

# **GEOSPATIAL AND TEMPORAL ANALYSIS OF PATTERNS AND TRENDS IN SALINITY IN YIGO-TUMON BASIN**

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## **ABSTRACT**

This study focuses on the geospatial-temporal analysis of patterns and trends of salinity in the Yigo-Tumon Basin. Using statistics in Microsoft Excel and ArcGIS, spatial and temporal trends of the increase or decrease of chloride concentrations are observed and analyzed. Of the wells in the Yigo-Tumon Basin, sixty-three are analyzed for this study. Fifty-three wells are in the basal groundwater zone, eight wells are in the para-basal zone, and two wells are in the supra-basal zone. Of all the wells analyzed in this basin, twenty-eight wells have passed the local MCL and of those twenty-eight, thirteen have passed the USEPA National Secondary Drinking Water Regulation Guideline. No wells in the Y-series have passed the local MCL. Forty seven of the sixty-three wells (74.6%) demonstrate a significant increasing trend, seven (11.1%) demonstrate a non-significant increasing trend, six (9.5%) demonstrate a non-significant decreasing trend, and three (4.76%) demonstrate a significant decreasing trend.

Temporal analysis not only gives the increasing or decreasing trends but allows for visualization of cyclical patterns. Across the basin, chloride concentrations are higher in the more recent years. Spatial analysis allows us to determine whether the wells being close to each other, or other external factors affect chloride concentrations.

## **1. INTRODUCTION**

### **1.1 Statement of the Problem**

The Yigo-Tumon basin, largest of the six in the Northern Guam Lens Aquifer, is the most productive basin by which the island of Guam produces drinking water. As the NGLA produces 90% of the island's drinking water, it must be carefully monitored to minimize risk of saltwater contamination and ensure our water remains fit for consumption. As the population of the island is projected to increase, the demand of water will rise and make it necessary that future endeavors to match the growing demands does not harm our aquifer. Geospatial and temporal analysis of the patterns and trends in salinity in the Yigo-Tumon basin may assist in making these planning choices.

### **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-) 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 this WERI Technical Report 1. 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 eventual abandonment due to their being set deeper than necessary and over pumped.

Mink determined that within 2,000 feet of the ocean be considered as a zone of mixture. This zone contains 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 6- 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 (CDM and Mink 1982)**

The 1982 Northern Guam Lens Study (NGLS) was conducted by Camp Dresser and McKee, Inc. (CDM) and John Mink. 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 became with 150 mg/L being 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 is 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 rate (gpm) suggested by this study are:

- 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 allow 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. This study saw the implementation of the USEPA Safe Drinking Water Guideline of 250 mg/L. This study calculated linear regression of 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 and they are as follows:

- 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 may 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.

For the Yigo-Tumon basin, seventy-nine production wells were analyzed with sixty-seven being in the basal groundwater zone, ten in the para-basal, and two in the supra-basal. Seven deep monitoring wells throughout the basal zone and the supra-basal zone were also analyzed. Three wells (D08, D13 and D26) demonstrated “Out of Standard” groundwater quality but are surrounded by many production wells that exhibit “Good” and “Standard” groundwater quality. This study’s linear regression analysis indicated that fifty-nine production wells showed a significant increasing trend, and thirteen production wells showed no significant increasing trend.

## 2. METHODOLOGY

Data was provided for the Yigo-Tumon basin production wells by the Guam Waterworks Authority (GWA) spanning January 1973 to June 2022. As there very few data points for GIAA1, GIAA2, GIAA3 and Tumon Maui Well they have been excluded from this study.

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 mean 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 mean 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 may be calculated. To determine the statistical significance of the linear regression lines, the correlation coefficient,  $r$ , was calculated from the scatter plot data. If these values were larger than the  $r_{crit}$  values found from Table B.17 of *Biostatistical Analysis* (Zar 1999), they were considered statistically significant according to a two-tailed test with a 95% confidence interval ( $\alpha = 0.05$ ). A summary of linear regression analysis and the linear regression scatter plots for chloride concentration is provided in the Appendix A and Appendix B, respectively.

The concentration data was also moved to ArcGIS and displayed in bar graphs. This allowed for important guidelines to be marked out for easier visualization of when chloride concentrations



passed the 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 dates with both chloride concentration data and production data were graphed against each other. These graphs for the relationship can be found in Appendix F and the linear regression summary for the relationship between chloride concentration can be found in Appendix E.

To further analyze the changes in chloride concentration spatially, the wells were plotted in ArcGIS 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 details about the production statistics and chloride statistics of all wells including the Maui Wells although Maui Wells was not included in the overall analysis of this basin due to the small number of data points. The decadal mean 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 are 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 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		D01	D02	D03A	D04	D05	D06
Groundwater Zone		Basal	Basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-38.10	-35.17	-23.34	-24.50	-31.81	-26.29
	Meters	-11.61	-10.72	-7.11	-7.47	-9.70	-8.01
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-40	-40
Well Screen Length (feet)		35	35	35	25	40	40
Well Construction Year		1973	1973	1973	1973	1973	1973
Status/Final Year of Production		GM - 5/23/2021	Operational	GM - 7/26/2019	Operational	2016	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	177.16	183.26	140.29	154.53	133.61	161.11
	1990-1999	211.96	199.35	161.65	151.61	173.45	205.35
	2000-2009	228.30	202.56		263.08	162.14	273.14
	2010-2019	252.44	225.91	135.49	253.93	169.63	228.52
	2020-Present	226.20	197.44	212.97	223.69		213.67
Chloride Statistics		D01	D02	D03	D04	D05	D06
Total Number of Chloride Samples		261	258	185	259	232	261
Minimum Concentration (mg/L)		24.00	24.00	22.10	22.00	34.00	29.10
Maximum Concentration (mg/L)		778.00	109.56	65.50	86.20	95.80	180.90
Standard Deviation		47.80	12.88	6.21	11.42	10.75	15.13
Mean Chloride Concentration (mg/L)	1973-1979	55.16	55.23	35.51	38.84	59.25	51.18
	1980-1989	58.91	61.82	36.97	43.61	63.38	50.45
	1990-1999	64.05	62.49	38.35	41.36	58.10	56.28
	2000-2009	73.67	72.82	45.11	58.13	71.10	68.65
	2010-2019	98.78	81.41		62.91	81.54	76.63
	2020-Present	63.37	66.29		51.23		52.93

Production Statistics		D07	D08	D09	D10	D11	D12
Groundwater Zone		Basal	Basal	Basal	Basal	Basal	Para-basal
Well Depth Elevation	Feet	-48.98	-35.68	-27.52	-25.09	-37.00	-48.20
	Meters	-14.93	-10.88	-8.39	-7.65	-11.28	-14.69
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-40	-50
Well Screen Length (feet)		60	40	35	35	50	50
Well Construction Year		1973	1973	1973	1973	1973	1973
Status/Final Year of Production		Operational	Operational	Operational	GM - 3/5/2022	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	200	500
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	147.09	136.72	168.15	161.16	165.10	144.94
	1990-1999	193.55	192.63	189.80	195.73	229.77	171.95
	2000-2009	212.48	185.80	226.67	234.15	200.46	197.17
	2010-2019	200.02	168.96	200.55	221.13	170.88	293.02
	2020-Present	189.81	164.09	200.45	220.08	210.00	208.99
Chloride Statistics		D07	D08	D09	D10	D11	D12
Total Number of Chloride Samples		266	263	257	250	260	263
Minimum Concentration (mg/L)		29.80	55.00	11.20	26.30	34.40	6.00
Maximum Concentration (mg/L)		234.00	531.90	289.00	210.00	214.00	172.00
Standard Deviation		19.00	79.44	41.44	20.26	19.62	15.61
Mean Chloride Concentration (mg/L)	1973-1979	50.81	135.06	110.51	38.56	82.45	18.22
	1980-1989	52.18	170.18	131.78	39.73	73.65	20.92
	1990-1999	58.29	227.21	156.75	41.90	94.43	26.36
	2000-2009	80.70	282.26	176.77	61.83	90.88	36.28
	2010-2019	83.39	241.61	196.46	79.32	83.42	43.43
	2020-Present	70.08	180.73	169.30	54.32	85.53	35.89

Production Statistics		D13	D14	D15	D16	D17A	D18B
Groundwater Zone		Para-basal	Basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-50.88	-55.75	-93.12	-58.40	-35.60	-59.63
	Meters	-15.51	-16.99	-23.38	-17.80	-10.85	-18.18
NGLS Max. Recommended Bottom Elevation (feet)		-50	-40	-40	-40	-40	-40
Well Screen Length (feet)		40	40	40	40	35	Unknown
Well Construction Year		1974	1973	1974	1979	1979	1980
Status/Final Year of Production		2009	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		500	200	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	149.42	166.61	161.15	189.29	148.97	117.64
	1990-1999	162.93	197.32	204.26	197.37	197.58	187.54
	2000-2009	181.38	259.72	246.54	229.48		
	2010-2019		200.07	170.73	194.56	131.13	181.32
	2020- Present		181.79	138.00	202.99	190.08	226.18
Chloride Statistics		D13	D14	D15	D16	D17A	D18B
Total Number of Chloride Samples		200	260	239	192	136	113
Minimum Concentration (mg/L)		39.00	21.80	51.00	54.00	15.90	35.50
Maximum Concentration (mg/L)		917.30	135.00	193.60	146.40	280.00	204.00
Standard Deviation		176.29	25.42	17.52	17.88	74.07	20.64
Mean Chloride Concentration (mg/L)	1973-1979	275.53	33.19	80.32	78.07	22.60	
	1980-1989	242.28	41.67	86.70	78.73	60.74	70.90
	1990-1999	308.32	61.61	96.63	87.58	182.58	86.02
	2000-2009	518.10	87.36	96.91	94.38	171.21	82.50
	2010-2019		84.90	97.39	106.56	36.14	89.15
	2020- Present		60.43	73.63	75.68	71.18	104.58

