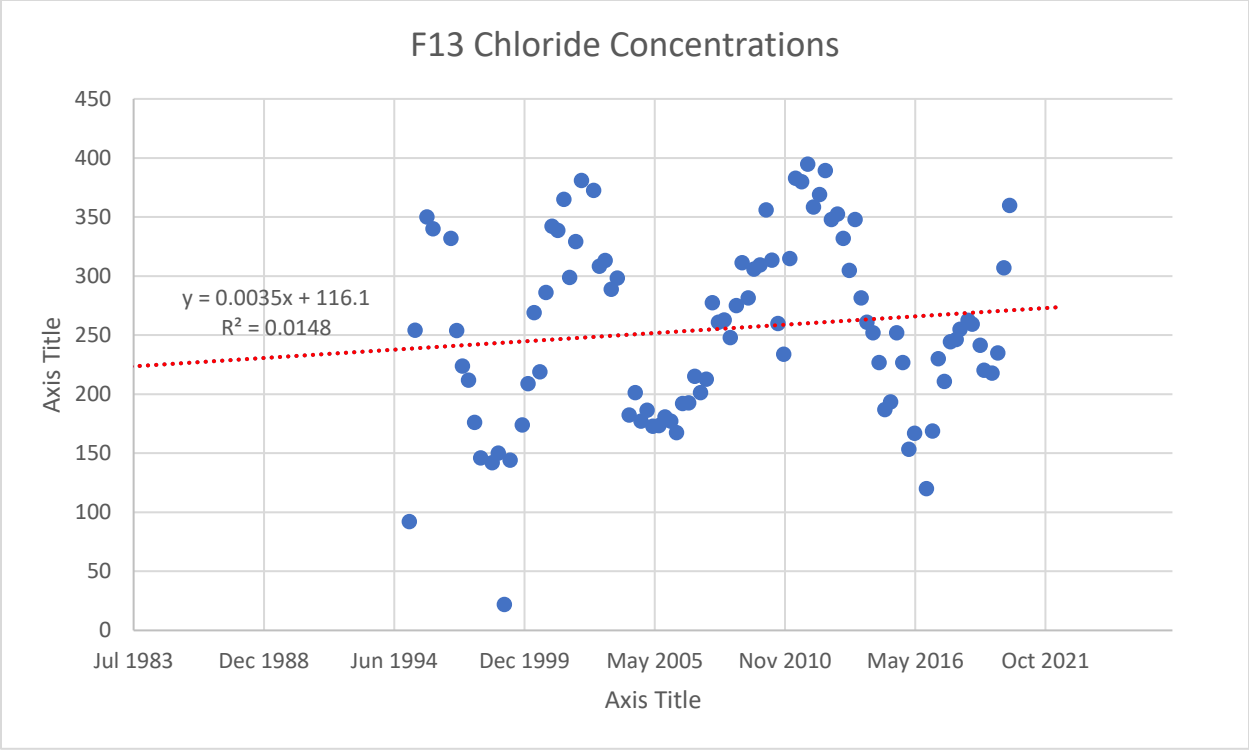
### F08 Chloride Concentrations

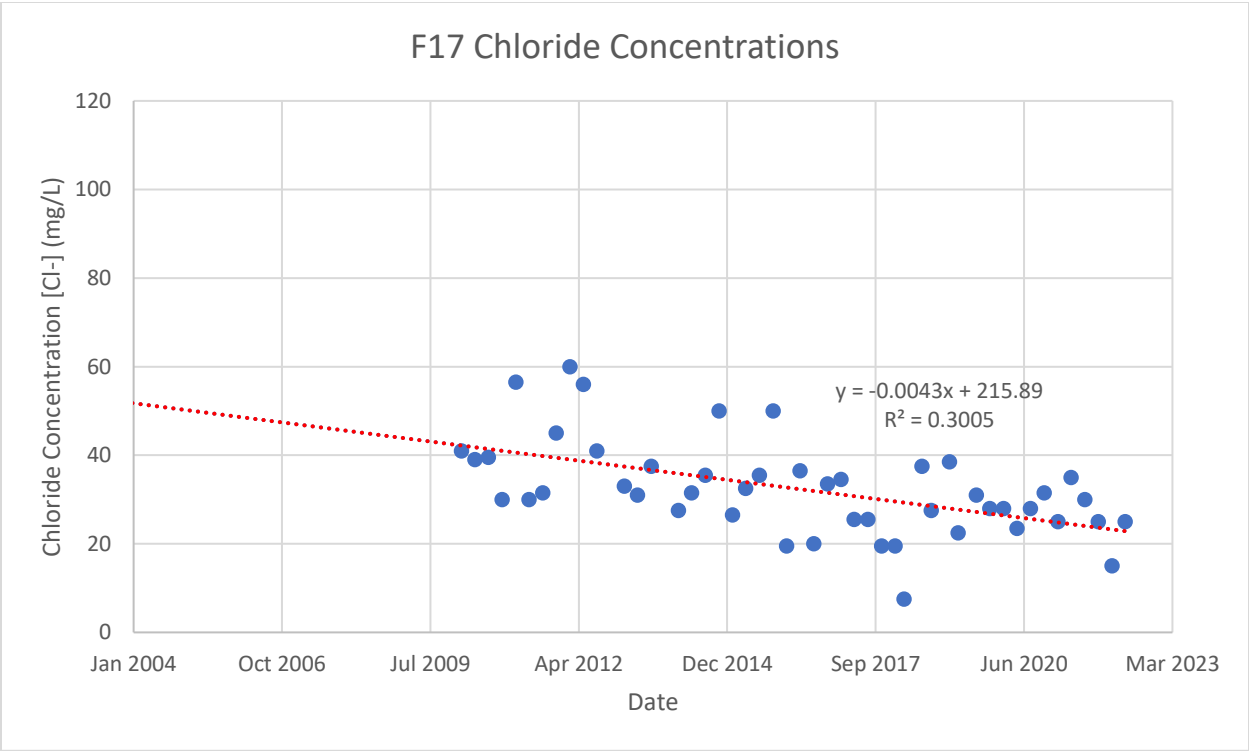
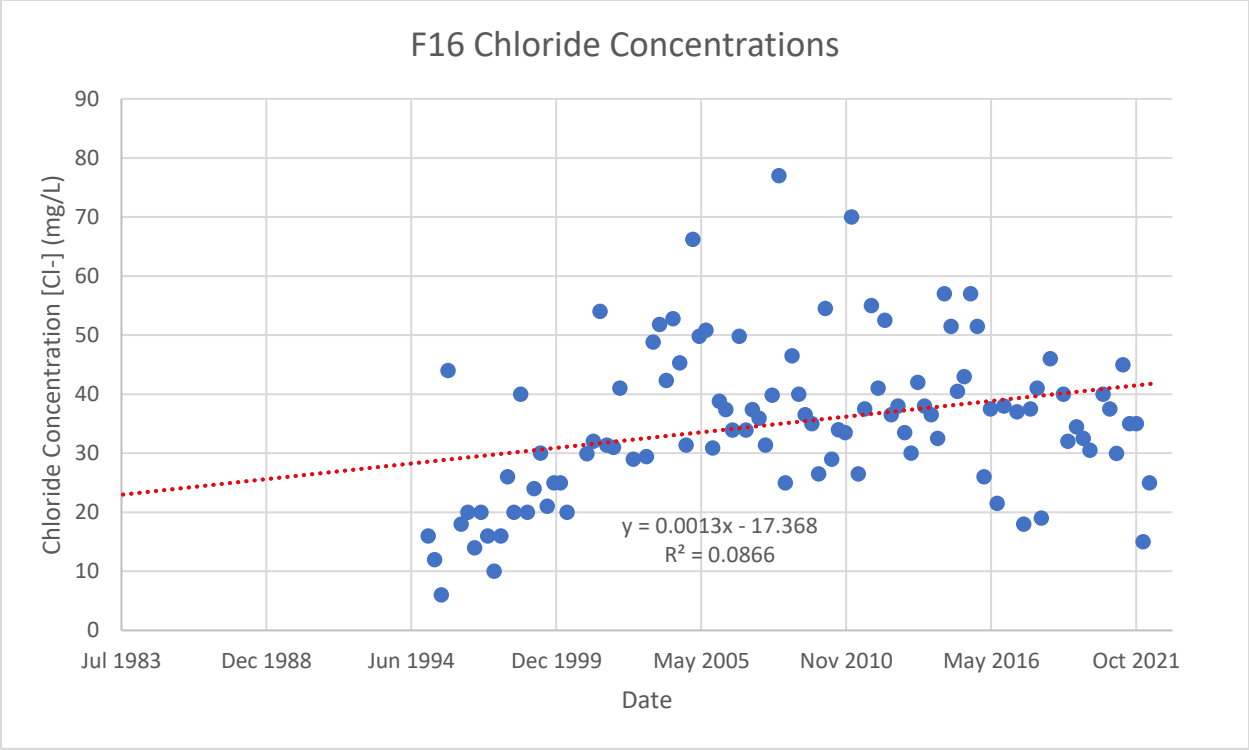


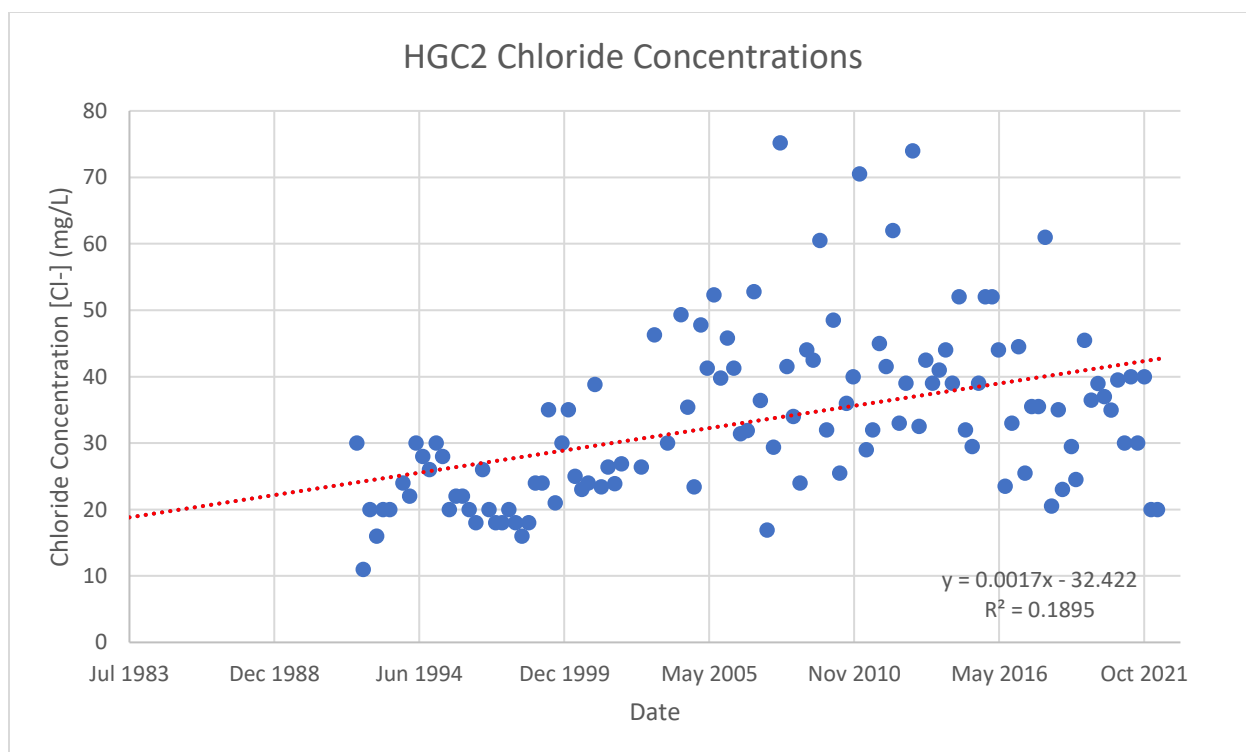
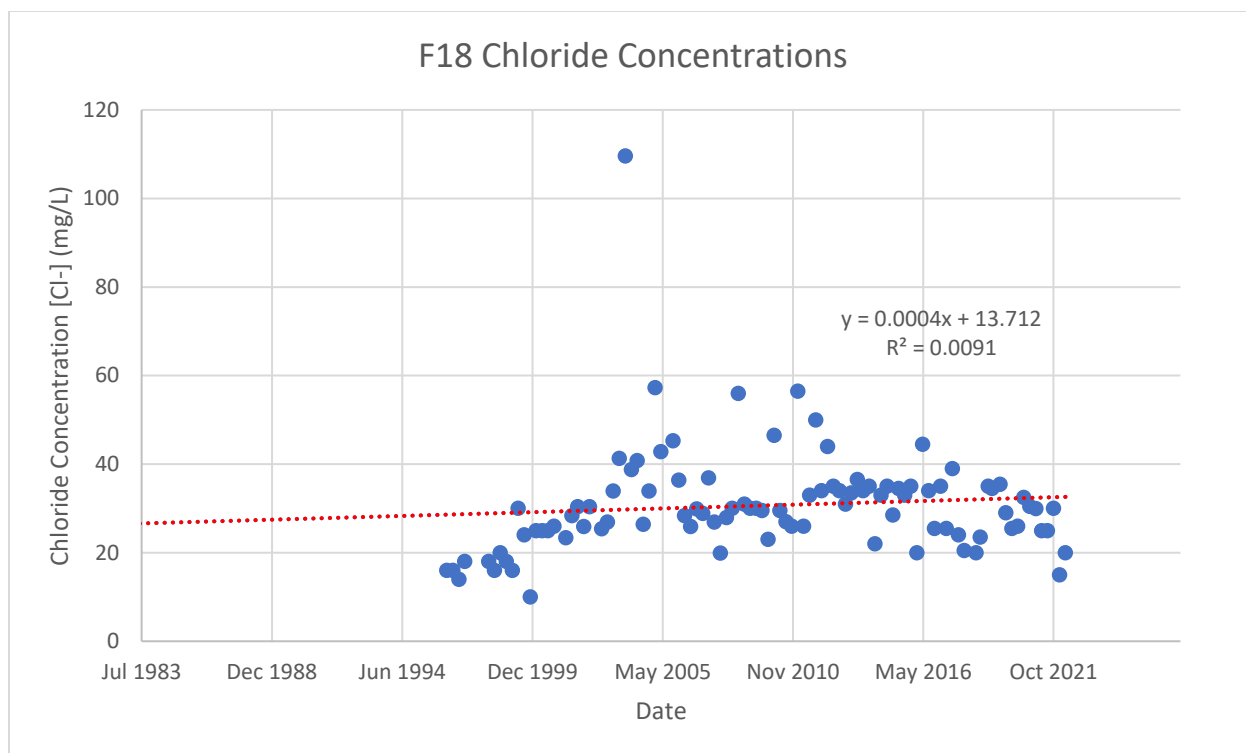
### F10 Chloride Concentrations