Production Statistics		D19	D20	D21	D25	D26	D27
Groundwater Zone		Basal	Basal	Basal	Para-basal	Para-basal	Para-basal
Well Depth Elevation	Feet	-49.84	-50.23	-56.93	-85.20	-44.81	-64.33
	Meters	-15.19	-15.31	-17.35	-25.97	-13.66	-19.61
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-50	-50	-50
Well Screen Length (feet)		Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Well Construction Year		1984	1984	1984	2004	2004	2004
Status/Final Year of Production		Operational	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	500	500
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	204.42	223.27	179.67			
	1990-1999	200.06	189.94	155.39			
	2000-2009	206.04	217.03	189.02	351.56	214.34	338.33
	2010-2019	205.87	202.23	113.94	346.63	253.02	429.86
	2020- Present	233.00	192.15	196.81	443.60	278.89	445.38
Chloride Statistics		D19	D20	D21	D25	D26	D27
Total Number of Chloride Samples		148	149	147	73	68	72
Minimum Concentration (mg/L)		14.40	42.00	32.00	23.60	82.00	16.30
Maximum Concentration (mg/L)		118.00	111.00	150.94	85.20	387.80	68.20
Standard Deviation		16.14	18.48	16.82	12.52	80.73	11.62
Mean Chloride Concentration (mg/L)	1973-1979						
	1980-1989	66.64	59.55	72.38			
	1990-1999	63.78	60.64	73.23			
	2000-2009	76.32	87.96	91.17	50.97	238.02	31.96
	2010-2019	85.56	91.42	88.64	55.41	233.25	38.44
	2020- Present	70.31	81.70	74.28	71.53	236.74	41.24

Production Statistics		D28	EX05	F05	F06	F07	F09
Groundwater Zone		Basal	Basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-47.92	-39.81	-35.65	-24.58	-24.16	-49.37
	Meters	-14.61	-12.13	-10.87	-7.49	-7.36	-15.05
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-40	-40
Well Screen Length (feet)		Unknown	Unknown	40	30	70	50
Well Construction Year		2004	1985	1975	1975	1975	1978
Status/Final Year of Production		GM - 12/11/2021	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989		208.34	132.57	124.16	128.52	163.37
	1990-1999		214.59	154.12	159.03	175.47	138.21
	2000-2009	166.92	357.80	196.69	214.87	182.04	158.82
	2010-2019	208.38	318.03	179.23	168.09	175.08	147.74
	2020- Present	220.17	286.91	138.23	201.67	191.46	178.47
Chloride Statistics		D28	EX05	F05	F06	F07	F09
Total Number of Chloride Samples		69	147	237	220	238	198
Minimum Concentration (mg/L)		25.50	24.00	23.8	32.00	18.90	38.00
Maximum Concentration (mg/L)		97.00	124.50	334	660.70	246.40	199.90
Standard Deviation		14.92	14.64	43.52	133.43	40.28	25.14
Mean Chloride Concentration (mg/L)	1973-1979			51.36	124.33	53.18	73.95
	1980-1989		38.80	64.78	173.02	66.07	64.49
	1990-1999		42.27	92.37	204.90	85.01	59.69
	2000-2009	60.80	58.18	138.24	340.24	127.78	96.00
	2010-2019	76.21	64.75	121.50	388.38	132.68	81.66
	2020- Present	62.42	49.79	84.92	265.00	94.85	74.88

Production Statistics		F19	F20	G501	H01	M05	M06
Groundwater Zone		Basal	Basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-46.00	-63.50	-46.95	-50.05	-92.09	-85.93
	Meters	-14.02	-19.35	-14.31	-15.26	-28.07	-26.19
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-40	-40
Well Screen Length (feet)		Unknown	Unknown	Unknown	Unknown	70	85
Well Construction Year		1996	1996	1983	1945	1973	1973
Status/Final Year of Production		Operational	GM - 5/22/2022	GM - 12/7/2021	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989			168.89	178.82	149.39	131.70
	1990-1999			176.86	246.75	163.69	188.63
	2000-2009	179.86	192.08	151.93	287.80	216.90	217.54
	2010-2019	218.05	218.00	197.22	265.48	197.68	145.65
	2020- Present	250.51	234.25	198.88	250.77	219.78	119.07
Chloride Statistics		F19	F20	G501	H01	M05	M06
Total Number of Chloride Samples		67	64	46	228	250	246
Minimum Concentration (mg/L)		152.90	149.40	97.5	52.30	14.00	16.00
Maximum Concentration (mg/L)		549.30	770.30	238.4	278.40	105.00	323.90
Standard Deviation		113.30	122.11	47.71	56.43	16.67	59.72
Mean Chloride Concentration (mg/L)	1973-1979				76.62	39.06	63.3
	1980-1989				113.06	46.56	60.86
	1990-1999				129.81	54.73	80.49
	2000-2009	242.58	257.60		170.37	66.96	119.41
	2010-2019	342.08	328.39	146.34	210.74	71.56	184.42
	2020- Present	293.12	322.98	109.31	152.06	58.98	102.07

Production Statistics		M07	M12	M14	M15	M17A	M17B
Groundwater Zone		Basal	Basal	Basal	Basal	Para-basal	Para-basal
Well Depth Elevation	Feet	-55.34	-53.11	-40.98	-51.21	-54.49	-41.28
	Meters	-16.87	-16.19	-12.49	-15.61	-16.61	-12.58
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-50	-50
Well Screen Length (feet)		50	60	40	40	Unknown	40
Well Construction Year		1973	1973	1974	1983	1990	1990
Status/Final Year of Production		Operational	GM - 9/26/2021	2006	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	500	500
Mean Pump Rate (gpm) (Mgal/month)	1973-1979		65.55				
	1980-1989	180.79	95.68	176.25	174.83		
	1990-1999	172.16	103.84	225.10	190.19	198.63	288.18
	2000-2009	209.39	114.06	159.18	248.38		283.76
	2010-2019	195.65	94.83		196.57	273.59	216.40
	2020- Present	154.73	98.85		123.66	206.26	400.97
Chloride Statistics		M07	M12	M14	M15	M17A	M17B
Total Number of Chloride Samples		243	128	179	158	57	124
Minimum Concentration (mg/L)		3.50	30.00	14.1	21.00	23.00	11.10
Maximum Concentration (mg/L)		90.00	251.90	127.1	159.40	116.00	106.00
Standard Deviation		13.09	28.69	19.88	32.84	21.16	15.61
Mean Chloride Concentration (mg/L)	1973-1979	33.05		35.22			
	1980-1989	37.92	94.93	38.60	42.41		
	1990-1999	41.48	92.01	51.77	47.32	71.24	61.48
	2000-2009	54.74	111.31	47.40	71.75	89.57	67.35
	2010-2019	61.20	117.67	70.00	87.21	77.98	74.45
	2020- Present	46.89	116.62	21.99	50.38	78.77	69.08



Production Statistics		M18	M20A	M21	Y01	Y02	Y03
Groundwater Zone		Basal	Para-basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-40.36	-21.40	-34.85	-35.16	-52.17	-25.39
	Meters	-12.30	-6.52	-10.62	-10.72	-15.90	-7.74
NGLS Max. Recommended Bottom Elevation (feet)		-40	-50	-40	-40	-40	-40
Well Screen Length (feet)		Unknown	Unknown	Unknown	40	70	Unknown
Well Construction Year		1997	1996	1998	1973	1973	1973
Status/Final Year of Production		Operational	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	500	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1973-1979						
	1980-1989				142.22	158.30	117.99
	1990-1999	371.57	257.77		134.71	157.04	154.50
	2000-2009	278.60	255.05	290.50	192.93	197.97	203.53
	2010-2019	260.91	257.42	262.61	196.06	176.68	165.67
	2020- Present	300.11	361.25	210.03	200.20	168.11	161.30
Chloride Statistics		M18	M20A	M21	Y01	Y02	Y03
Total Number of Chloride Samples		46	101	89	257	263	257
Minimum Concentration (mg/L)		68.00	43.30	45	12.80	12.80	10.00
Maximum Concentration (mg/L)		108.00	151.40	191	73.50	94.00	117.00
Standard Deviation		10.25	21.15	37.26	10.74	11.58	11.96
Mean Chloride Concentration (mg/L)	1973-1979				18.56	18.62	17.41
	1980-1989				23.07	23.99	21.79
	1990-1999		69.15	63.68	24.02	25.12	22.67
	2000-2009		79.54	108.54	33.31	36.25	35.18
	2010-2019	72.90	88.96	126.48	44.95	44.64	39.71
	2020- Present	53.33	69.33	89.23	35.54	38.24	29.09

Production Statistics		Y04A	Y05	Y06	Y07	Y09	Y10
Groundwater Zone		Basal	Basal	Basal	Basal	Basal	Basal
Well Depth Elevation	Feet	-52.97	-47.40	-47.27	-30.70	-50.57	-54.99
	Meters	-16.15	-14.45	-14.41	-9.36	-15.41	-16.76
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	-40	-40	-40
Well Screen Length (feet)		Unknown	35	Unknown	30	Unknown	Unknown
Well Construction Year		1994	1979	1980	1983	1988	1997
Status/Final Year of Production		GM - 3/4/2022	Operational	Operational	Operational	Operational	Operational
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	200	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989	127.09	150.15	140.85	361.18	421.99	
	1990-1999	141.38	147.22	157.95	339.28	317.92	181.72
	2000-2009	222.99	187.85	237.72	190.77	483.86	238.93
	2010-2019	191.64	207.37	184.07	463.23	473.39	220.04
	2020- Present	192.91	199.90	176.22	486.79	447.23	208.21
Chloride Statistics		Y04A	Y05	Y06	Y07	Y09	Y10
Total Number of Chloride Samples		214	201	188	130	134	92
Minimum Concentration (mg/L)		12.80	16.00	12	14.00	6.70	27.00
Maximum Concentration (mg/L)		74.00	124.00	81	63.50	61.00	89.00
Standard Deviation		10.86	23.97	12.26	9.23	10.16	14.30
Mean Chloride Concentration (mg/L)	1973-1979	20.59	30.89				
	1980-1989	24.80	36.03	21.91	22.45	21.00	
	1990-1999	29.25	46.46	23.60	23.23	21.69	36.38
	2000-2009	38.01	72.29	35.26	32.91	35.26	57.71
	2010-2019	48.01	88.29	42.32	39.55	40.05	64.17
	2020- Present	36.63	78.28	34.09	32.59	30.44	51.03

Production Statistics		Y12	Y14	Y16	Y17	Y18	Y19
Groundwater Zone		Basal	Basal	Basal	Supra-basal	Basal	Basal
Well Depth Elevation	Feet	-40.91	-37.78	-41.06	194.13	-46.37	-41.70
	Meters	-12.47	-11.52	-12.52	59.17	-14.13	-12.71
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	-40	NA	-40	-40
Well Screen Length (feet)		Unknown	Unknown	Unknown	Unknown	40	40
Well Construction Year		1996	1998	2001	2002	2004	2004
Status/Final Year of Production		Operational	Operational	GM - 9/4/2020	Operational	Operational	GM - 5/11/2022
NGLS Max. Recommended Pump Rate (gpm)		200	200	200	NA	200	200
Mean Pump Rate (gpm) (Mgal/month)	1980-1989						
	1990-1999	280.33	250.00				
	2000-2009	317.92	325.49	295.05	316.77	197.64	408.49
	2010-2019	341.65	416.37	332.54	275.34	284.89	565.58
	2020- Present	335.17	437.24	327.37	308.17	298.72	573.43
Chloride Statistics		Y12	Y14	Y16	Y17	Y18	Y19
Total Number of Chloride Samples		98	63	77	79	70	71
Minimum Concentration (mg/L)		33.00	32.00	13.9	22.00	24.00	26.60
Maximum Concentration (mg/L)		115.50	96.00	71.2	80.50	81.00	77.00
Standard Deviation		14.41	16.93	10.97	10.18	12.89	11.32
Mean Chloride Concentration (mg/L)	1973-1979						
	1980-1989						
	1990-1999	55.14	44.00				
	2000-2009	71.58	51.59	46.54	37.13	34.16	44.90
	2010-2019	73.93	73.26	51.17	38.27	51.60	53.63
	2020- Present	56.08	60.63	45.32	27.69	41.54	38.39

Production Statistics		Y20	Y22	Y23	Maui Well
Groundwater Zone		Basal	Basal	Supra-basal	
Well Depth Elevation	Feet	-45.04	-57.31	87.25	
	Meters	-13.73	-17.47	26.59	
NGLS Max. Recommended Bottom Elevation (feet)		-40	-40	NA	
Well Screen Length (feet)		40	Unknown	Unknown	
Well Construction Year		2004	2004	2002	
Status/Final Year of Production		Operational	Operational	Operational	
NGLS Max. Recommended Pump Rate (gpm)		200	200	NA	
Mean Pump Rate (gpm) (Mgal/month)	1980-1989				
	1990-1999				
	2000-2009	482.20	236.49	311.99	
	2010-2019	653.81	295.54	277.66	711.79
	2020- Present	600.53	379.88	309.07	643.63
Chloride Statistics		Y12	Y14	Y16	Maui Well
Total Number of Chloride Samples		59	72	80	22
Minimum Concentration (mg/L)		21.00	18.70	19.4	85
Maximum Concentration (mg/L)		83.50	61.00	69.5	122
Standard Deviation		14.05	8.77	9.27	
Mean Chloride Concentration (mg/L)	1973-1979				
	1980-1989				
	1990-1999				
	2000-2009	36.26	28.56	41.01	
	2010-2019	51.80	35.89	38.57	105.92
	2020- Present	40.98	27.09	32.49	95.58

Decadal mean averages of chloride concentrations show that D08, D09, D13, D17A, D26, F06, F19, F20, H01 and M06 have decadal chloride benchmarks that pass the MCL and D08, D13, F06, F19, and F20 also surpass the USEPA Guideline. However, from graphing the chloride concentrations in bar graphs as shown in Appendix C, we can see that more wells have passed the chloride concentration benchmarks although not listed in the decadal averages. Of all the wells analyzed in this basin, twenty-eight wells have passed the local MCL at least once, and of those twenty-eight, thirteen have passed the USEPA National Secondary Drinking Water Regulation Guideline. For many of the wells that have surpassed the guidelines, there were few readings that may be considered outliers, but were still taken into consideration. The twenty-eight wells that passed the local MCL guideline are D01, D06, D07, D08, D09, D10, D11, D12, D13, D15, D16, D17A, D18B, D21, D26, F05, F06, F07, F09, F19, F20, G501, H01, M06, M12, M15, M20A and M21. Of these wells, the thirteen that have passed the USEPA Guideline are D01, D08, D09, D13, D17A, D26, F05, F06, F19, F20 H01, M06, and M12.

Through temporal analysis of the changes in chloride concentration, forty seven of the sixty-three wells (74.6%) demonstrate a significant increasing trend, seven (11.1%) demonstrate a non-significant increasing trend, six (9.5%) demonstrate a non-significant decreasing trend, and three (4.76%) demonstrate a 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 their 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 D02, D09, D13, D15, D16, D18B, D19, D20, D21, EX05, F05, F06, F07, F09, H01, M05, M06, M15, M17B, and Y05.

Through spatial analysis of the changes over time from the visualization in ArcGIS, wells can be grouped by how they follow similar patterns. There are three wells, F19, F20, and F06, along Route 3 that follow similar chloride concentration trends. Towards the center of the island, the groundwater quality rarely surpasses the “standard” groundwater quality and is usually categorized as “good.”

In terms of production, some wells had the ability to surpass their NGLS recommended production rates while maintaining a “good” to “standard” chloride concentration. Notable wells that have at least “standard” chloride concentration and surpass the recommended pump rate are D02, D03A, D04, D05, D14, D19, D20, D25, D27, D28, EX05, M07, M14, M18, Y01, Y02, Y03, Y04A, Y05, Y06, Y07, Y09, Y10, Y12, Y14, Y16, Y18, Y19, Y20, and Y22. There are a few wells that can fit in this category include D01, D06, D07, D10, D11, D15, D16, D18B, and D21 however they have a few anomalies of abnormally high readings of chloride concentrations that do pass the Local MCL. A few wells that have had high chloride concentrations (passed the USEPA Guideline) and did not meet their pump rate include D13, D26, and M20A. Regarding M20A, it passed the local MCL once but has never hit the 500 gpm max recommended pump rate. The last important category are low chloride concentrations that did not meet their recommended pump rate and they include wells M05, M17A, and M17B. Well D12 also falls under this category but this well has an abnormally high production once of 7,835 gpm on 5/1/2014.

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. Thirty-three wells (52.4%) showed a significant increasing relationship, nineteen wells (30.2%) showed a not significant increasing relationship, ten wells (15.9%) showed a not significant decreasing relationship, and one well (1.6%) showed a significant decreasing relationship.

#### **4. DISCUSSION**

In comparison to the previous study done by Simard only sixty-three wells of seventy-nine well were investigated in this study. In comparison to the percentage of production wells showing a significant increasing trend of chloride concentrations in the Yigo-Tumon basin, the percentage remains unchanged. This study saw the percentage to be forty-seven out of sixty-three (74.6%) and Simard’s study saw the percentage to be fifty-nine out of seventy-nine (74.7%). In Simard’s study, thirteen production wells showed no significant increasing trend (16.5%) which has gone down in this study to (11.1%). The percentage of wells demonstrating decreasing trends increased from the percentage of no significant decreasing trend being 7.6% increasing to 9.5% and the percentage of significant decreasing trends being 1.27% to 4.76%.

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 possibly 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**