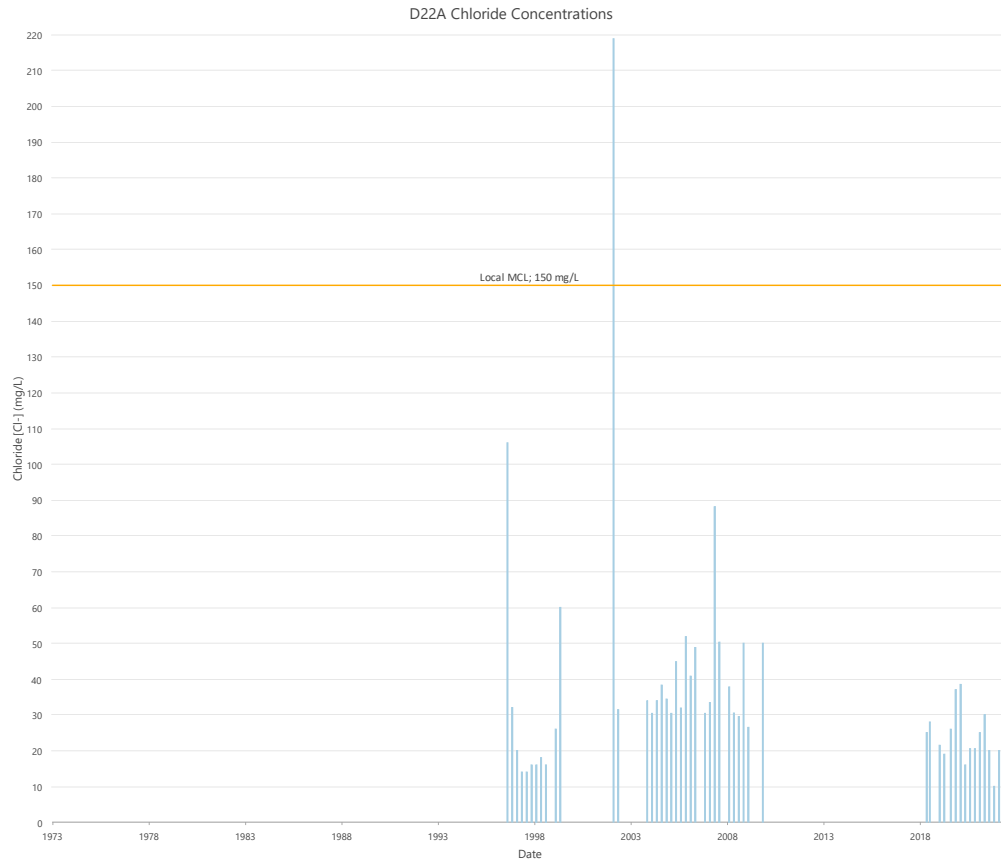




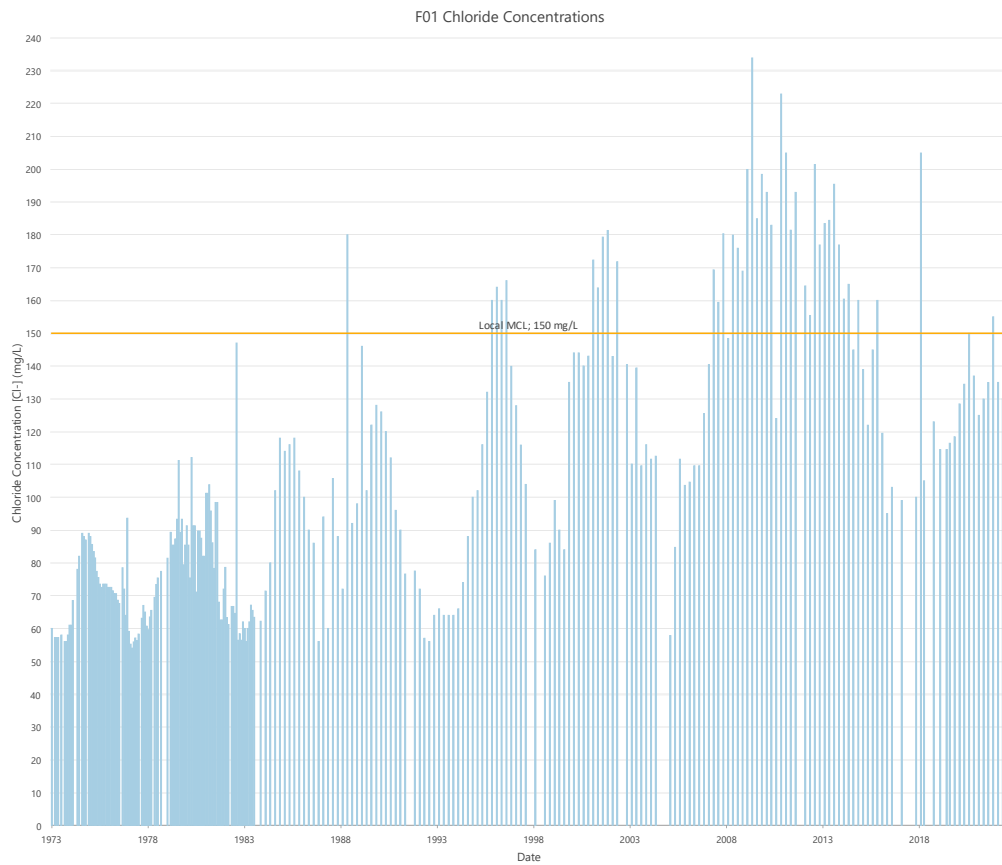
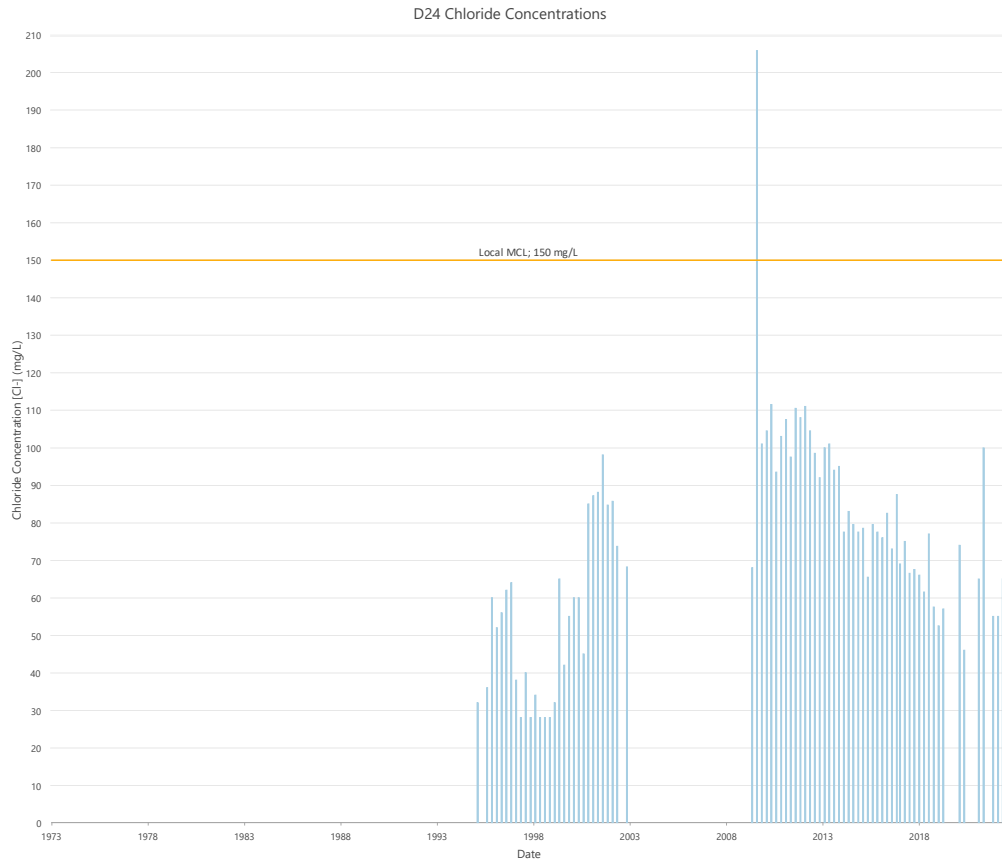


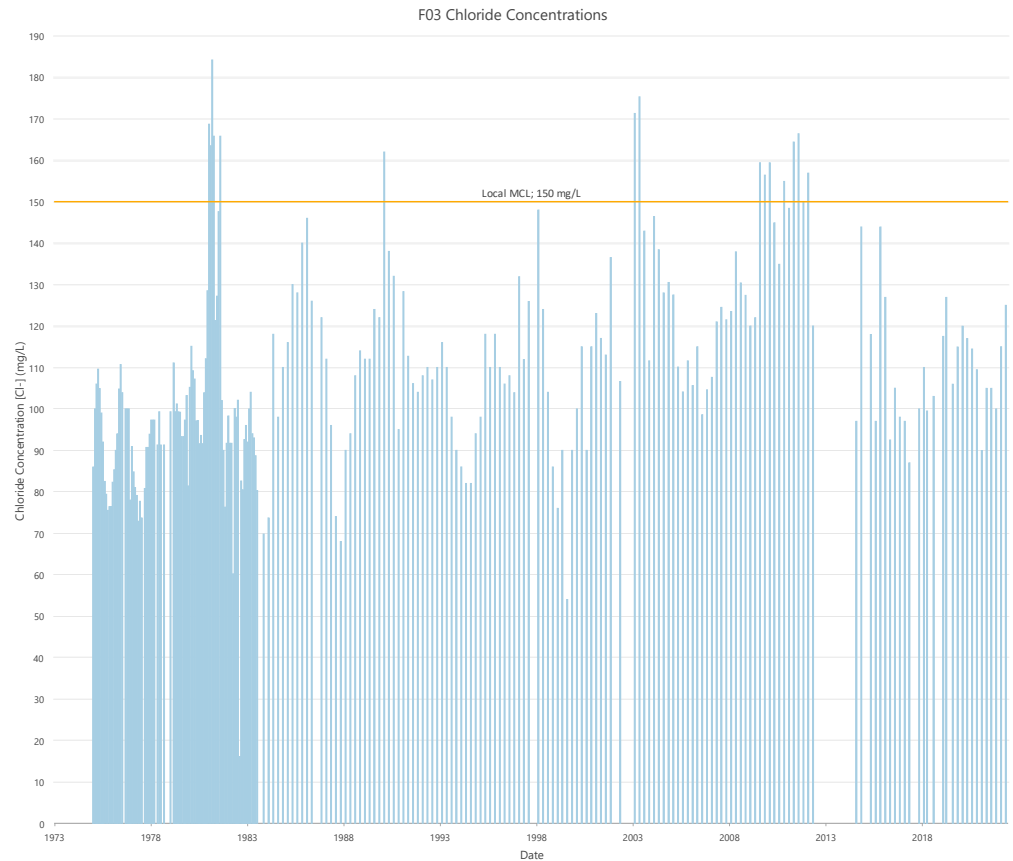
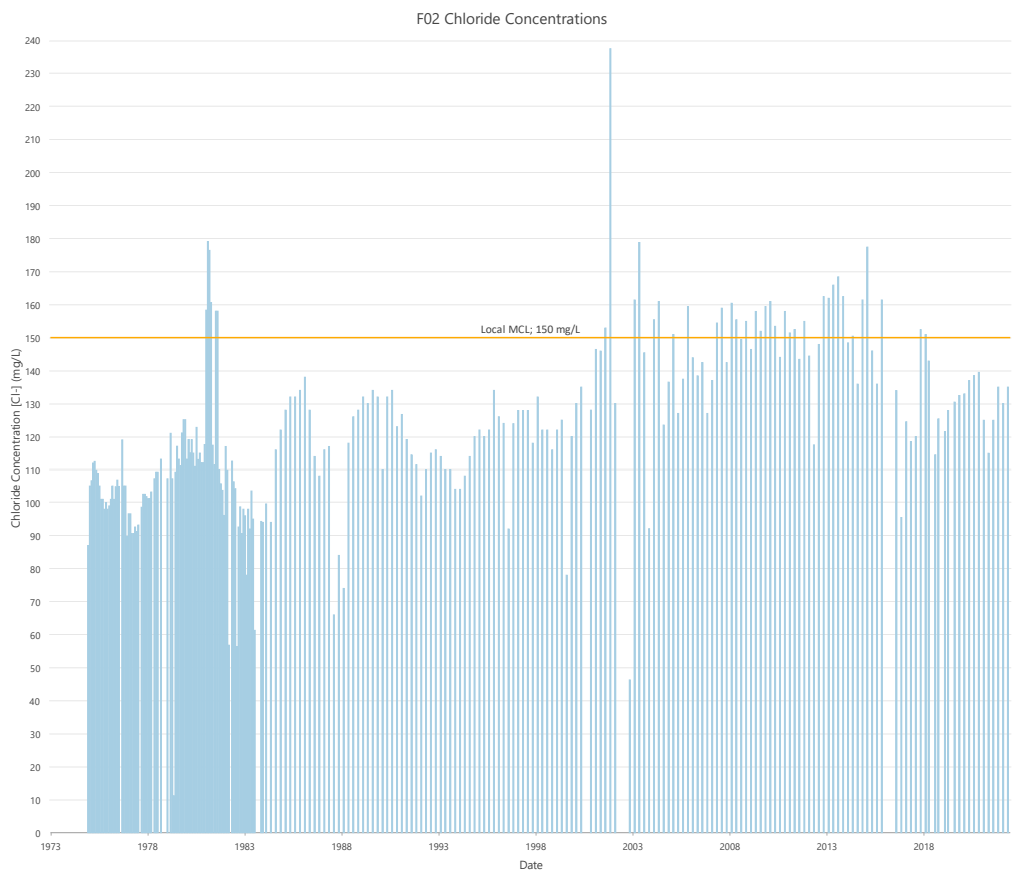
## Appendix C: Bar Graphs with Guidelines for the Chloride Concentrations of Individual Wells

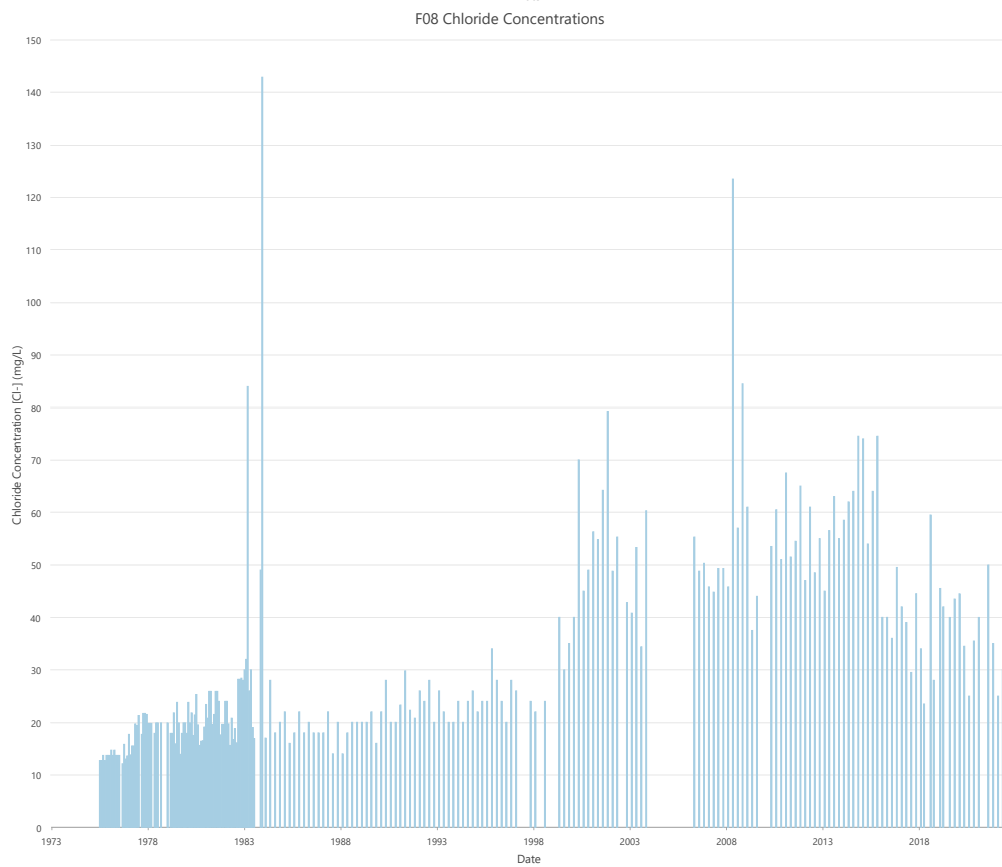
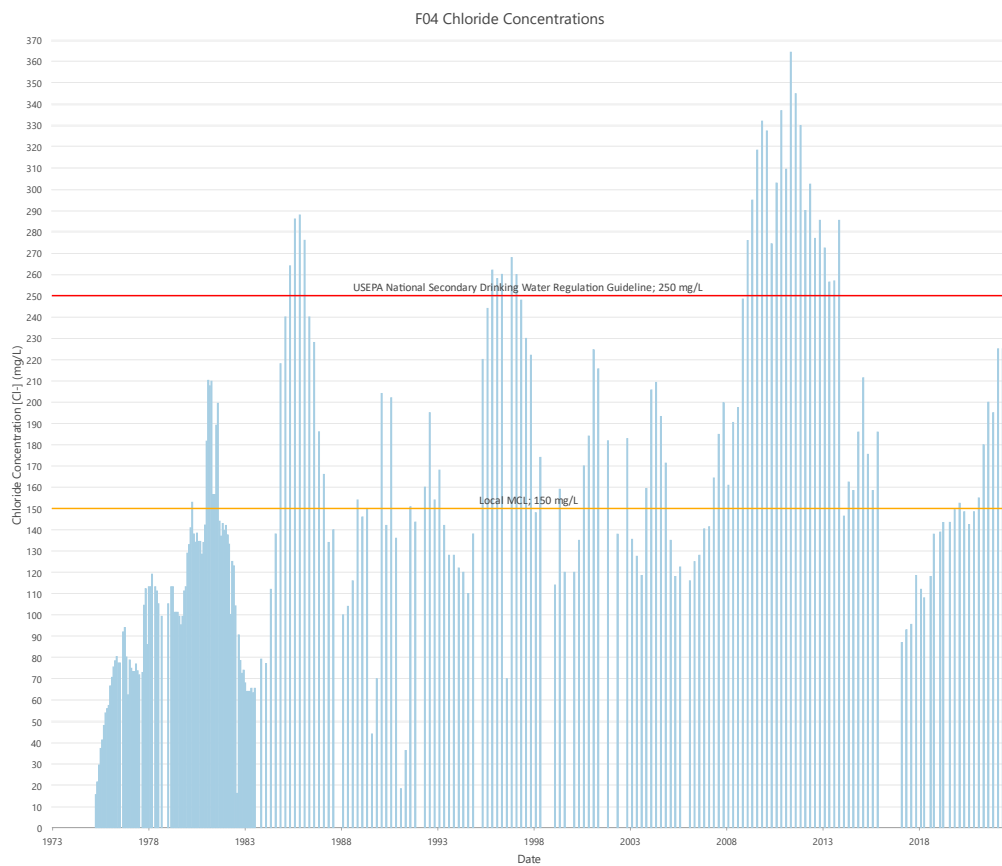
If there are no guidelines, the chloride concentrations did not come close enough to warrant depiction of said guidelines.