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## APPENDICES

### 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
D01	$y = 0.0025x - 15.912$	0.0799	0.282666	0.121	261	259	Significant	Increase
D02	$y = 0.0015x + 14.316$	0.3803	0.616685	0.122	258	256	Significant	Increase
D03A	$y = 0.0006x + 19.001$	0.0864	0.293939	0.144	185	183	Significant	Increase
D04	$y = 0.0014x - 1.2028$	0.4643	0.681396	0.122	259	257	Significant	Increase
D05	$y = 0.0011x + 28.889$	0.1913	0.437379	0.129	232	230	Significant	Increase
D06	$y = 0.0015x + 6.8608$	0.3062	0.553353	0.121	261	259	Significant	Increase
D07	$y = 0.0022x - 10.828$	0.3375	0.580948	0.12	266	264	Significant	Increase
D08	$y = 0.0073x - 50.86$	0.276	0.525357	0.121	263	261	Significant	Increase
D09	$y = 0.0054x - 34.024$	0.5057	0.711126	0.122	257	255	Significant	Increase
D10	$y = 0.0023x - 27.515$	0.3391	0.582323	0.124	250	248	Significant	Increase
D11	$y = 0.0007x + 60.467$	0.034	0.184391	0.122	260	258	Significant	Increase
D12	$y = 0.0017x - 29.261$	0.3293	0.573847	0.121	263	261	Significant	Increase
D13	$y = 0.0204x - 338.41$	0.192	0.438178	0.139	200	198	Significant	Increase
D14	$y = 0.0036x - 66.525$	0.6251	0.790633	0.122	260	258	Significant	Increase
D15	$y = 0.0008x + 63.334$	0.0363	0.190526	0.127	239	237	Significant	Increase
D16	$y = 0.0015x + 34.15$	0.1399	0.374032	0.142	192	190	Significant	Increase
D17A	$y = 0.0036x - 20.696$	0.0522	0.228473	0.168	136	134	Significant	Increase
D18B	$y = 0.0024x - 1.7767$	0.2563	0.506261	0.185	113	111	Significant	Increase
D19	$y = 0.0016x + 12.341$	0.1742	0.417373	0.161	148	146	Significant	Increase
D20	$y = 0.003x - 36.425$	0.4554	0.674833	0.161	149	147	Significant	Increase
D21	$y = 0.0012x + 35.409$	0.0974	0.31209	0.162	147	145	Significant	Increase
D25	$y = 0.0033x - 78.325$	0.2087	0.456837	0.23	73	71	Significant	Increase
D26	$y = -0.0079x + 561.72$	0.0394	0.198494	0.239	68	66	Not Significant	Decrease
D27	$y = 0.0017x - 35.03$	0.057	0.238747	0.232	72	70	Significant	Increase
D28	$y = 0.0009x + 31.092$	0.0167	0.129228	0.237	69	67	Not Significant	Increase
EX05	$y = 0.002x - 24.368$	0.3444	0.586856	0.162	147	145	Significant	Increase
F05	$y = 0.0049x - 81.194$	0.3958	0.629126	0.127	237	235	Significant	Increase
F06	$y = 0.0179x - 377.32$	0.4711	0.686367	0.132	220	218	Significant	Increase
F07	$y = 0.0053x - 94.927$	0.5372	0.732939	0.127	238	236	Significant	Increase
F09	$y = 0.0015x + 19.781$	0.1003	0.316702	0.139	198	196	Significant	Increase
F19	$y = 0.0037x + 150.46$	0.0049	0.07	0.24	67	65	Not Significant	Increase
F20	$y = 0.0041x + 131.56$	0.0061	0.078102	0.246	64	62	Not Significant	Increase
G501	$y = -0.0305x + 1429.7$	0.7114	0.843445	0.291	46	44	Significant	Decrease
H01	$y = 0.0078x - 136.51$	0.6887	0.82988	0.13	228	226	Significant	Increase

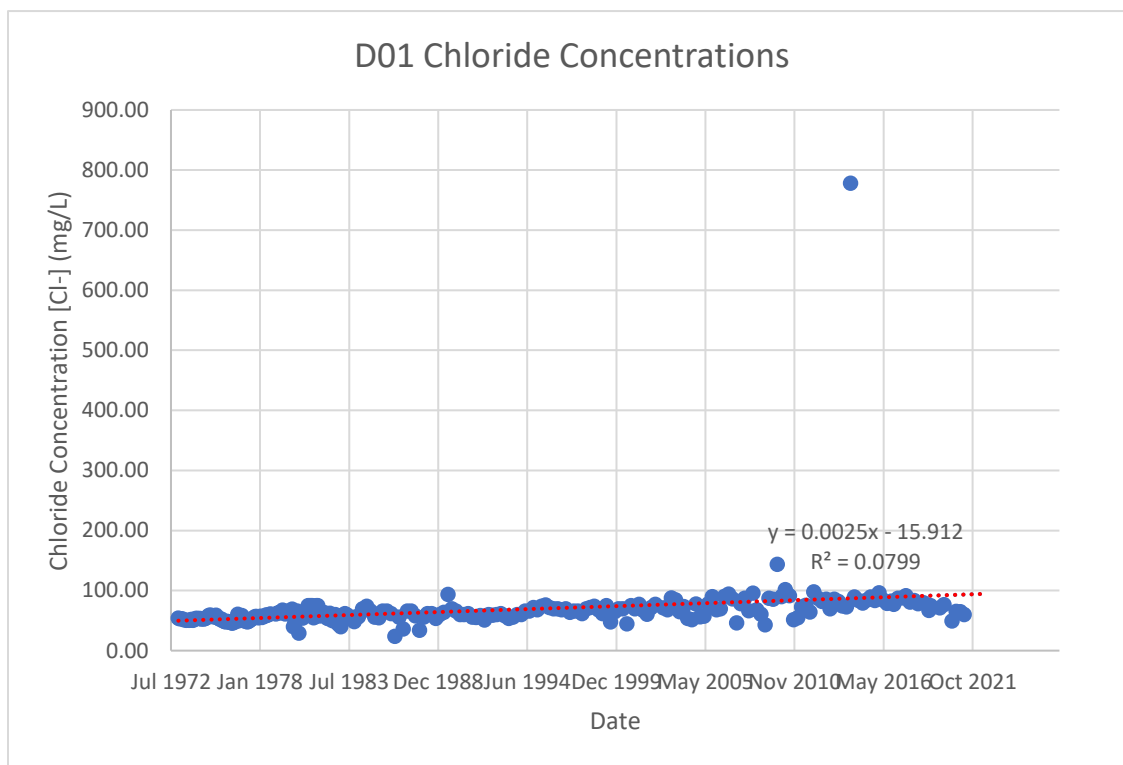


M05	$y = 0.0021x - 18.098$	0.4952	0.703704	0.124	250	248	Significant	Increase
M06	$y = 0.0061x - 115.57$	0.3267	0.571577	0.125	246	244	Significant	Increase
M07	$y = 0.0017x - 13.13$	0.4823	0.694478	0.126	243	241	Significant	Increase
M12	$y = 0.0014x + 51.519$	0.0398	0.199499	0.174	128	126	Significant	Increase
M14	$y = 0.0019x - 17.226$	0.1146	0.338526	0.147	179	177	Significant	Increase
M15	$y = 0.0031x - 51.795$	0.1721	0.414849	0.156	158	156	Significant	Increase
M17A	$y = 0.0006x + 53.669$	0.0142	0.119164	0.261	57	55	Not Significant	Increase
M17B	$y = 0.0009x + 31.106$	0.0492	0.221811	0.176	124	122	Significant	Increase
M18	$y = -0.0096x + 478.66$	0.589	0.767463	0.291	46	44	Significant	Decrease
M20A	$y = -0.0002x + 89.291$	0.0007	0.026458	0.196	101	99	Not Significant	Decrease
M21	$y = -0.0003x + 122.91$	0.0003	0.017321	0.208	89	87	Not Significant	Decrease
Y01	$y = 0.0015x - 22.688$	0.5083	0.712952	0.122	257	255	Significant	Increase
Y02	$y = 0.0016x - 25.007$	0.4896	0.699714	0.121	263	261	Significant	Increase
Y03	$y = 0.0013x - 18.857$	0.349	0.590762	0.122	257	255	Significant	Increase
Y04A	$y = 0.0017x - 27.339$	0.6026	0.776273	0.134	214	212	Significant	Increase
Y05	$y = 0.0041x - 89.387$	0.7121	0.84386	0.138	201	199	Significant	Increase
Y06	$y = 0.0015x - 24.338$	0.368	0.60663	0.143	188	186	Significant	Increase
Y07	$y = 0.0014x - 22.061$	0.4381	0.661891	0.172	130	128	Significant	Increase
Y09	$y = 0.0017x - 34.318$	0.3657	0.604731	0.17	134	132	Significant	Increase
Y10	$y = 0.0014x - 0.5011$	0.0757	0.275136	0.205	92	90	Significant	Increase
Y12	$y = 0.0006x + 44.056$	0.0135	0.11619	0.199	98	96	Not Significant	Increase
Y14	$y = 0.0026x - 44.027$	0.134	0.36606	0.248	63	61	Significant	Increase
Y16	$y = 0.0002x + 41.824$	0.0001	0.01	0.224	77	75	Not Significant	Increase
Y17	$y = -0.001x + 75.602$	0.0341	0.184662	0.221	79	77	Not Significant	Decrease
Y18	$y = 0.0023x - 48.67$	0.12	0.34641	0.235	70	68	Significant	Increase
Y19	$y = -0.0003x + 61.346$	0.0025	0.05	0.234	71	69	Not Significant	Decrease
Y20	$y = 0.0016x - 17.868$	0.0459	0.214243	0.256	59	57	Not Significant	Increase
Y22	$y = 0.0002x + 22.41$	0.0027	0.051962	0.232	72	70	Not Significant	Increase
Y23	$y = -0.0016x + 103.74$	0.1105	0.332415	0.22	80	78	Significant	Decrease
Maui Well*	$y = -0.0097x + 526.64$	0.3207	0.566304	0.423	22	20	Significant	Decrease

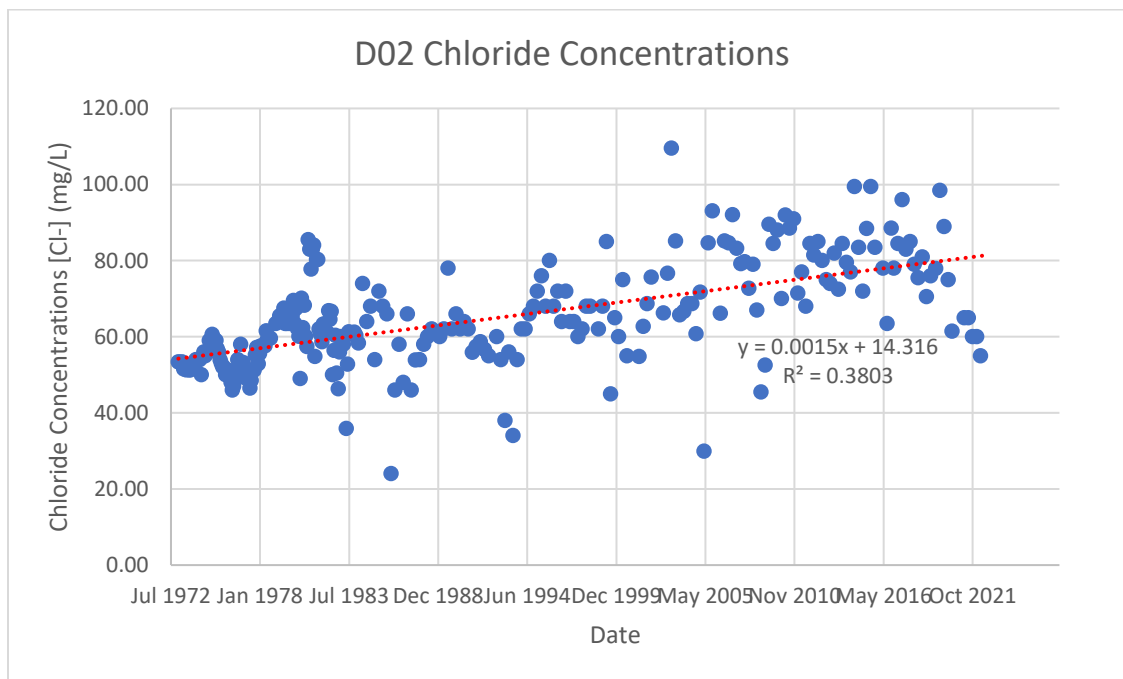
\*Maui Well was not included in the overall analysis of the basin but was still analyzed.