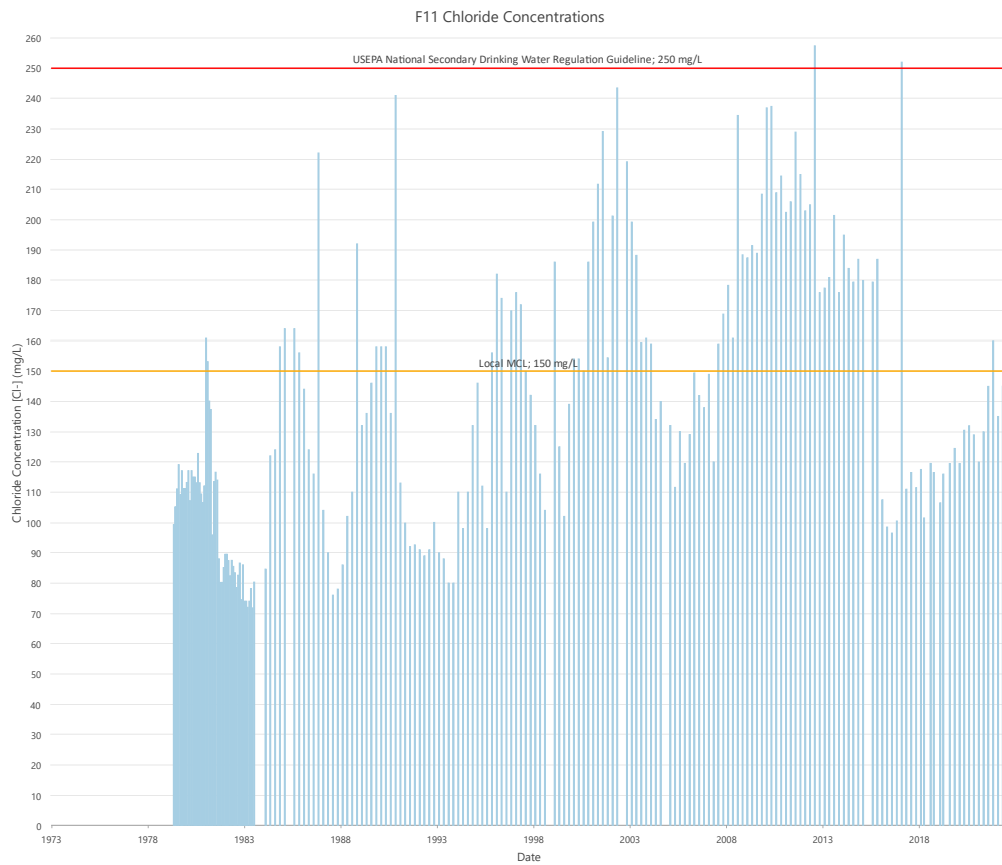
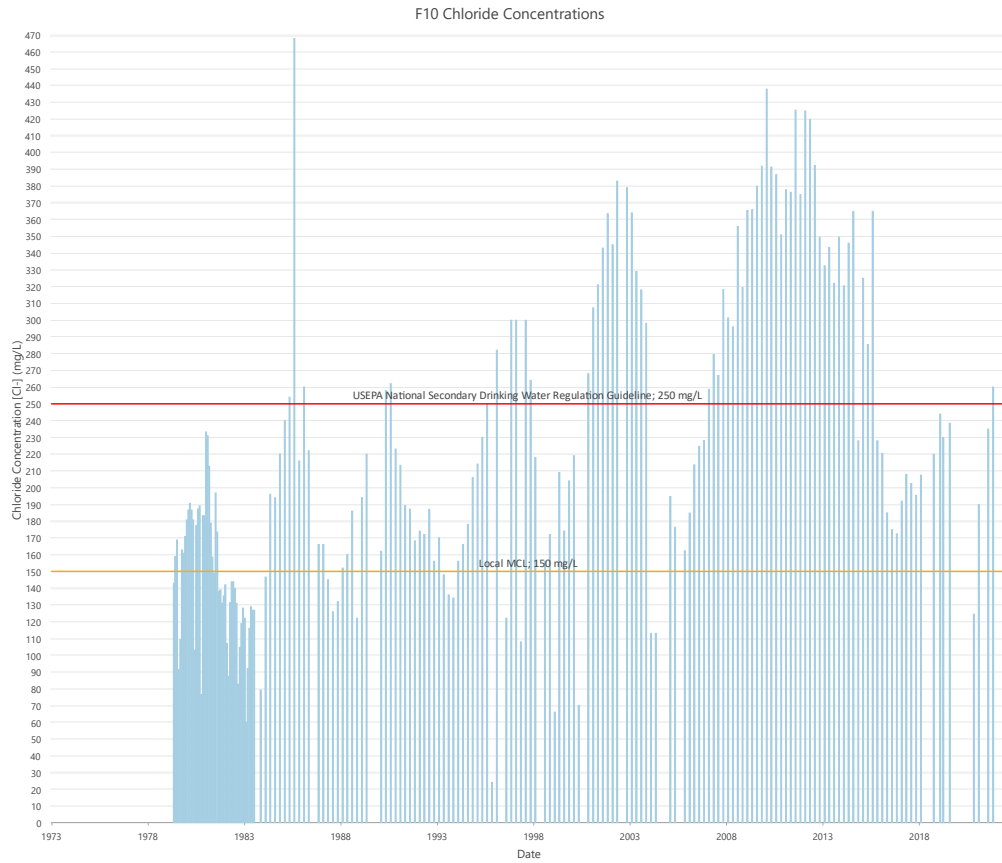


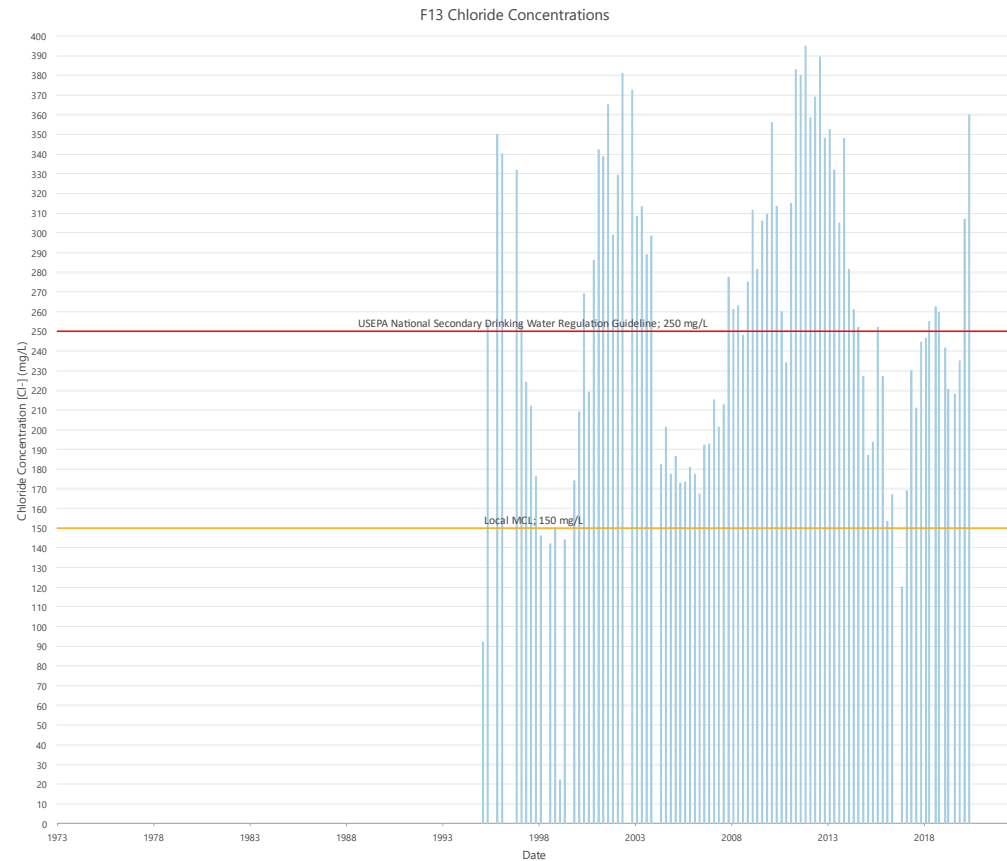
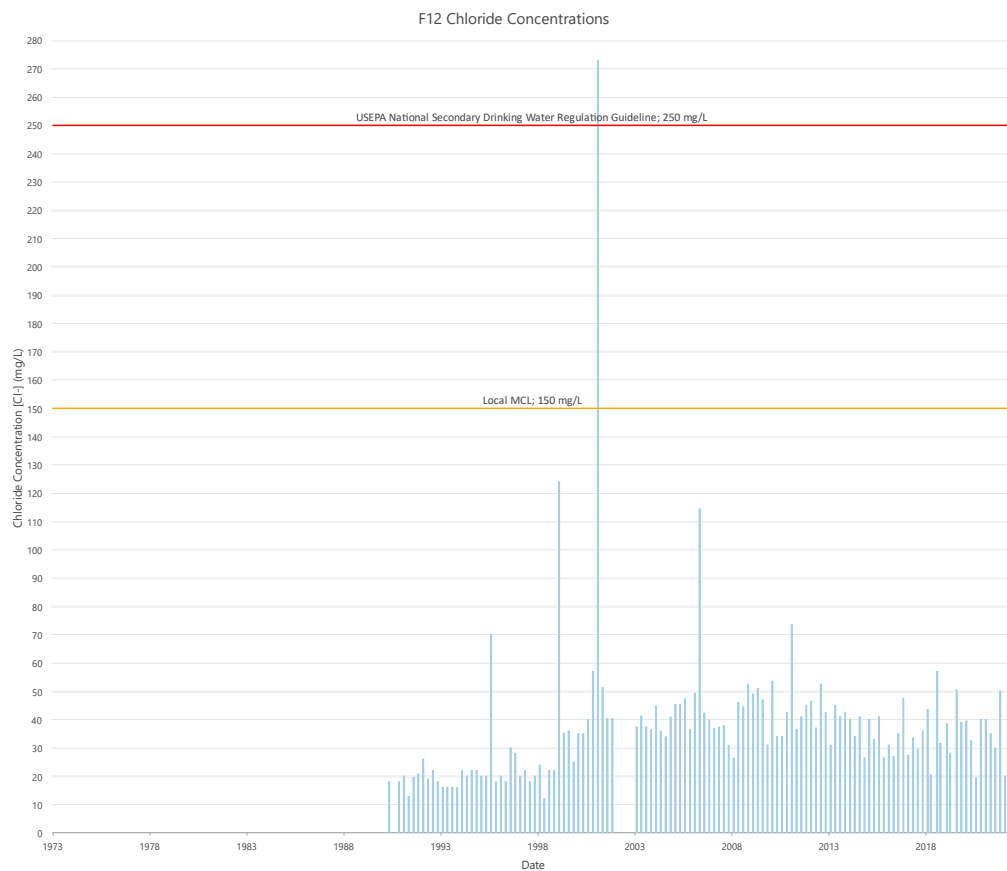


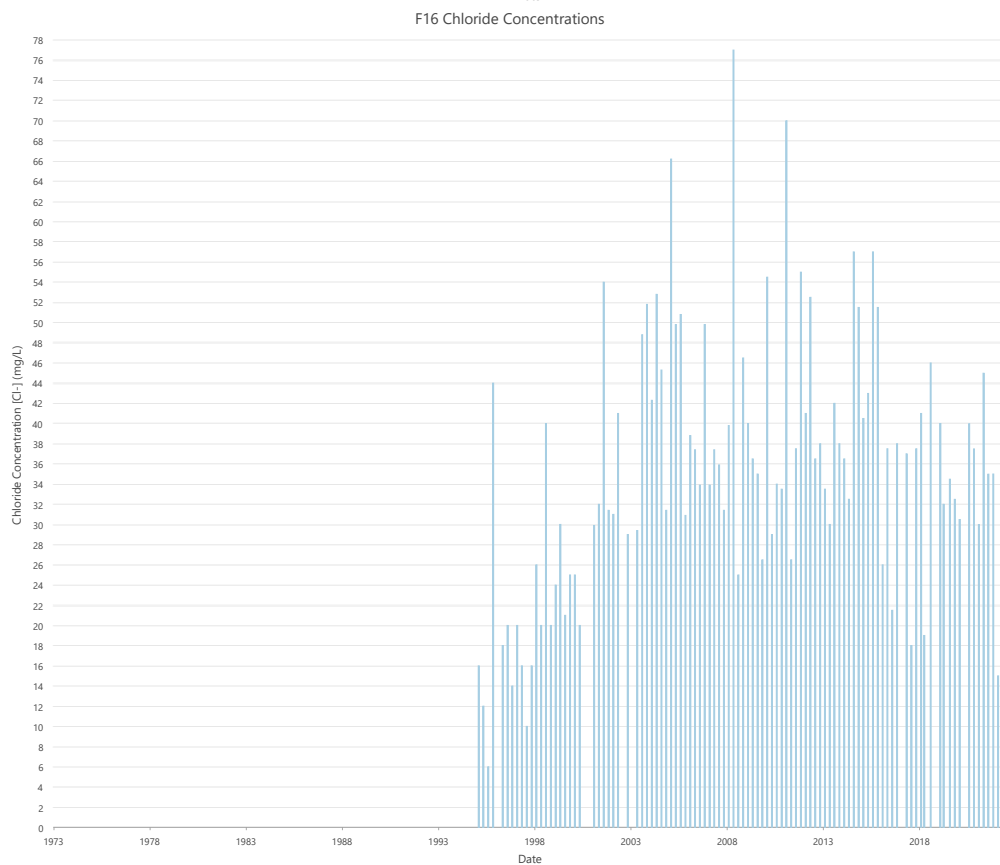
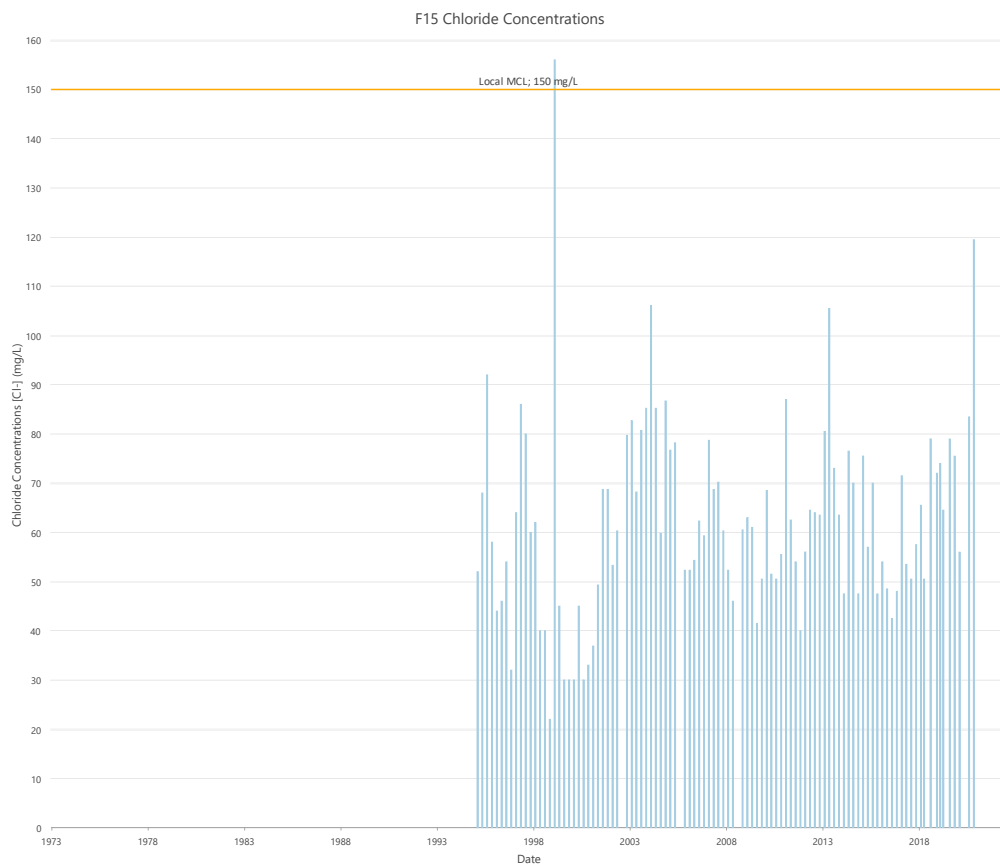


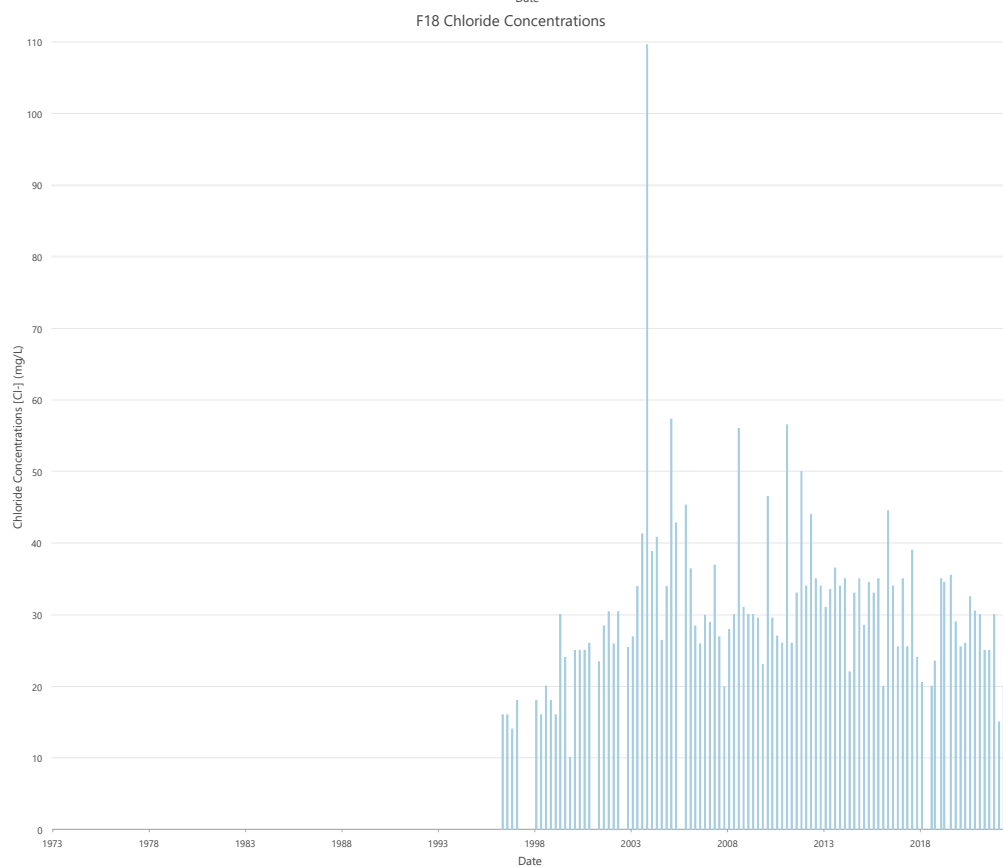
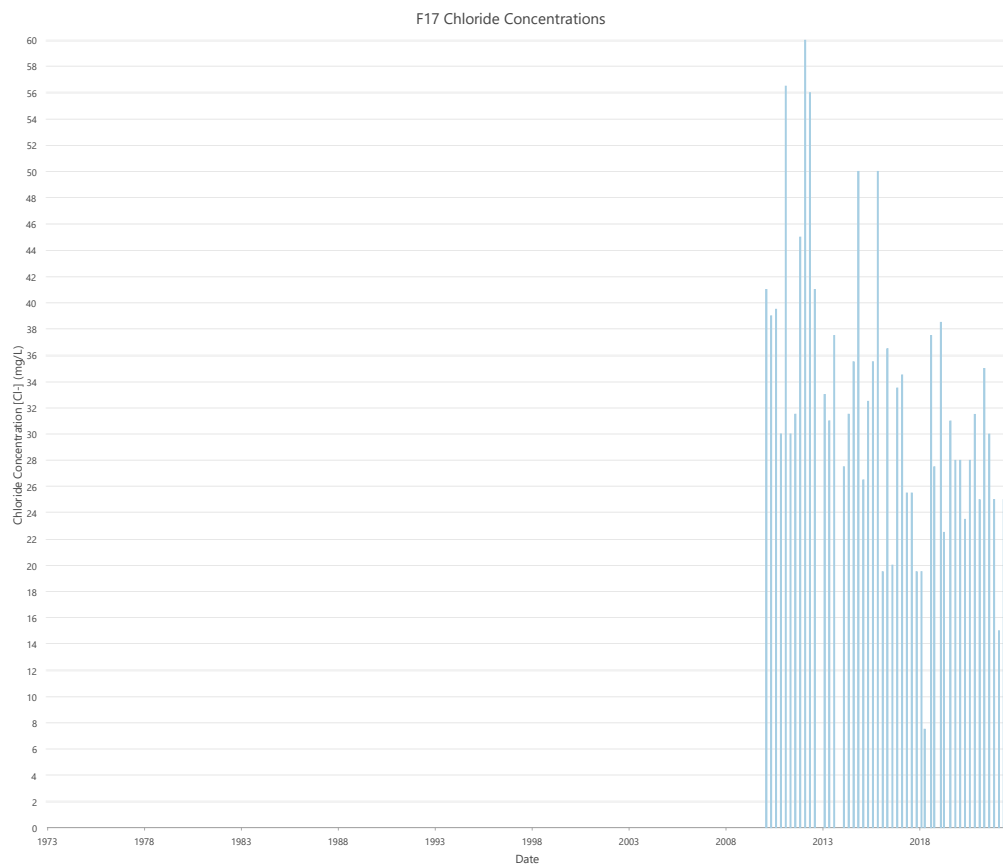


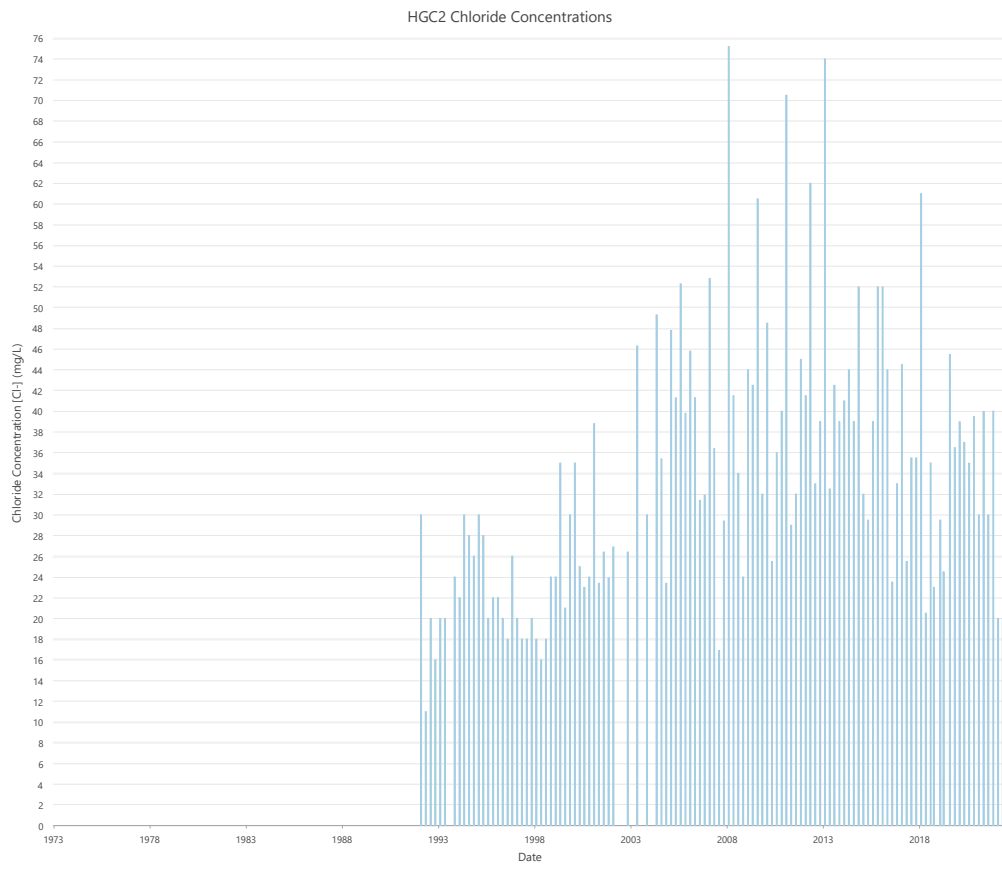








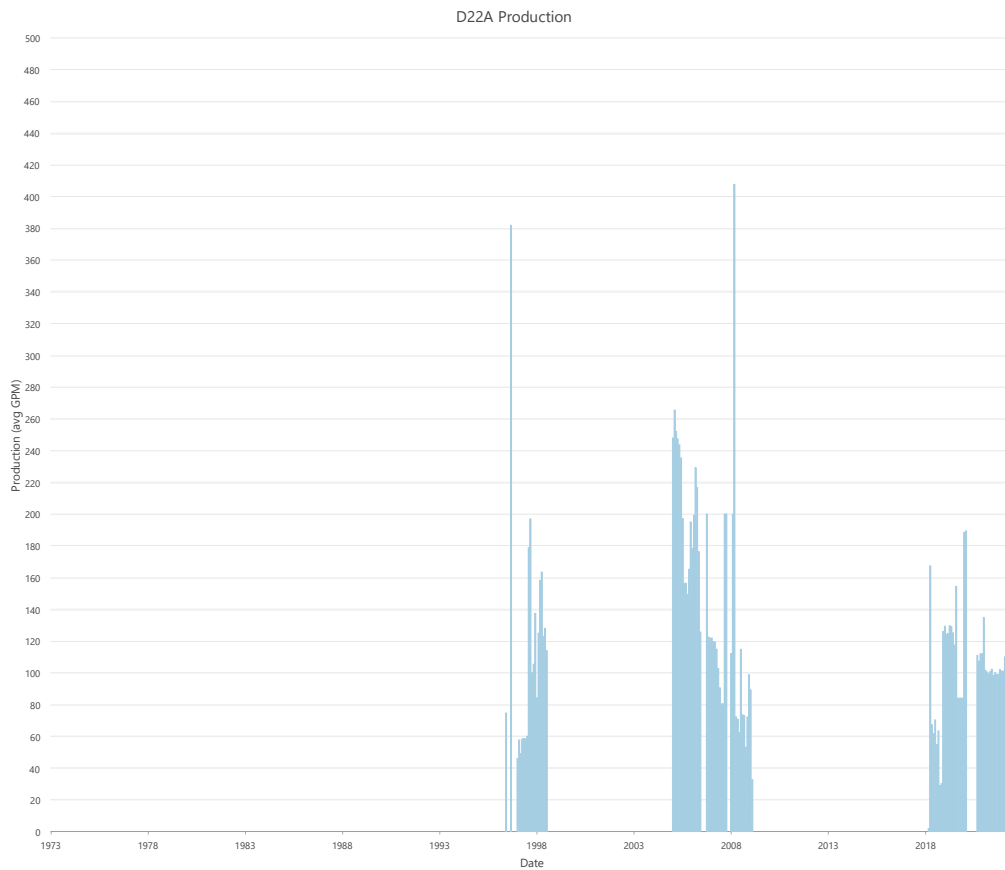


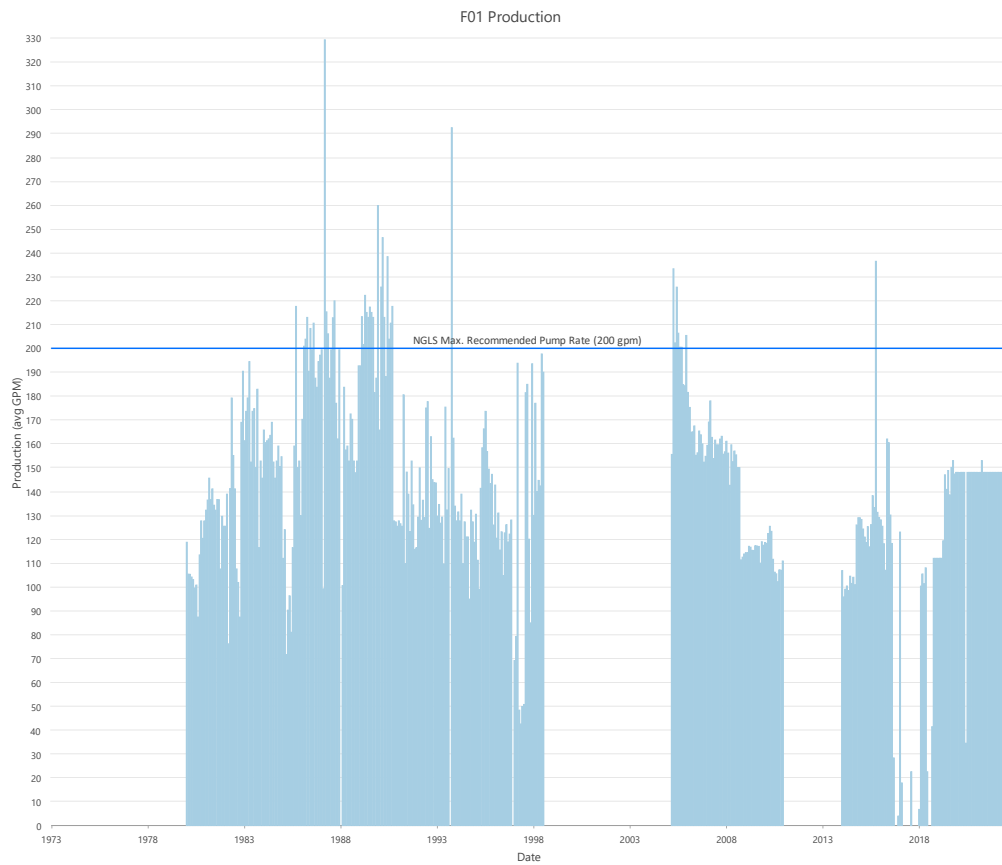
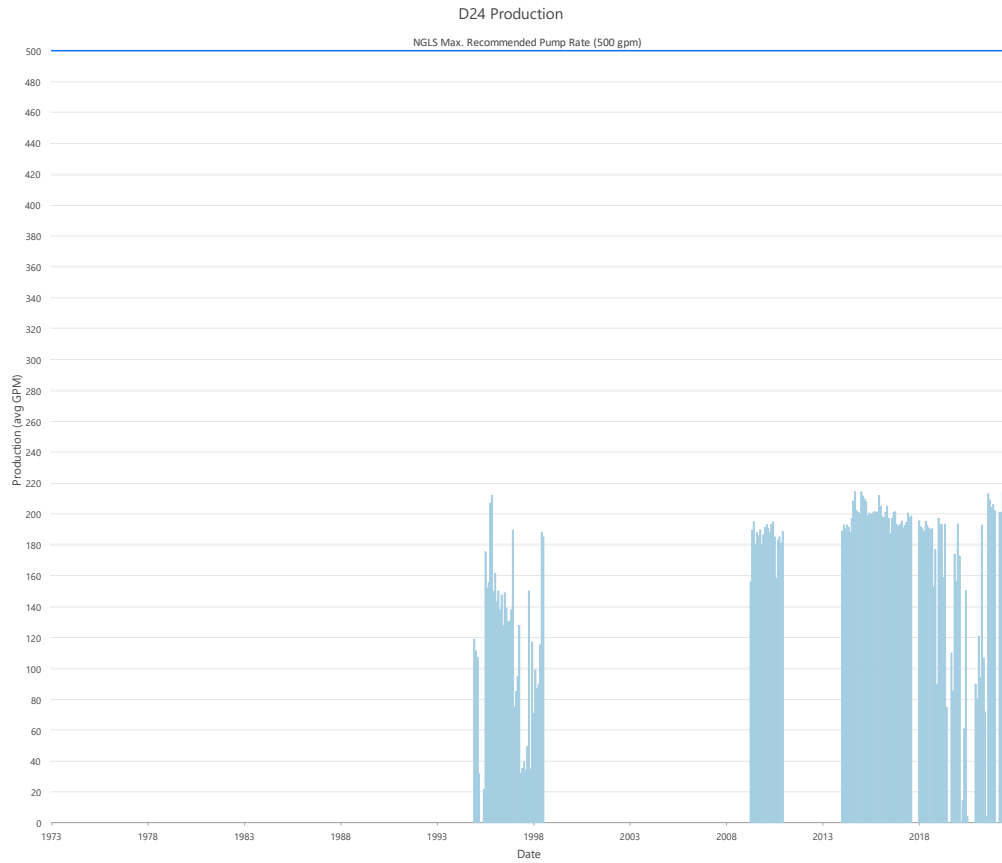


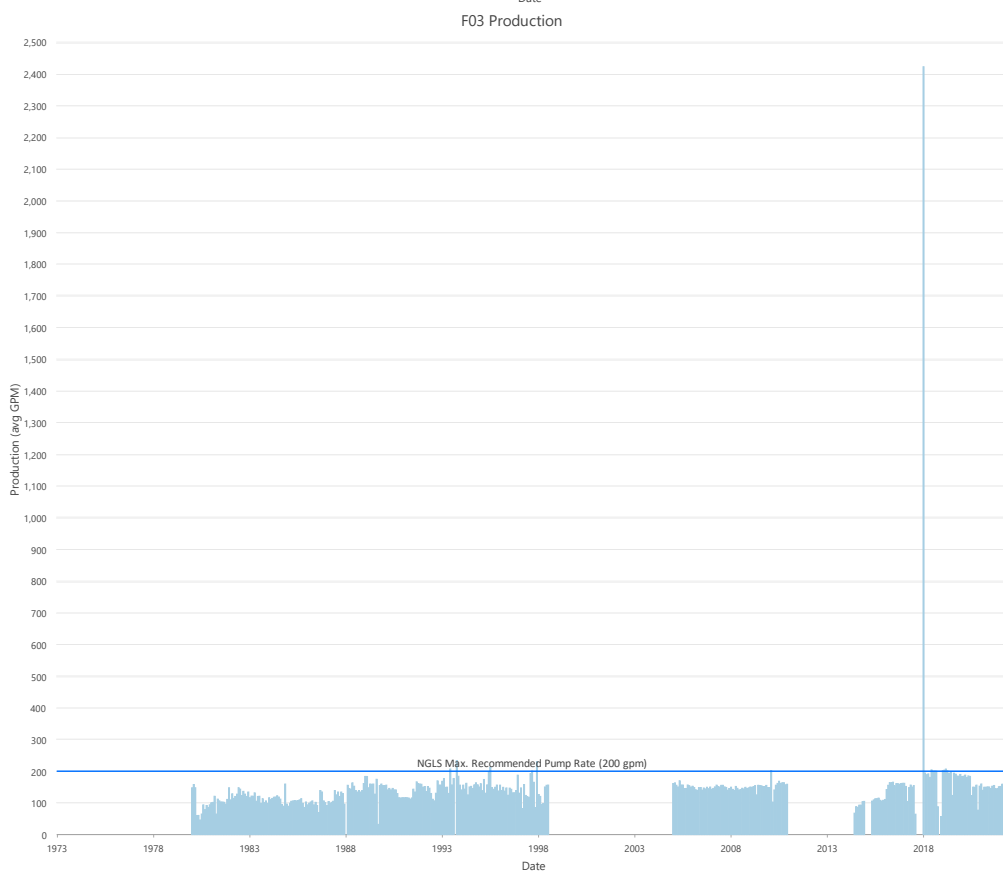
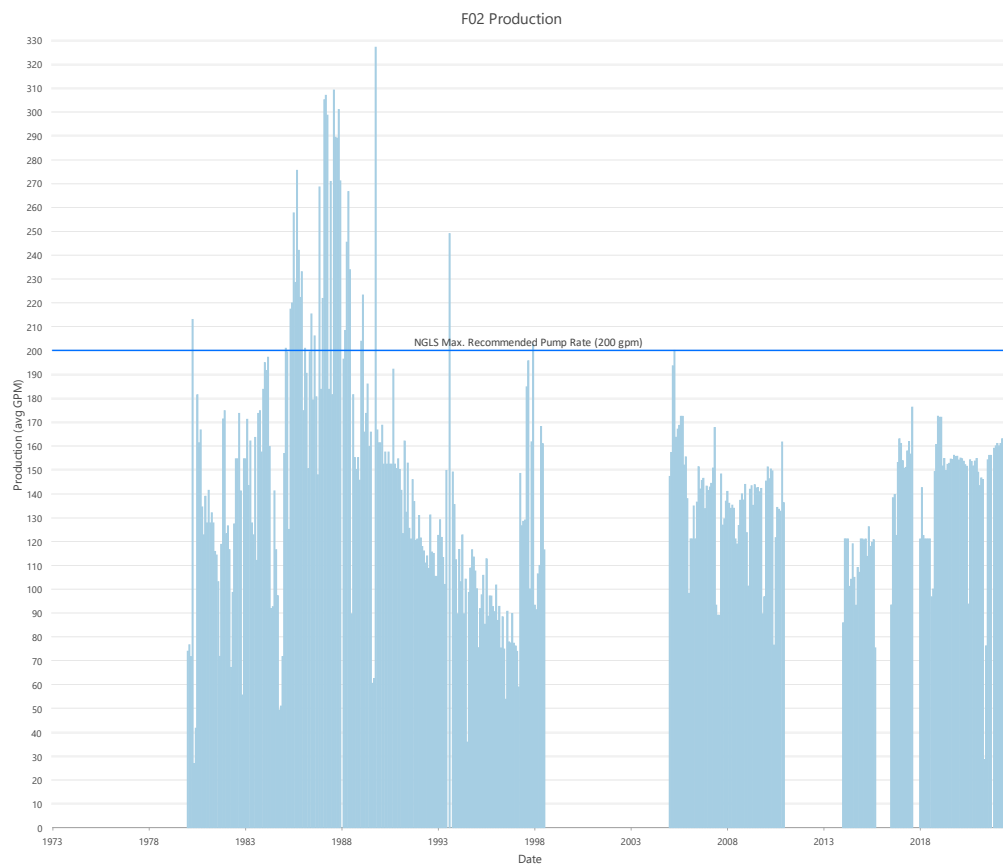