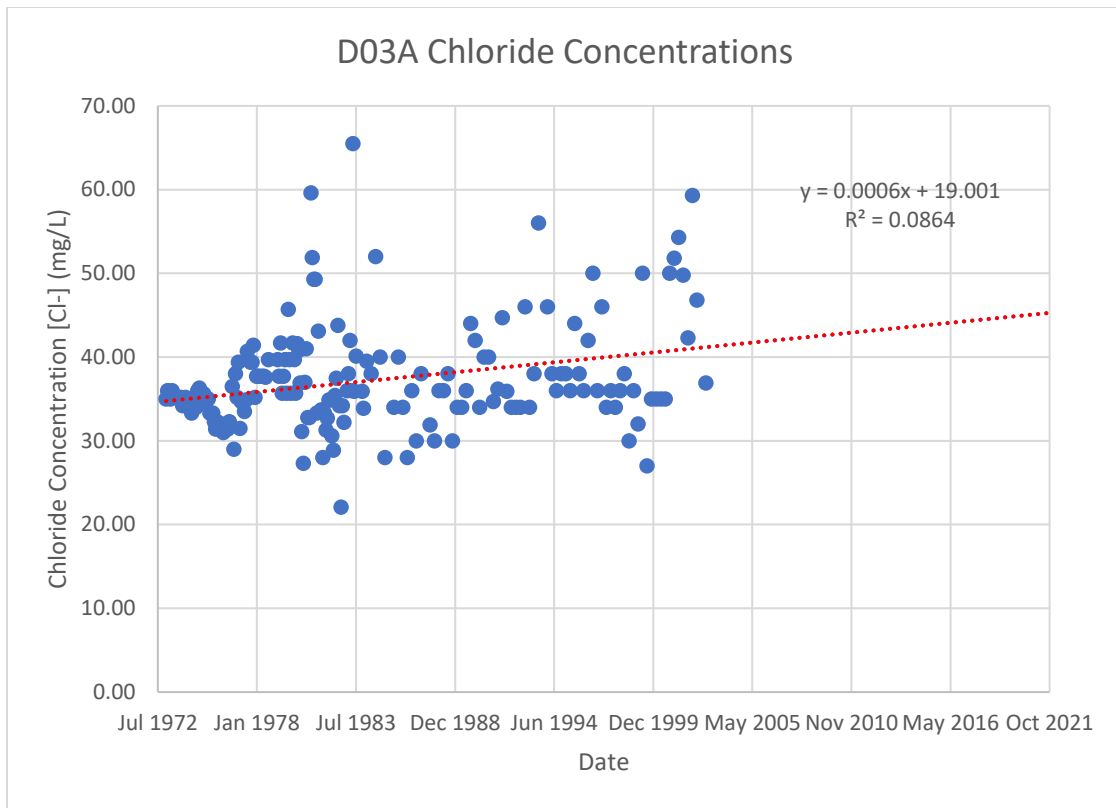
## Appendix B: Scatter Plots for Individual Wells' Chloride Concentrations Over Time

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).

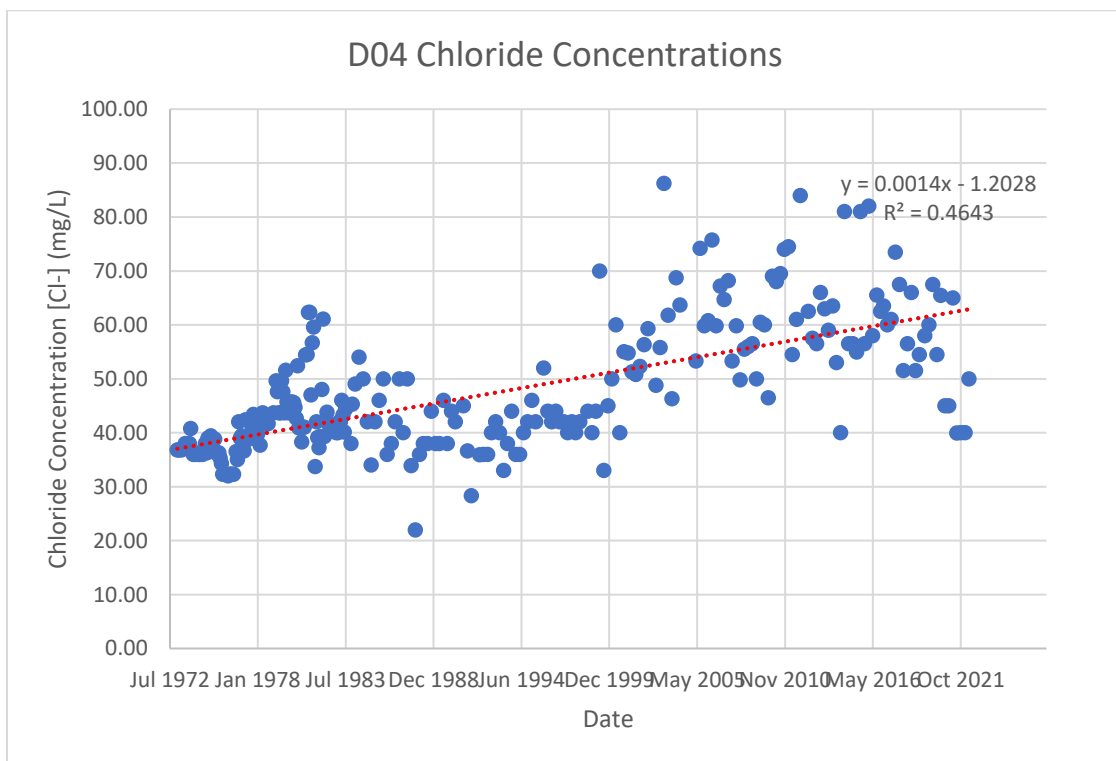


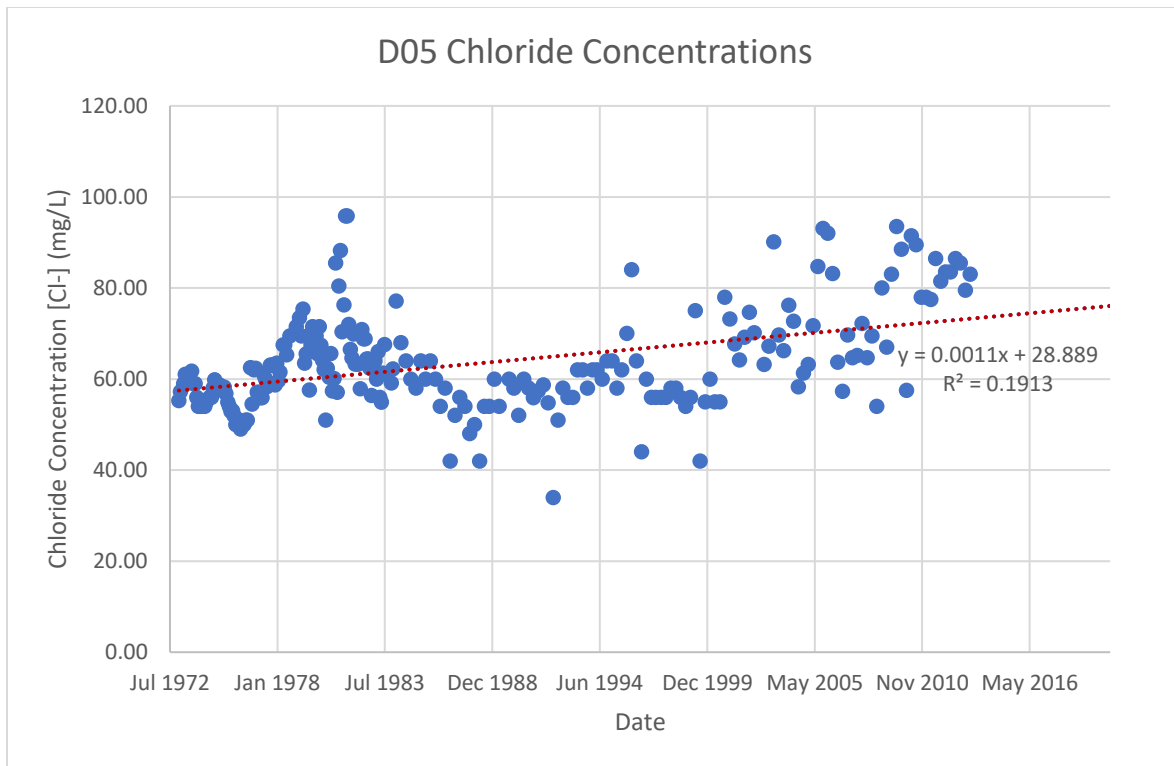
As of 5/23/2021, D01 is currently not online due to a Grounded Motor.



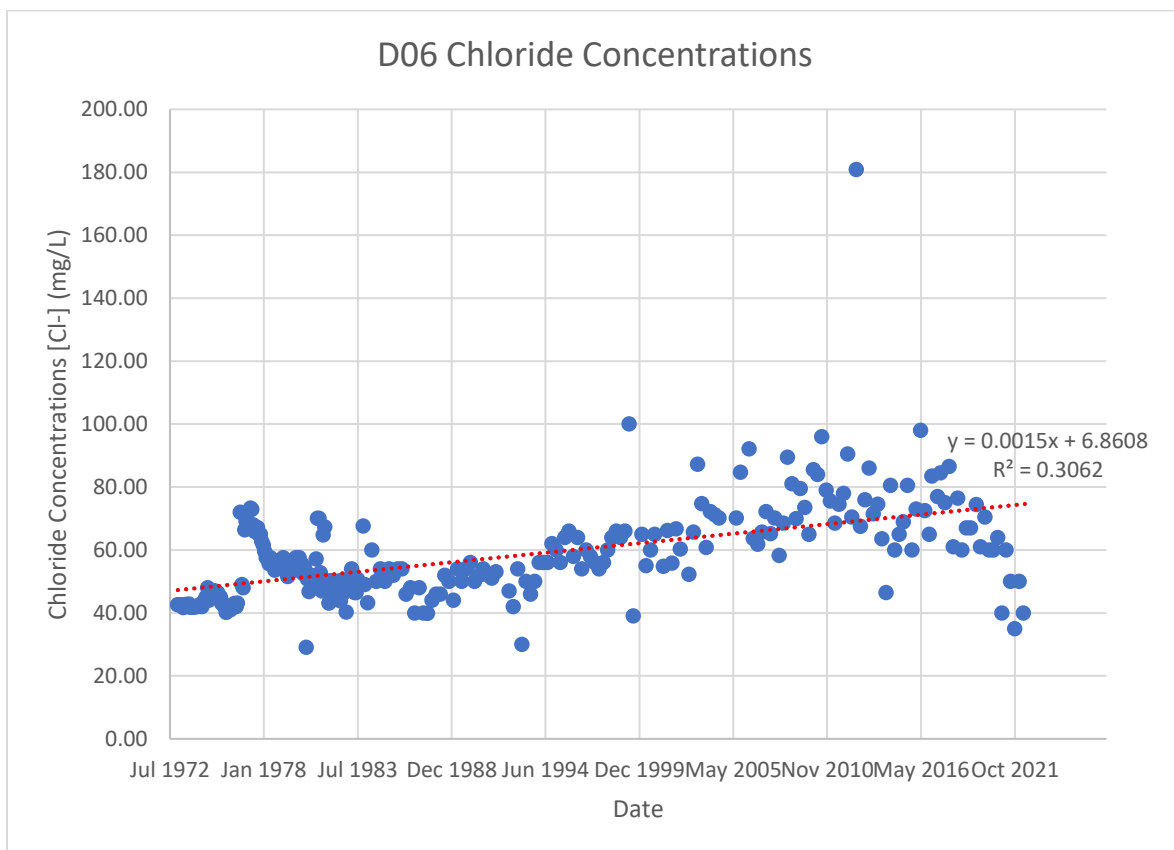


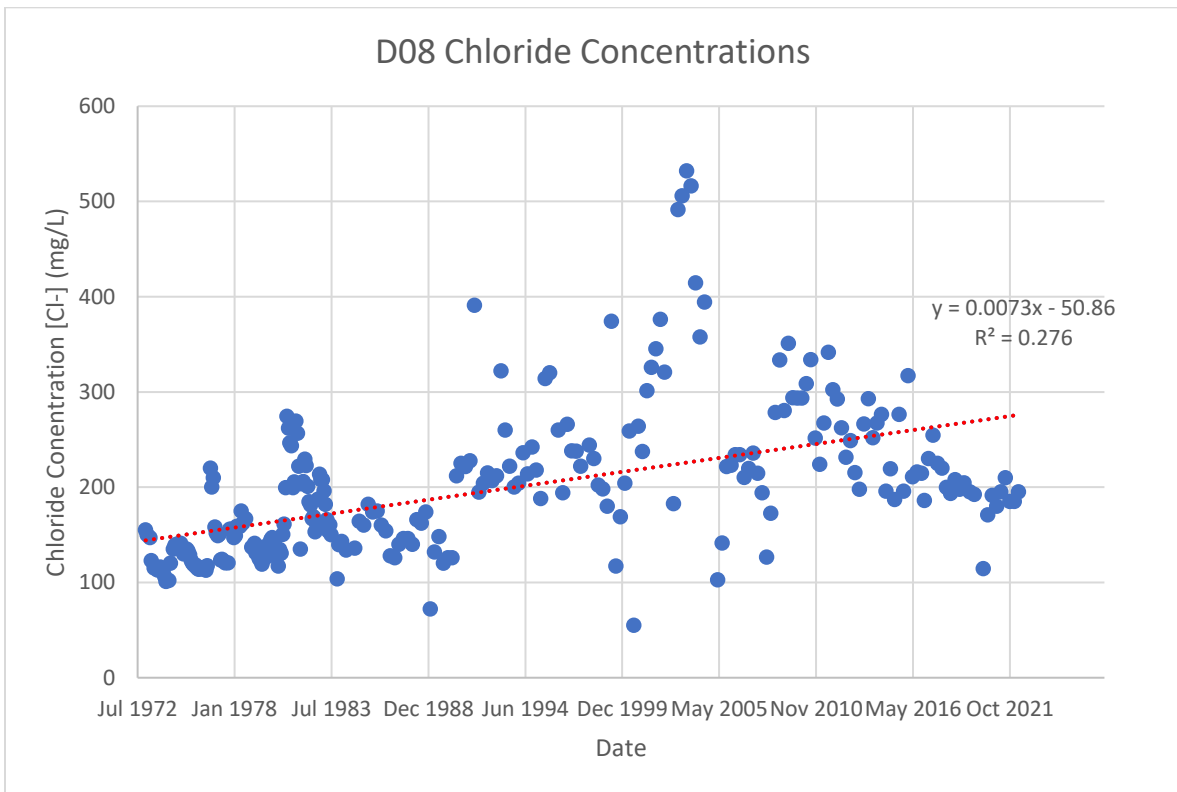
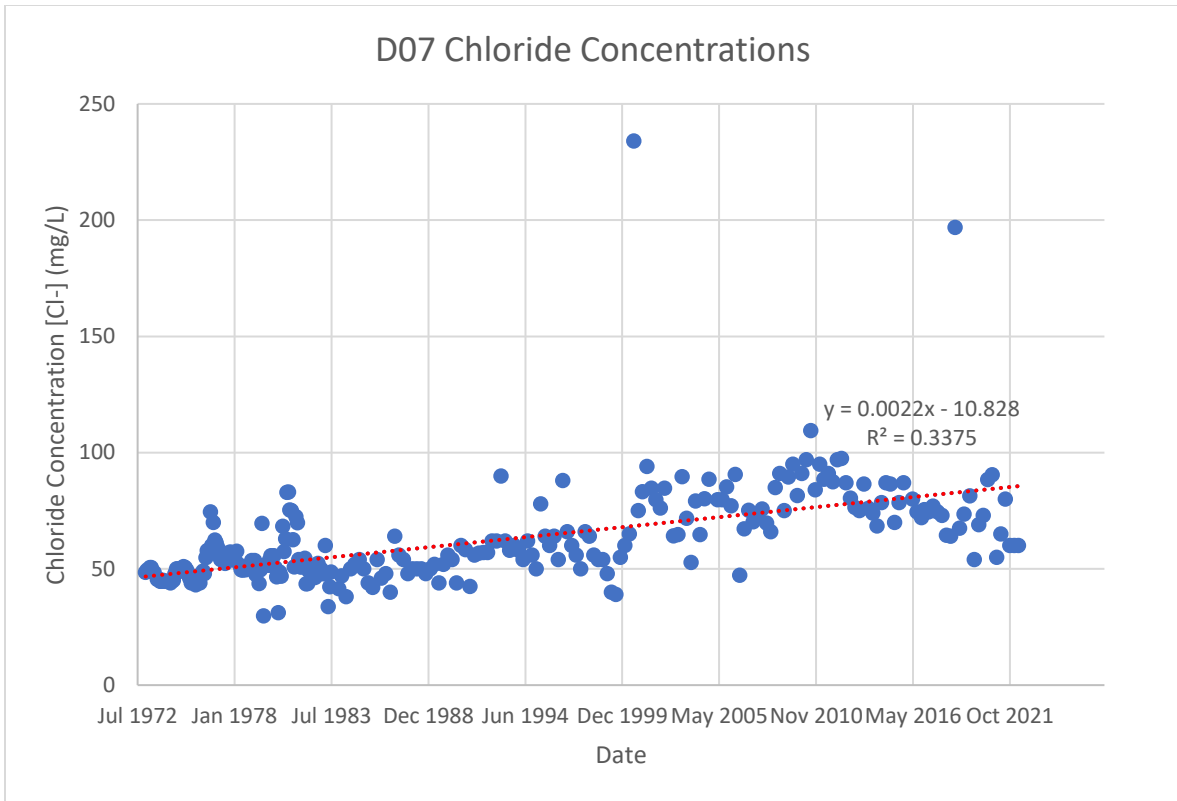
The lack of chloride concentration readings towards the later part is due to D03A breaking in January 2004 and then being taken offline due to a Grounded Motor on 7/26/2019.