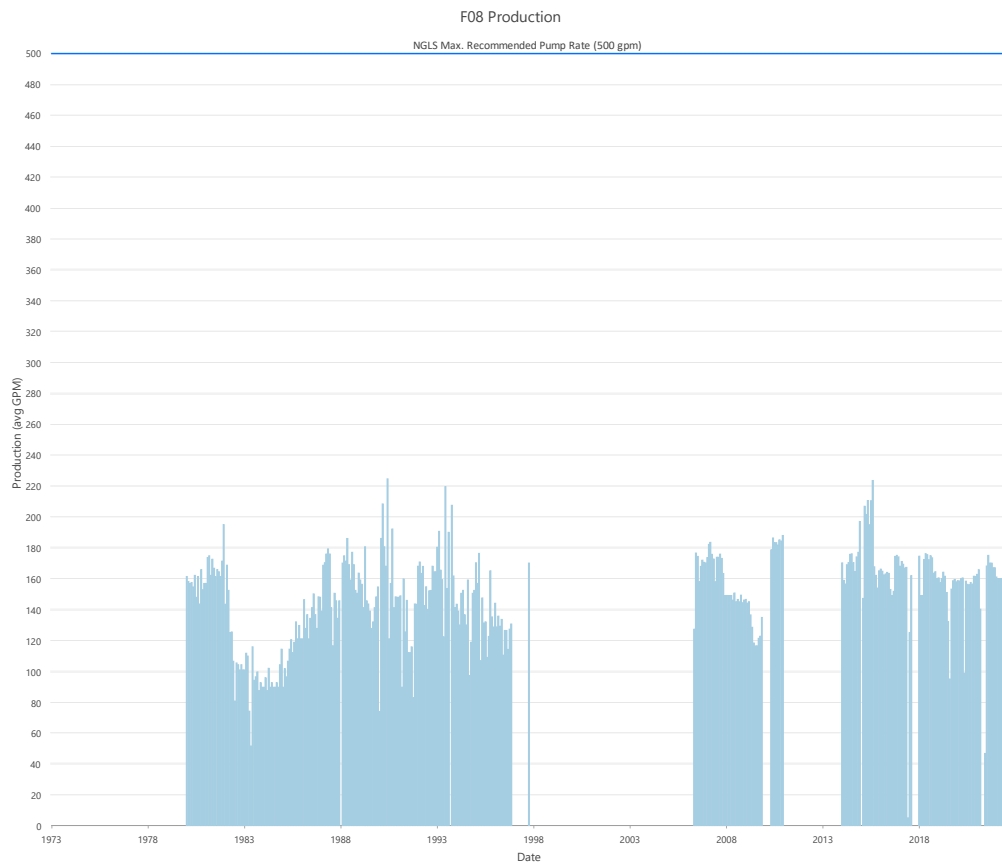
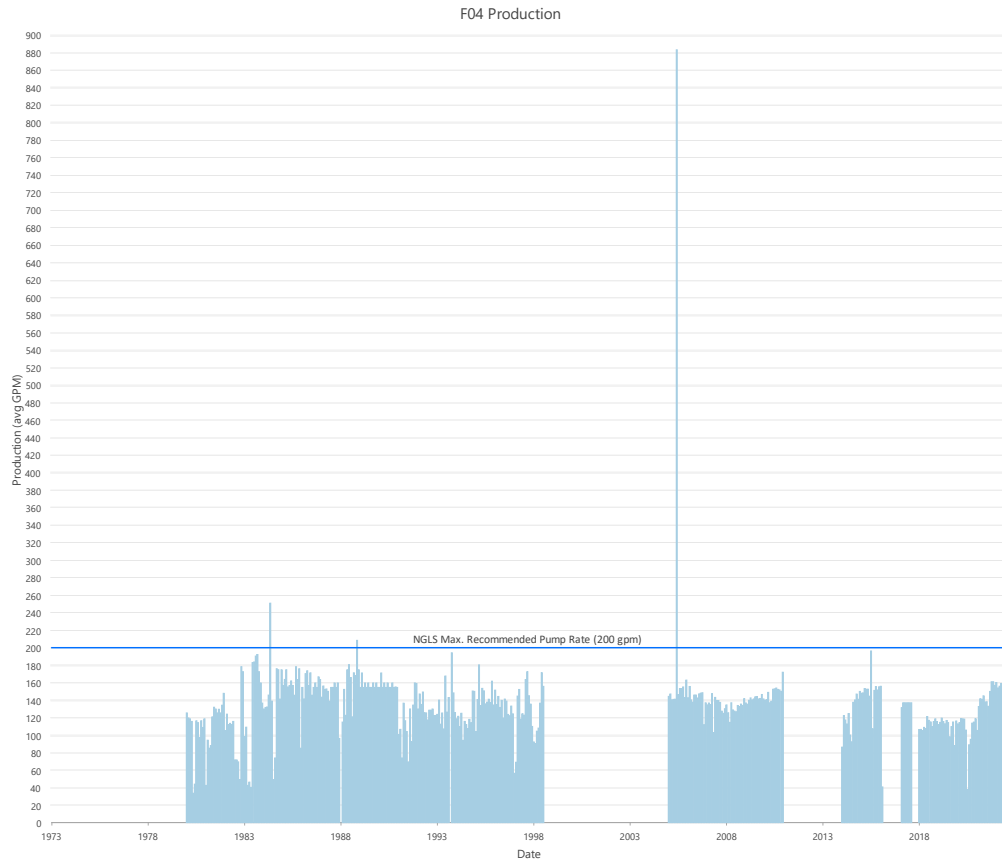
## Appendix D: Bar Graphs of the Average Production of Individual Wells Over Time

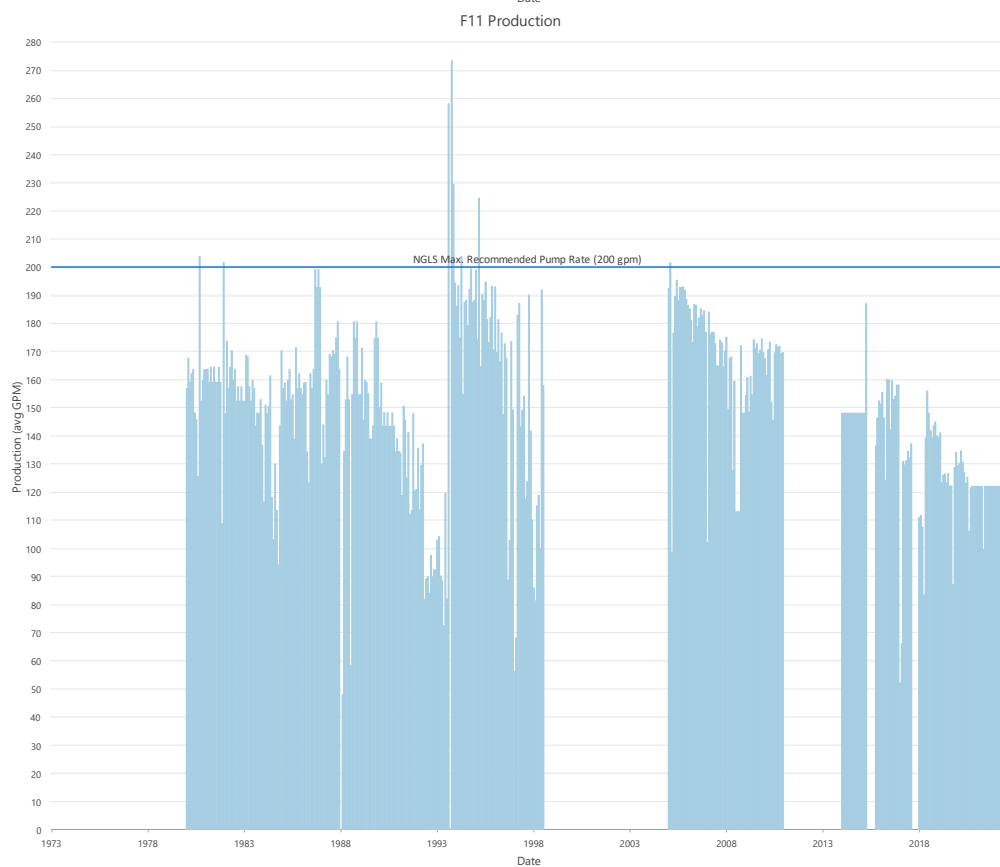
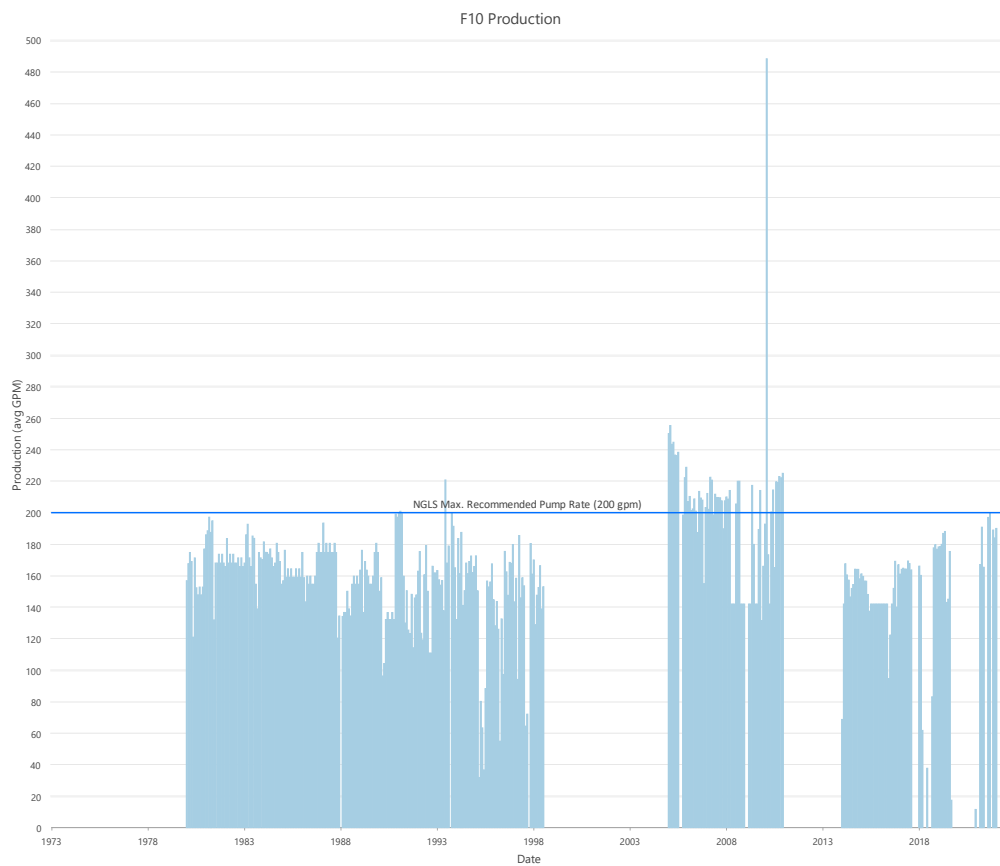
The guidelines depicted are the NGLS Recommended Pump Rate for each groundwater zone. There are no recommended pump rates for horizontal wells or wells located in the suprabasal groundwater zone. D22A does not have a NGLS Max Recommended Pump Rate due to it being a supra-basal well, a category that was not defined at the time of the study. The outliers, or anomalies, were given in the data sets provided from GWA. The wells with these outliers are F03 (January 2018 – 2423 gpm), F04 (June 2005 – 883 gpm), and F10 (February 2010 – 488 gpm).

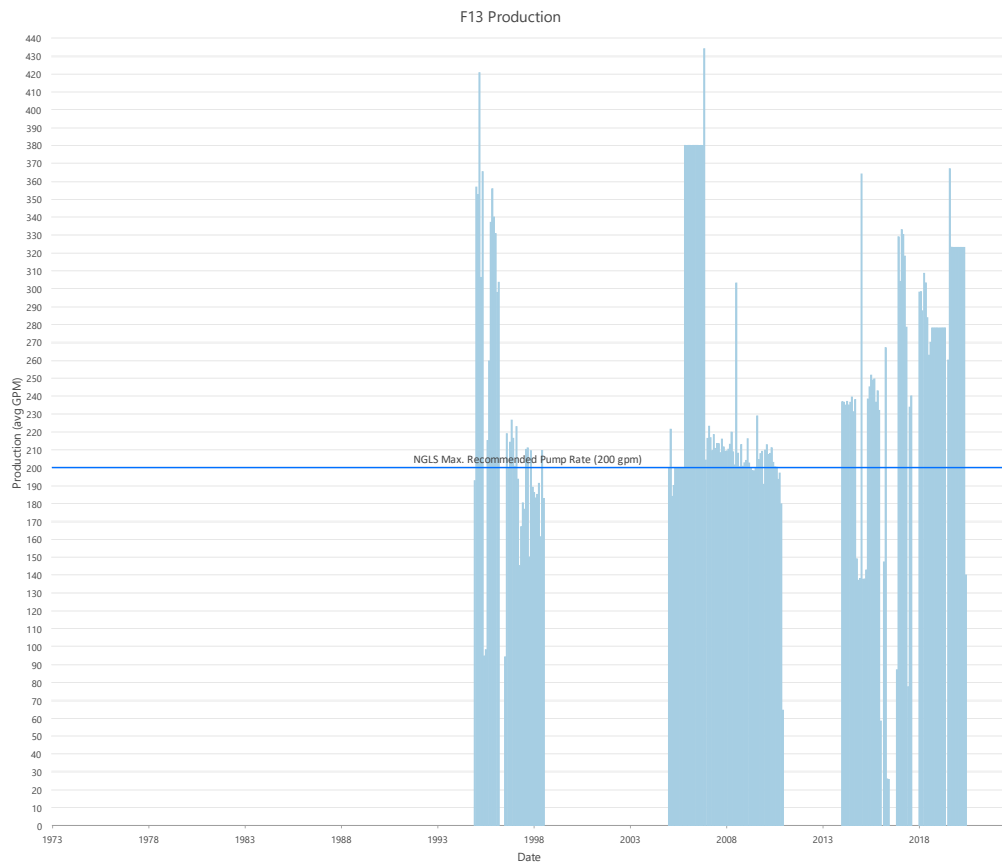
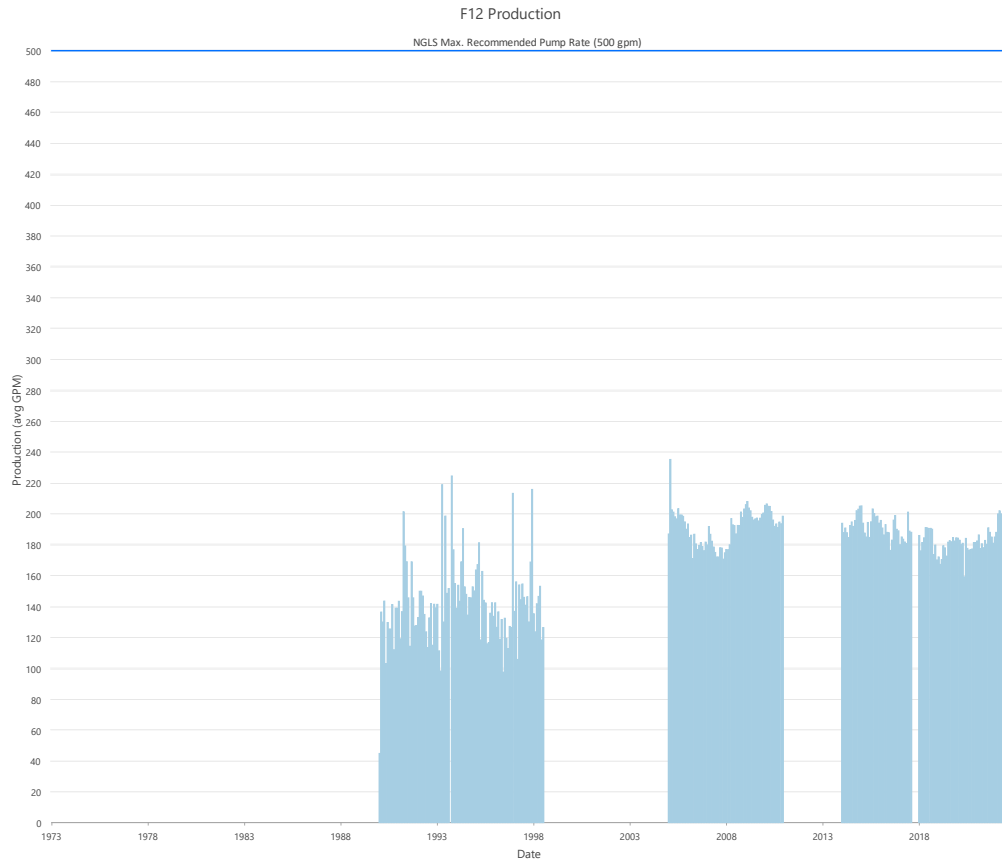