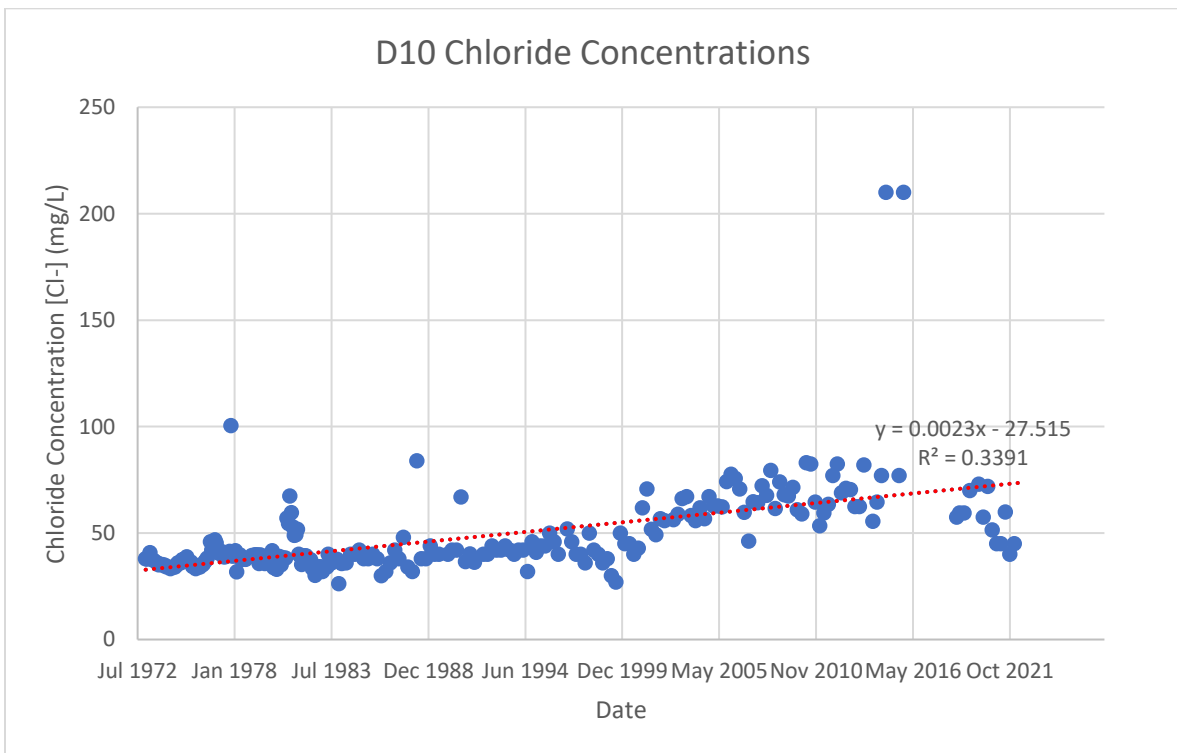
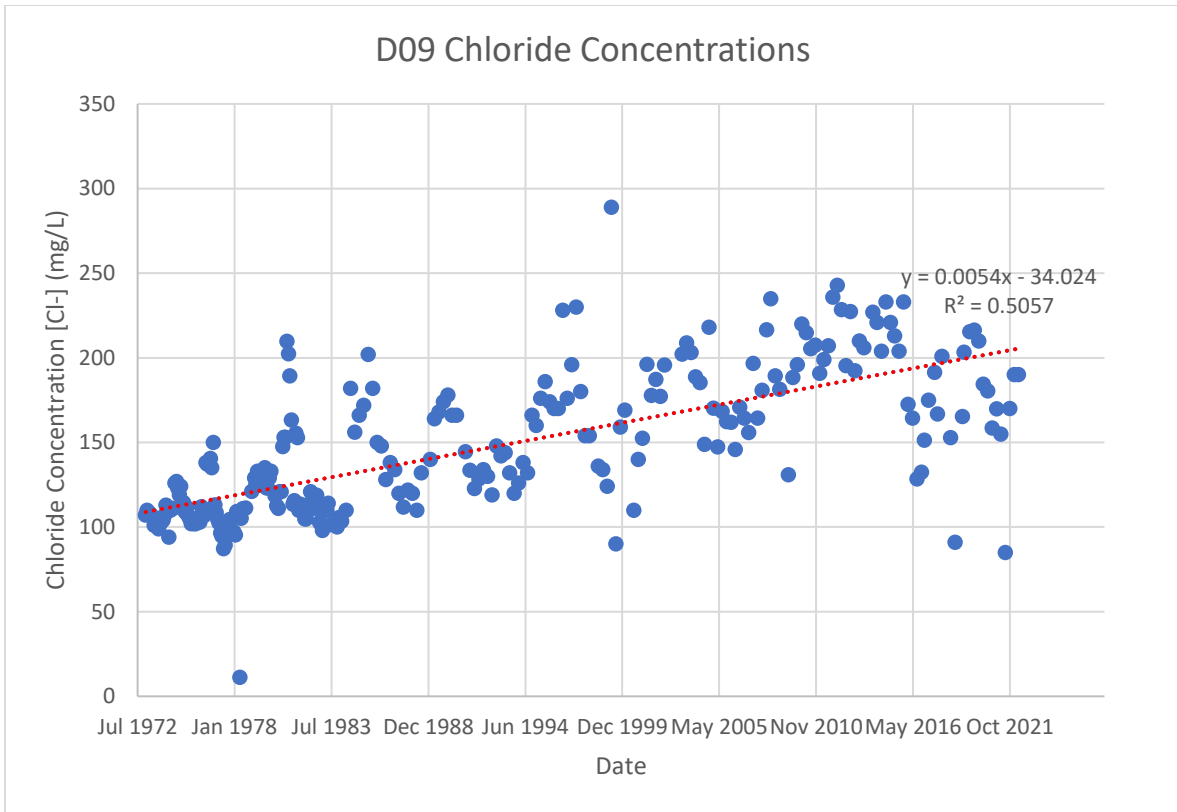


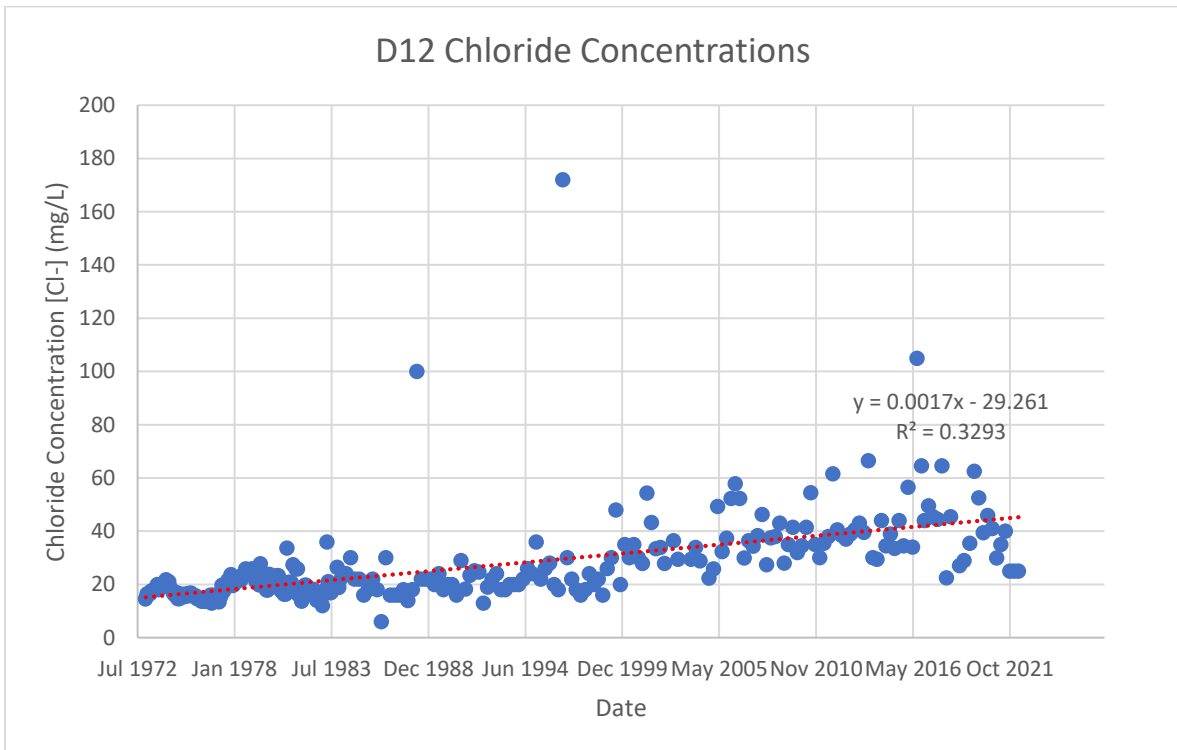
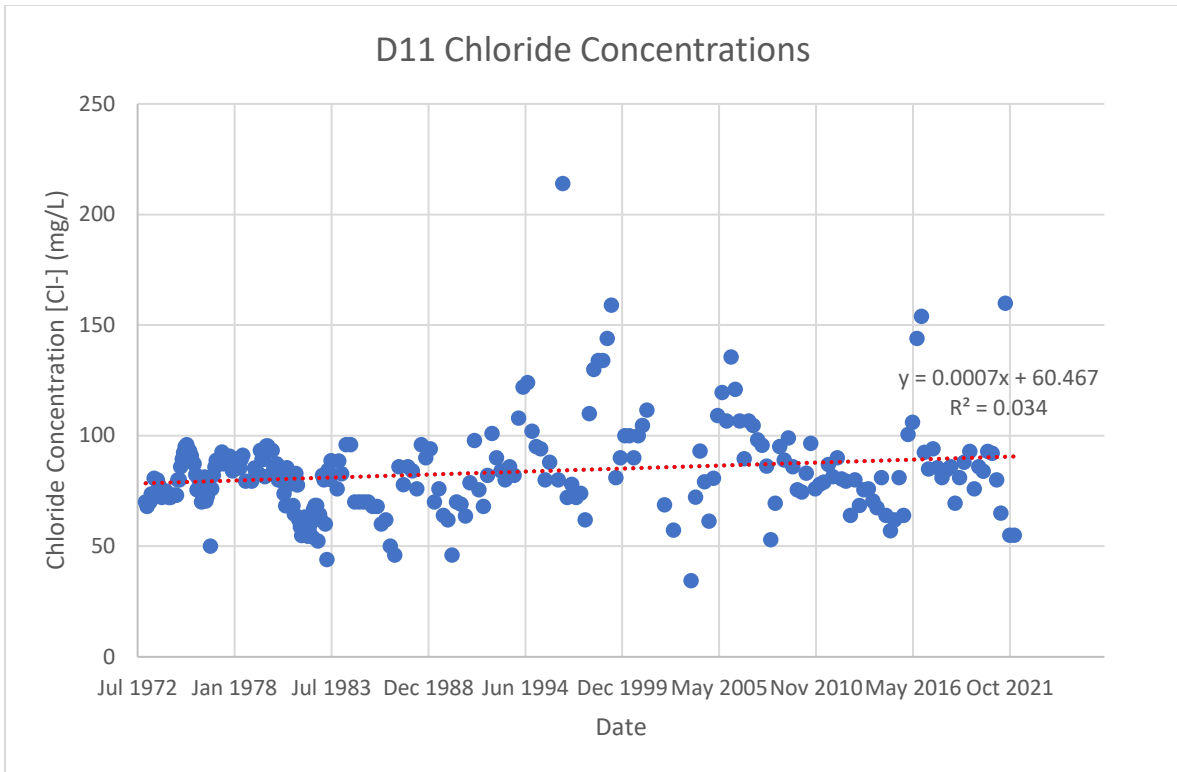