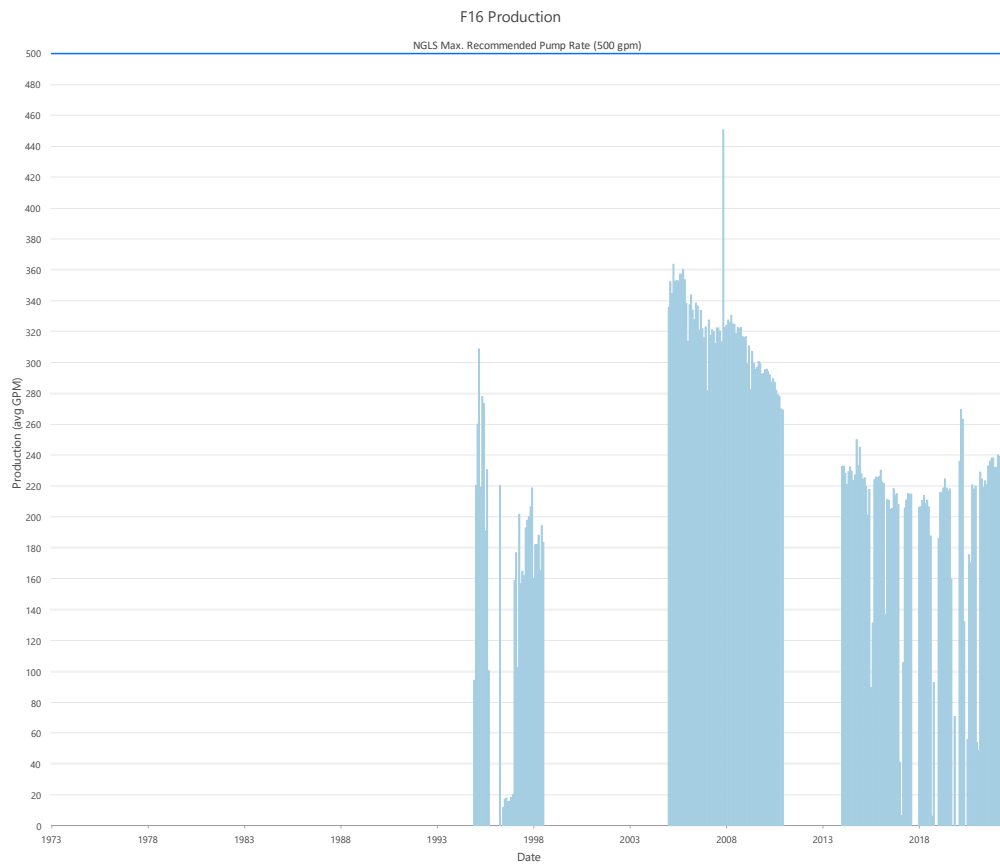
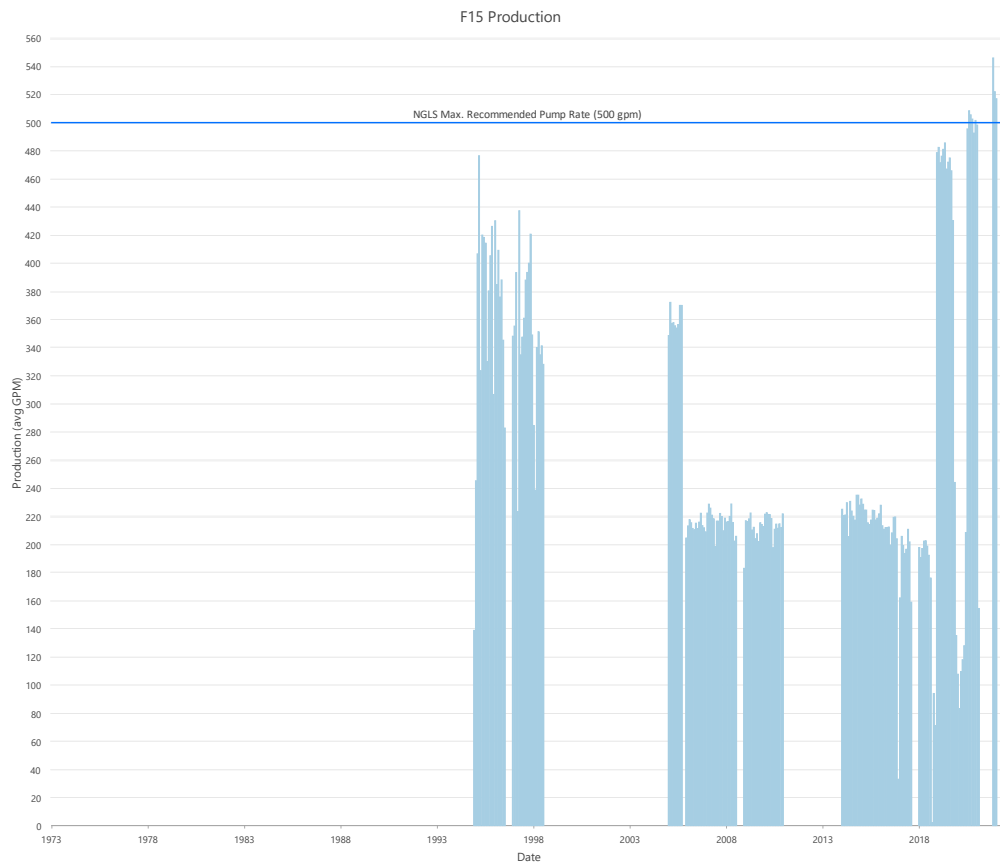


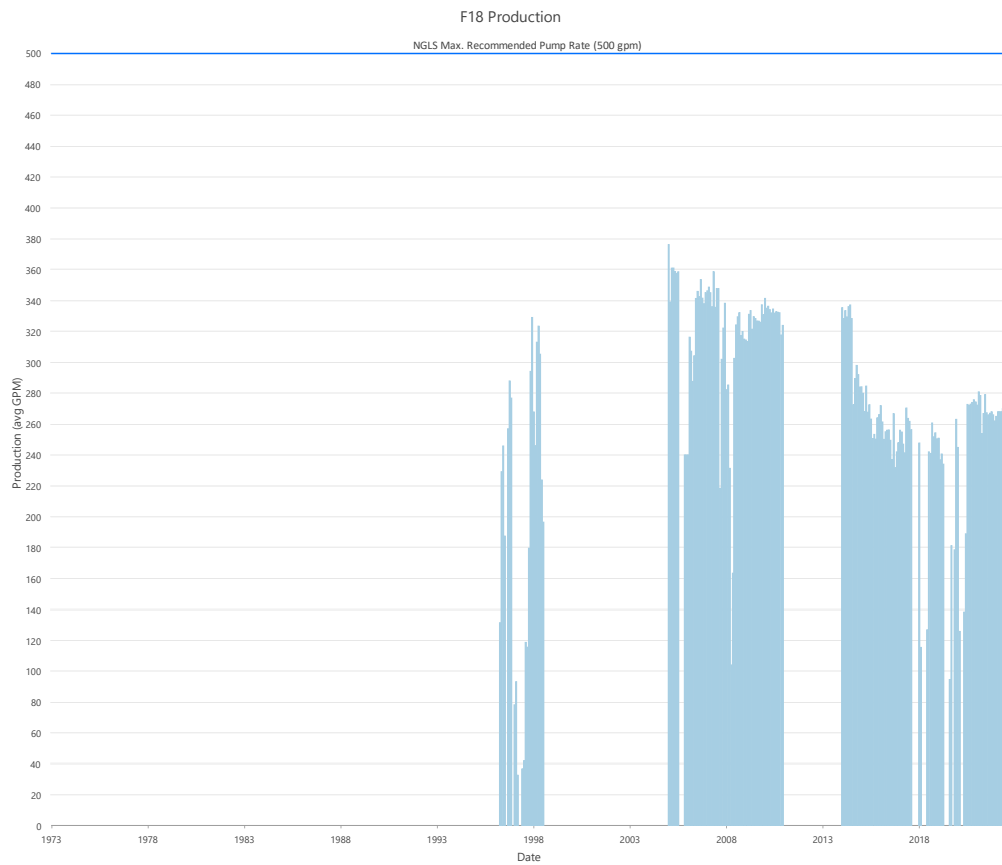
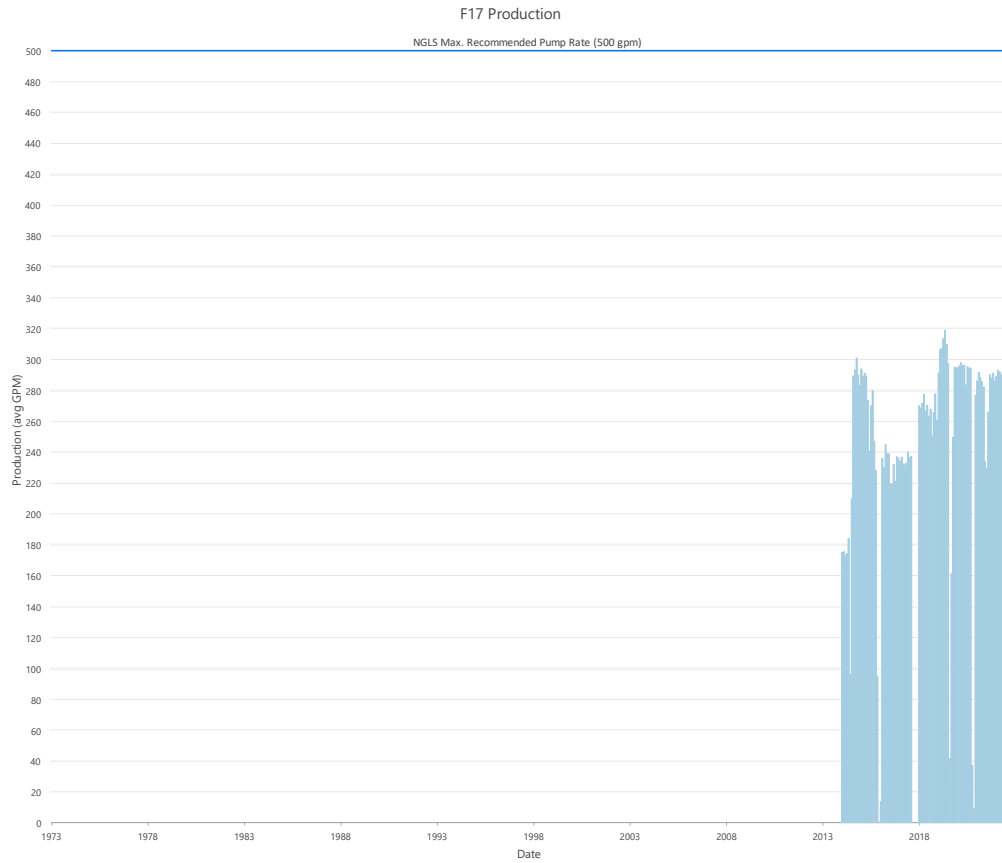




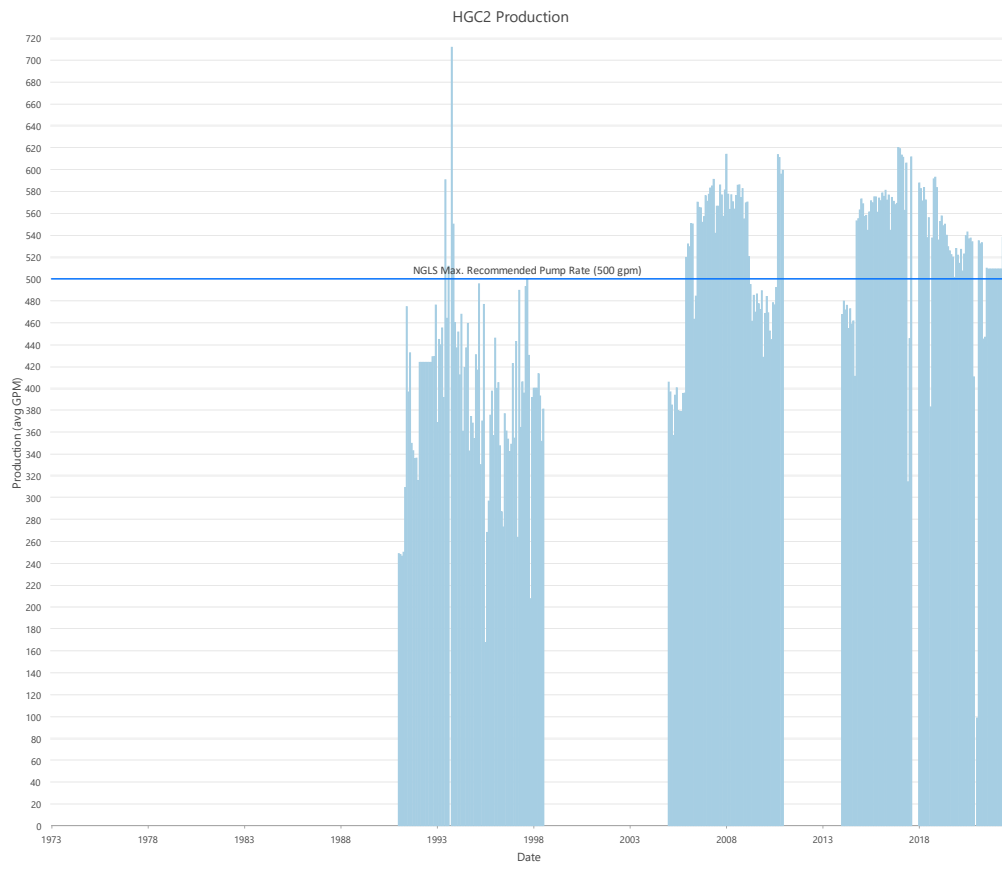












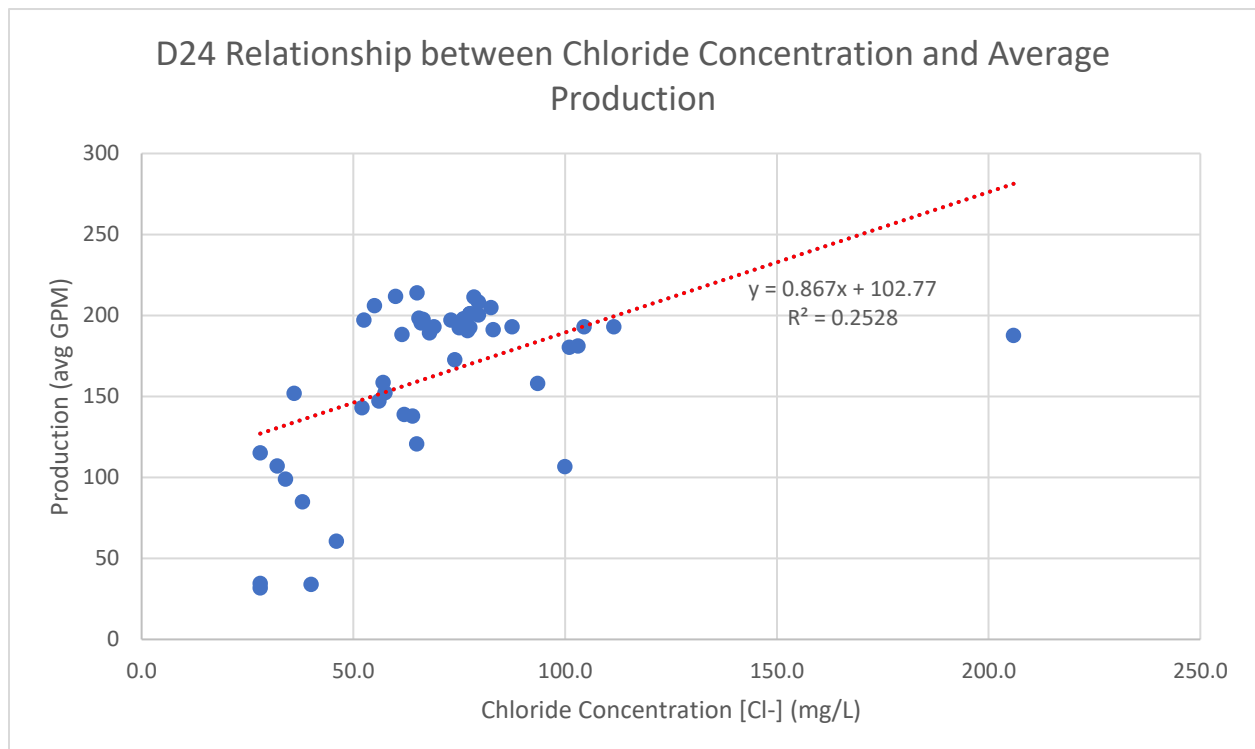
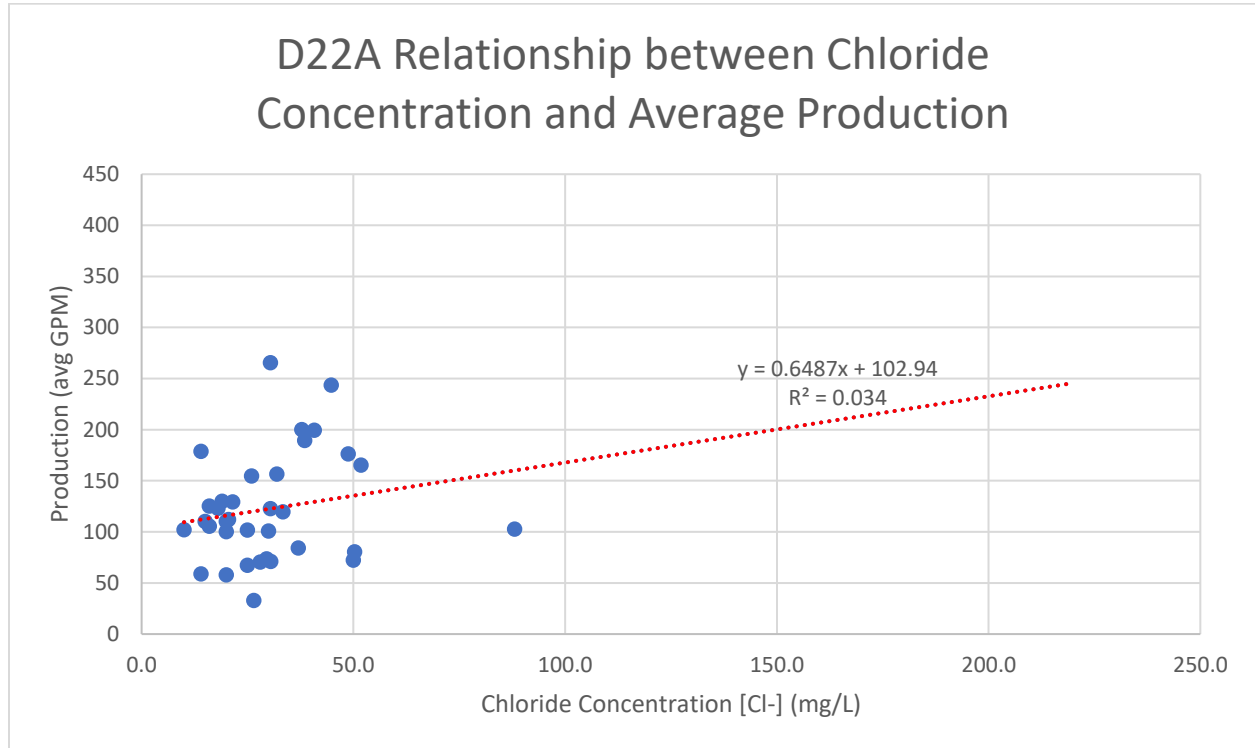
## Appendix E: Linear Regression Summary of the Relationship between Chloride Concentration and Production for Individual Wells

For these summaries, the n = number of data values that had both a chloride concentration and average production reading on that given date. The regression equations showed whether or not there was a significant increase or decrease relationship between chloride concentration and average production. If there is an increase, this may be interpreted as the increase of production is directly related with the increase in chloride concentration.

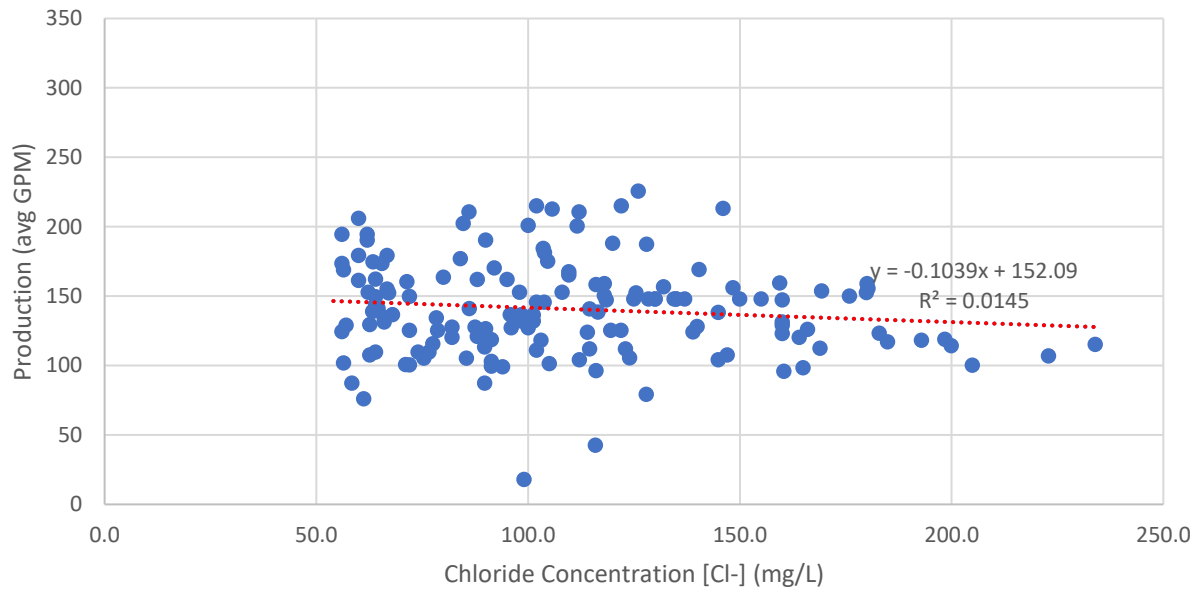
Well ID	Regression Equation	$r^2$	r	$r_{crit}$	n	df = n - 2	Significant if $r > r_{crit}$	Trend
D22A	$y = 0.6487x + 102.94$	0.034	0.184391	0.334	35	33	Not Significant	Increase
D24	$y = 0.867x + 102.77$	0.2528	0.502792	0.288	47	45	Significant	Increase
F01	$y = -0.1039x + 152.09$	0.0145	0.120416	0.16	150	148	Not Significant	Decrease
F02	$y = -0.2994x + 178.57$	0.0206	0.143527	0.157	156	154	Not Significant	Decrease
F03	$y = 0.0568x + 129.21$	0.0018	0.042426	0.159	152	150	Not Significant	Increase
F04	$y = 0.1195x + 109.56$	0.0578	0.240416	0.16	151	149	Significant	Increase
F08	$y = 0.1253x + 142.87$	0.0071	0.084261	0.163	146	144	Not Significant	Increase
F10	$y = 0.0885x + 151.48$	0.0339	0.18412	0.165	141	139	Significant	Increase
F11	$y = -0.0151x + 152.76$	0.0004	0.02	0.158	155	153	Not Significant	Decrease
F12	$y = 0.8723x + 142.91$	0.2204	0.469468	0.208	89	87	Significant	Increase
F13	$y = 0.0527x + 237.22$	0.0016	0.04	0.261	57	55	Not Significant	Increase
F15	$y = 2.9289x + 93.159$	0.1744	0.417612	0.259	58	56	Significant	Increase
F16	$y = 1.9672x + 175.37$	0.1103	0.332114	0.244	65	63	Significant	Increase
F17	$y = -1.8901x + 302.09$	0.0506	0.224944	0.344	33	31	Not Significant	Decrease
F18	$y = 1.6548x + 223$	0.0526	0.229347	0.254	60	58	Not Significant	Increase
HGC2	$y = 2.5686x + 400.44$	0.1268	0.35609	0.217	82	80	Significant	Increase

## Appendix F: Linear Regression Graphs of Chloride Concentration Against the Average Production

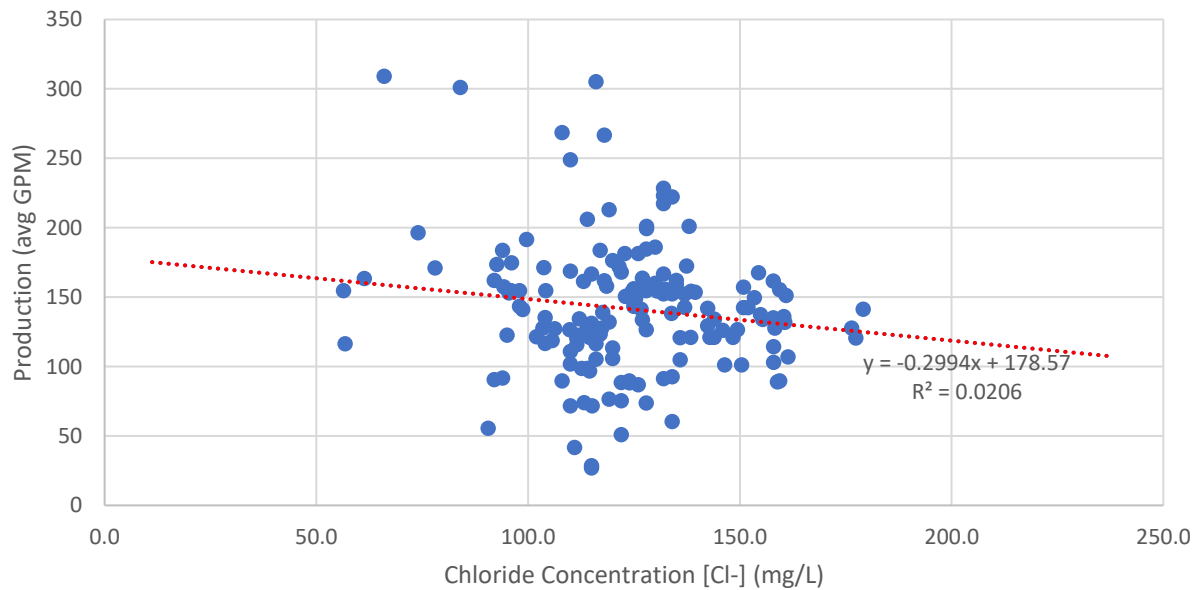
Only data points with both the chloride concentration and production were graphed. The x-axis is chloride concentration (mg/L) and the y-axis is the average production (avg GPM).



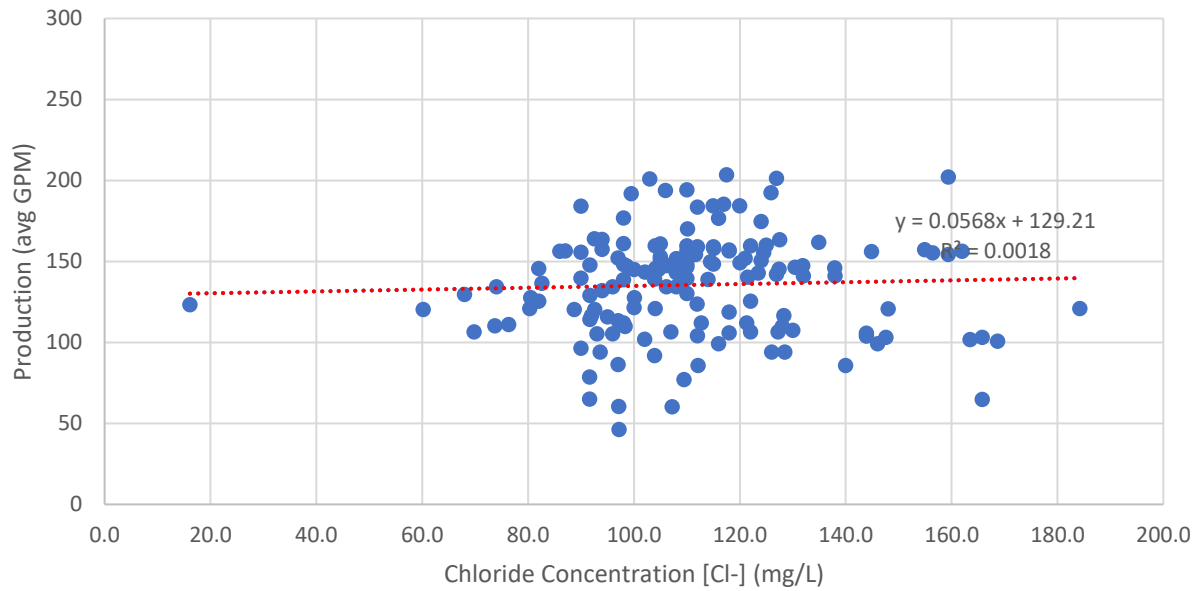
F01 Relationship between Chloride Concentration and Average Production



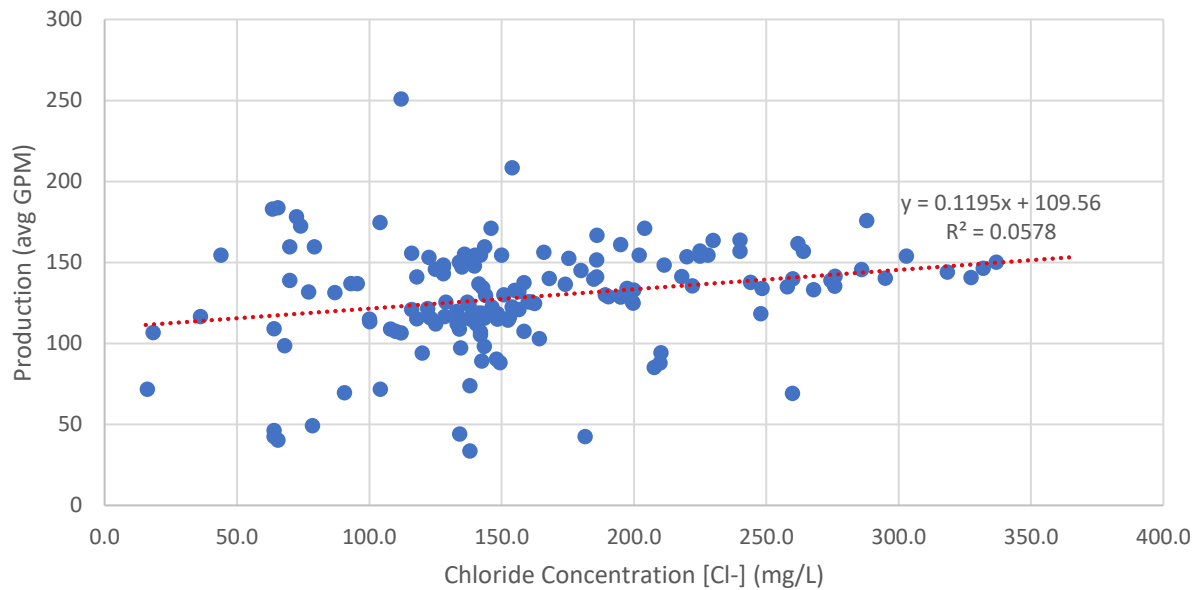
F02 Relationship between Chloride Concentration and Average Production



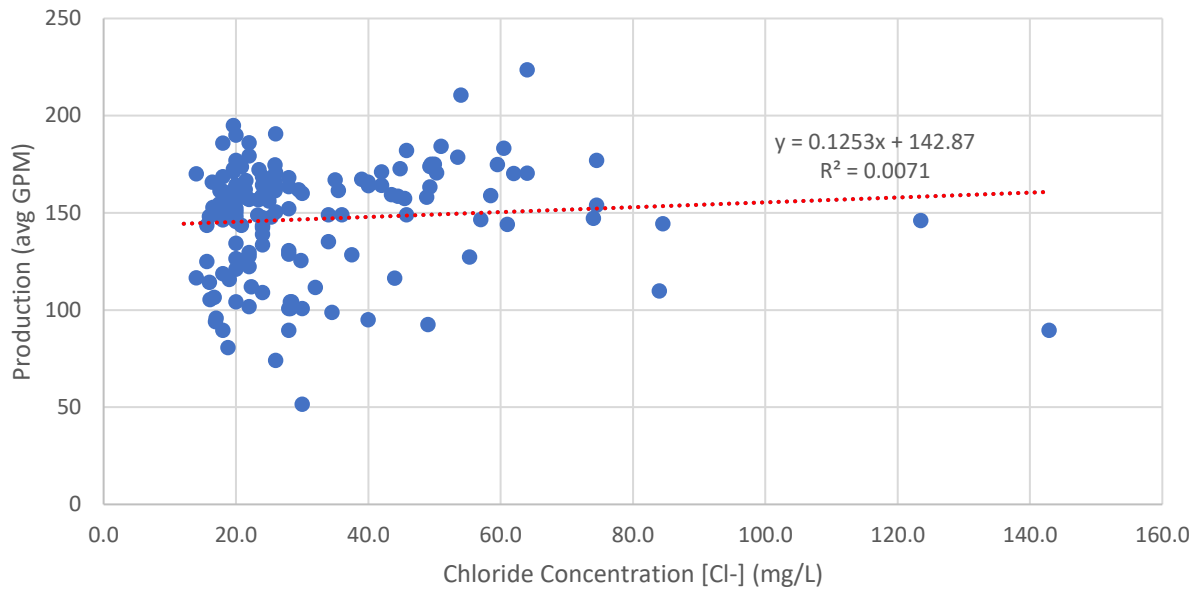
F03 Relationship between Chloride Concentration and Average Production



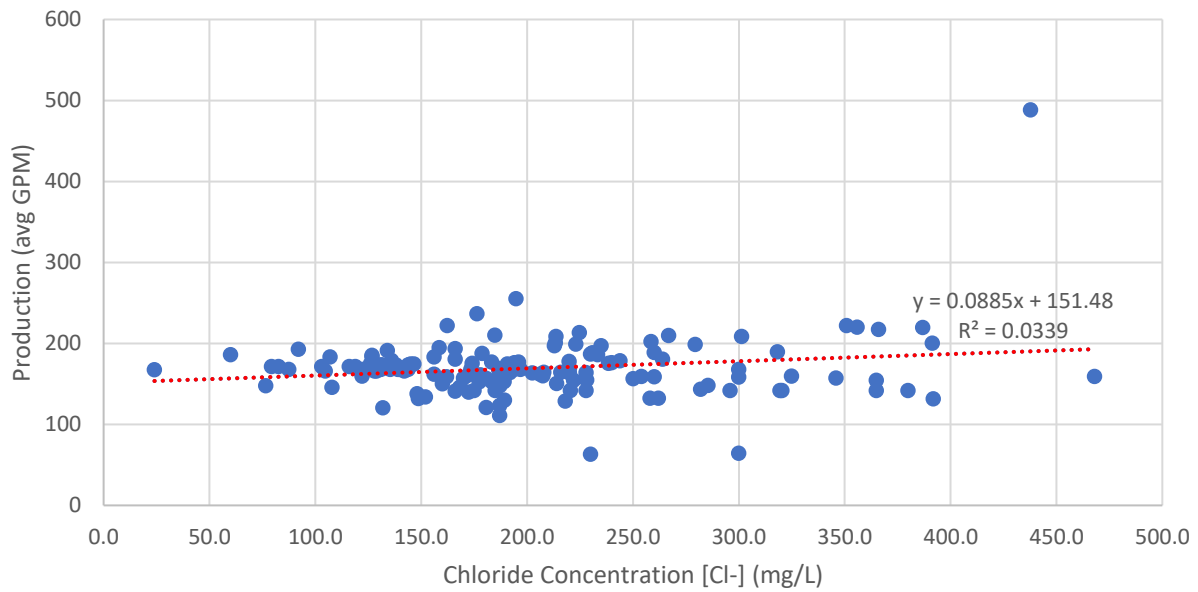
F04 Relationship between Chloride Concentration and Average Production



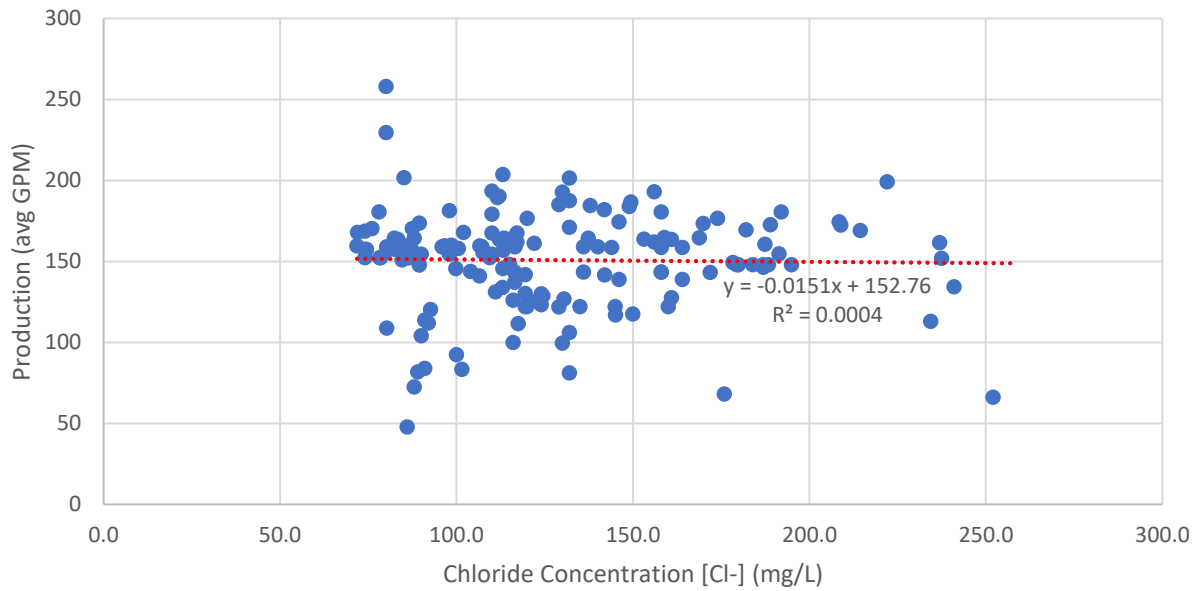
F08 Relationship between Chloride Concentration and Average Production



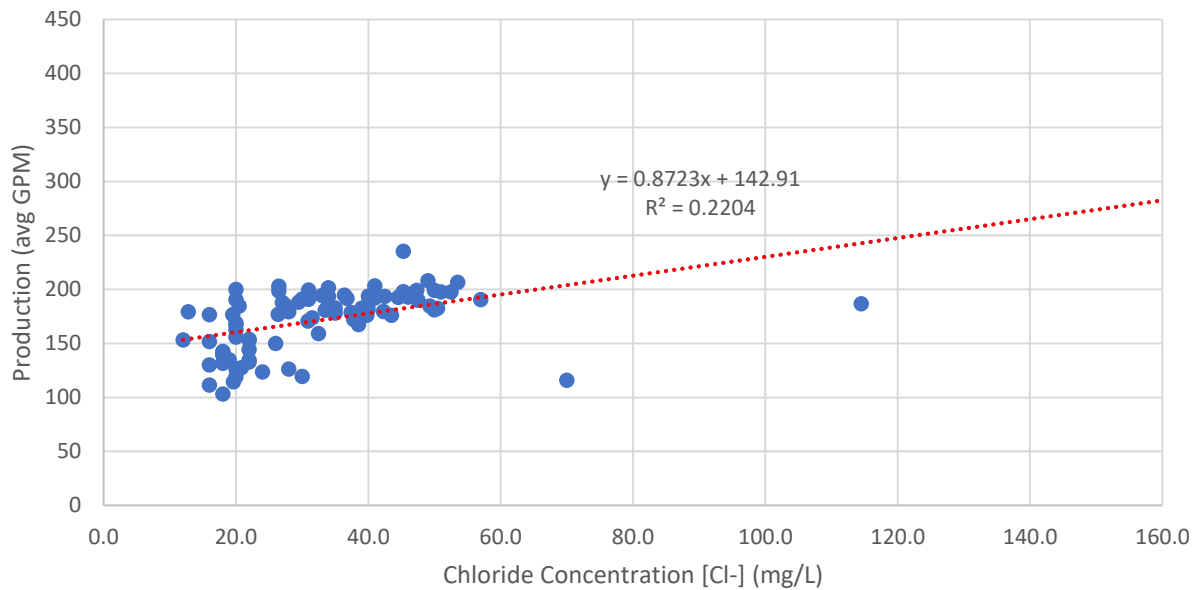
F10 Relationship between Chloride Concentration and Average Production



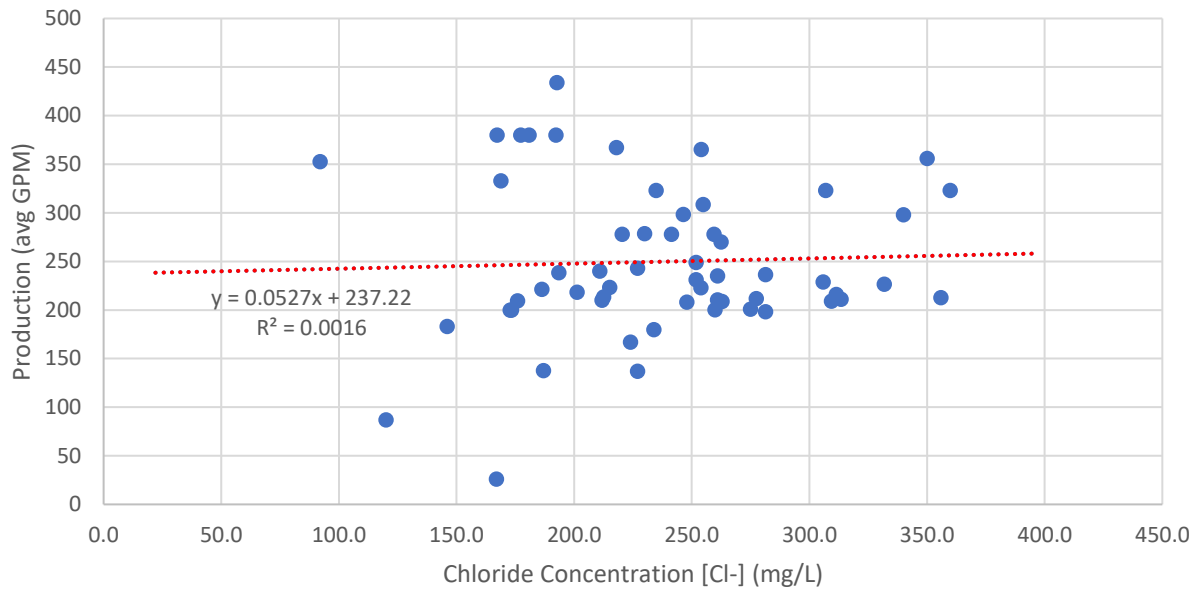
F11 Relationship between Chloride Concentration and Average Production



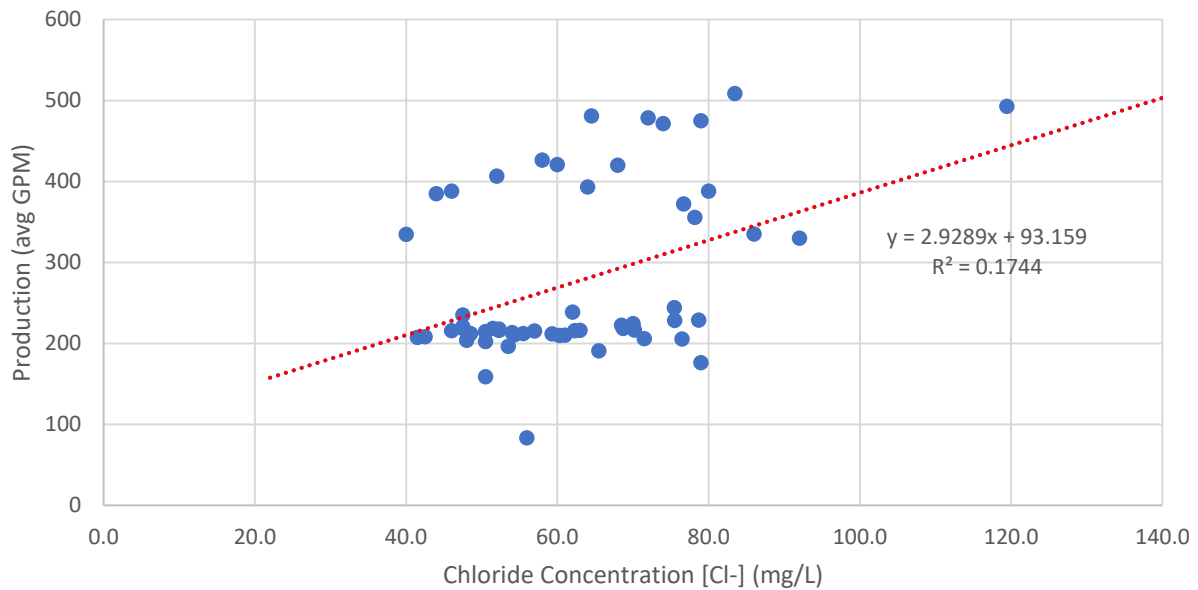
F12 Relationship between Chloride Concentration and Average Production



F13 Relationship between Chloride Concentration and Average Production

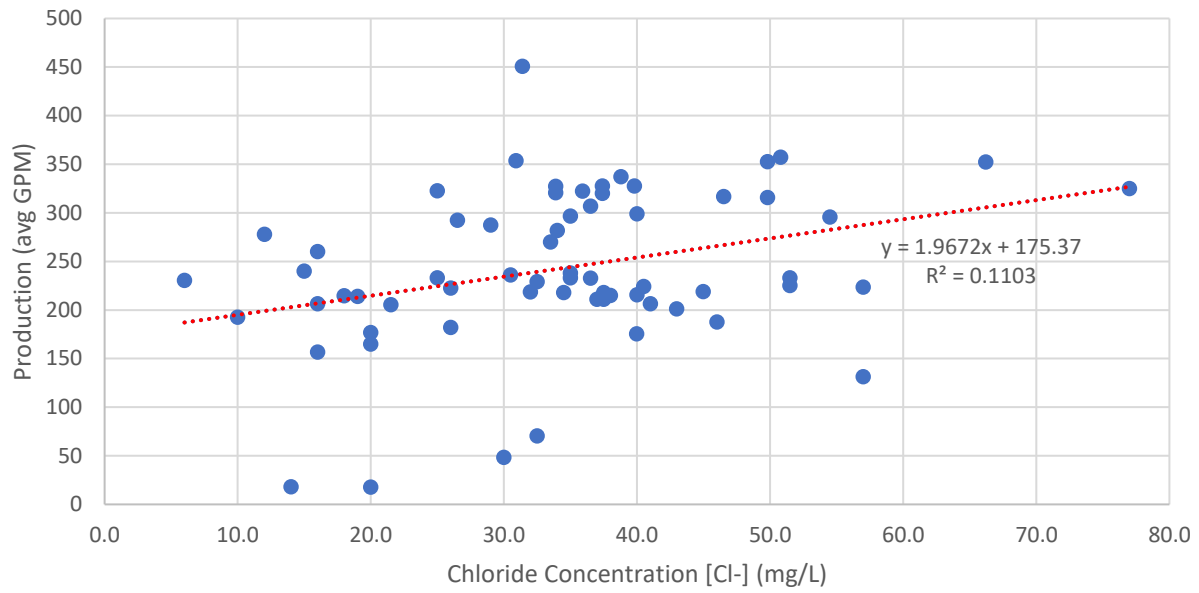


F15 Relationship between Chloride Concentration and Average Production

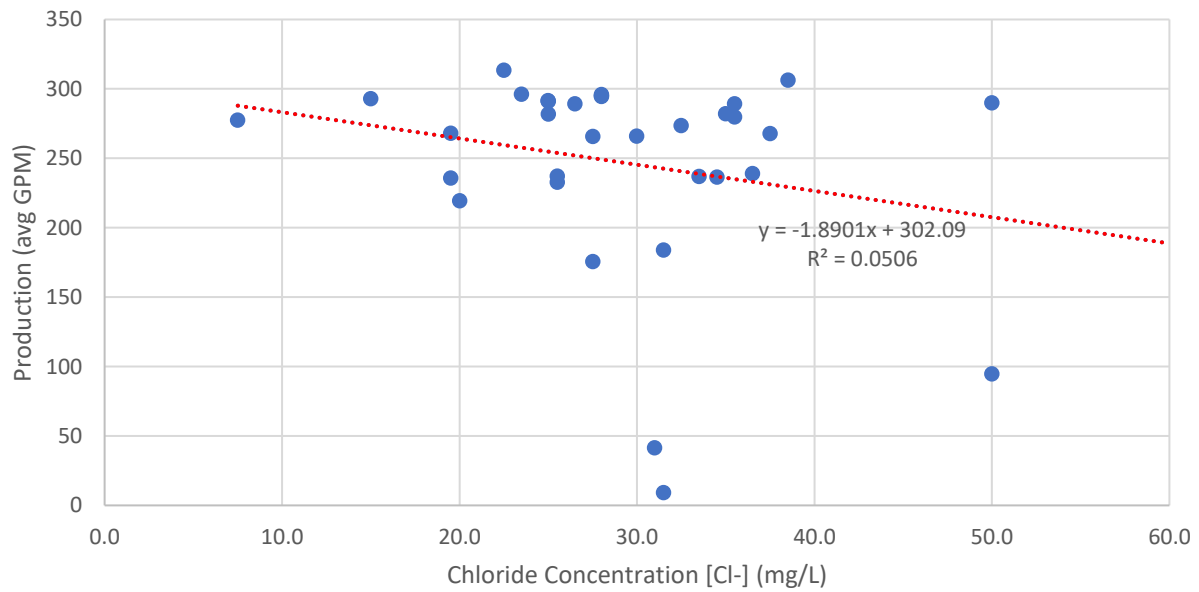




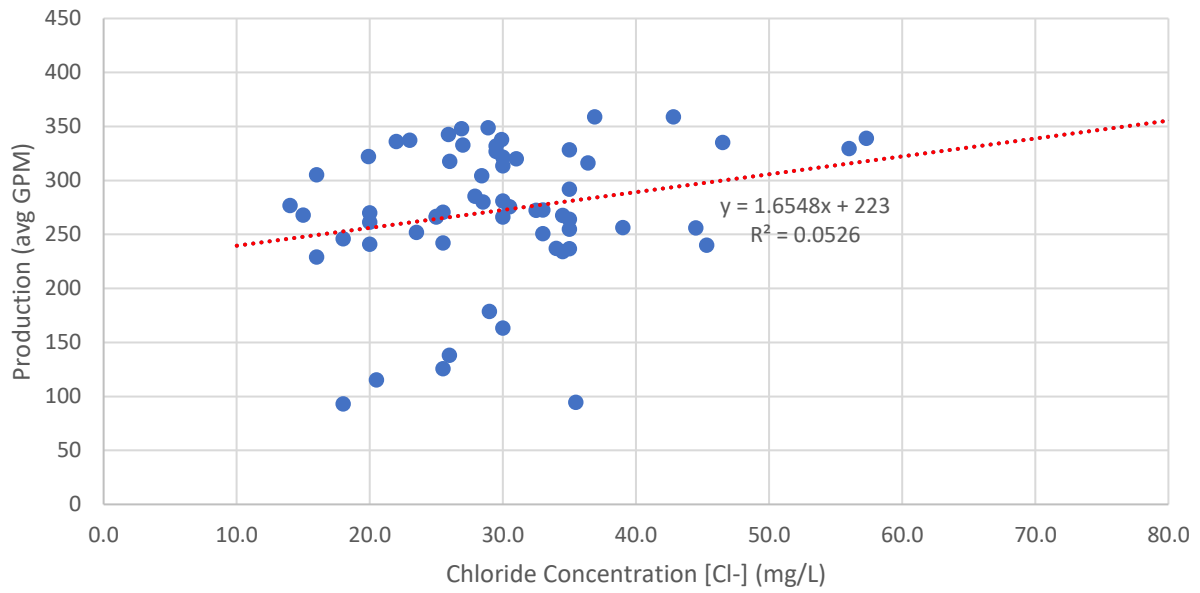
F16 Relationship between Chloride Concentration and Average Production



F17 Relationship between Chloride Concentration and Average Production



F18 Relationship between Chloride Concentration and Average Production



HGC2 Relationship between Chloride Concentration and Average Production