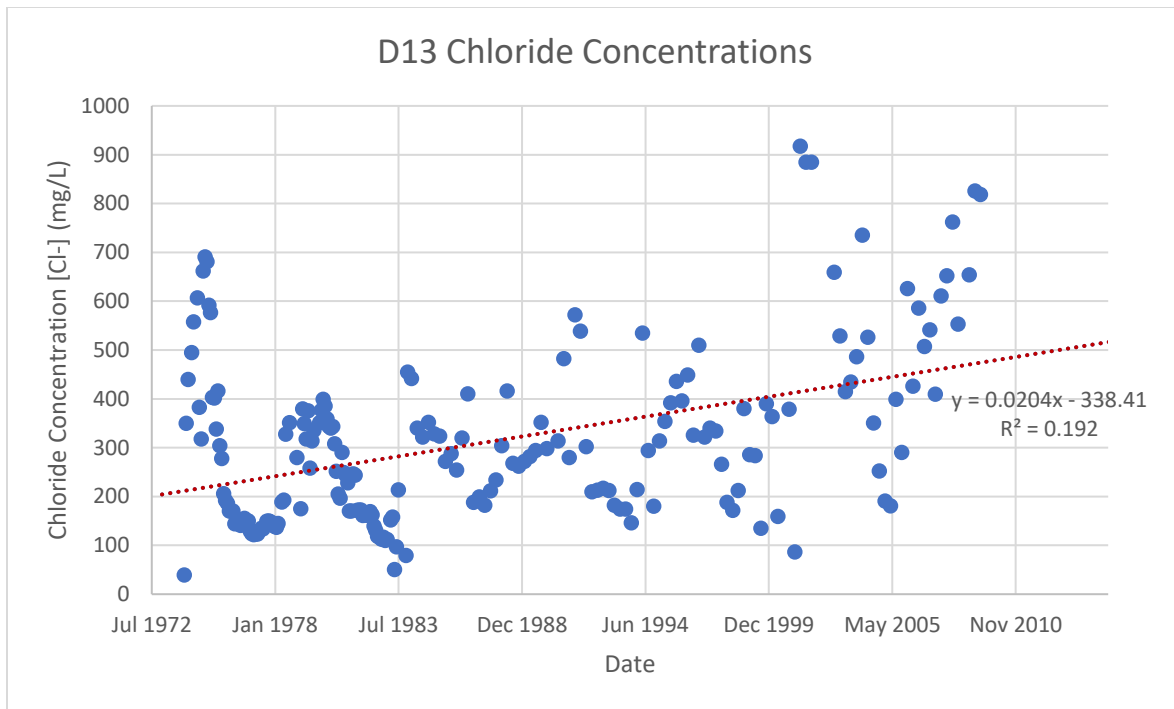
D05 was taken out of commission on 9/28/2016 due to a Grounded Motor on 7/8/2013.



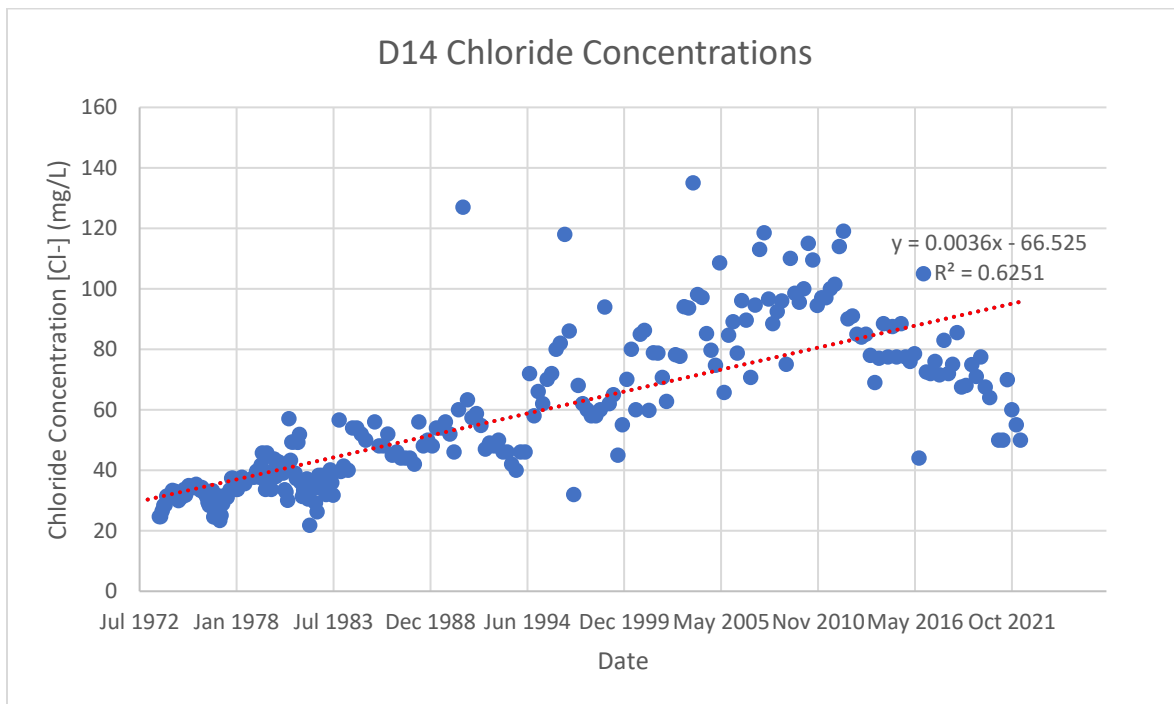




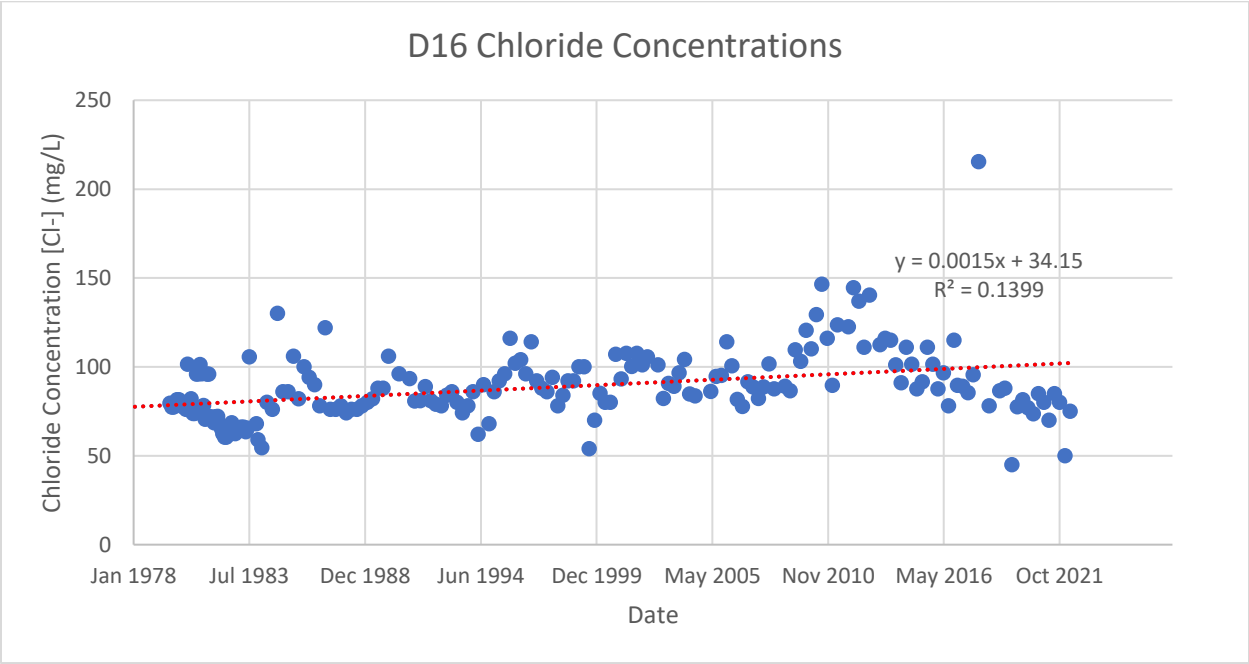
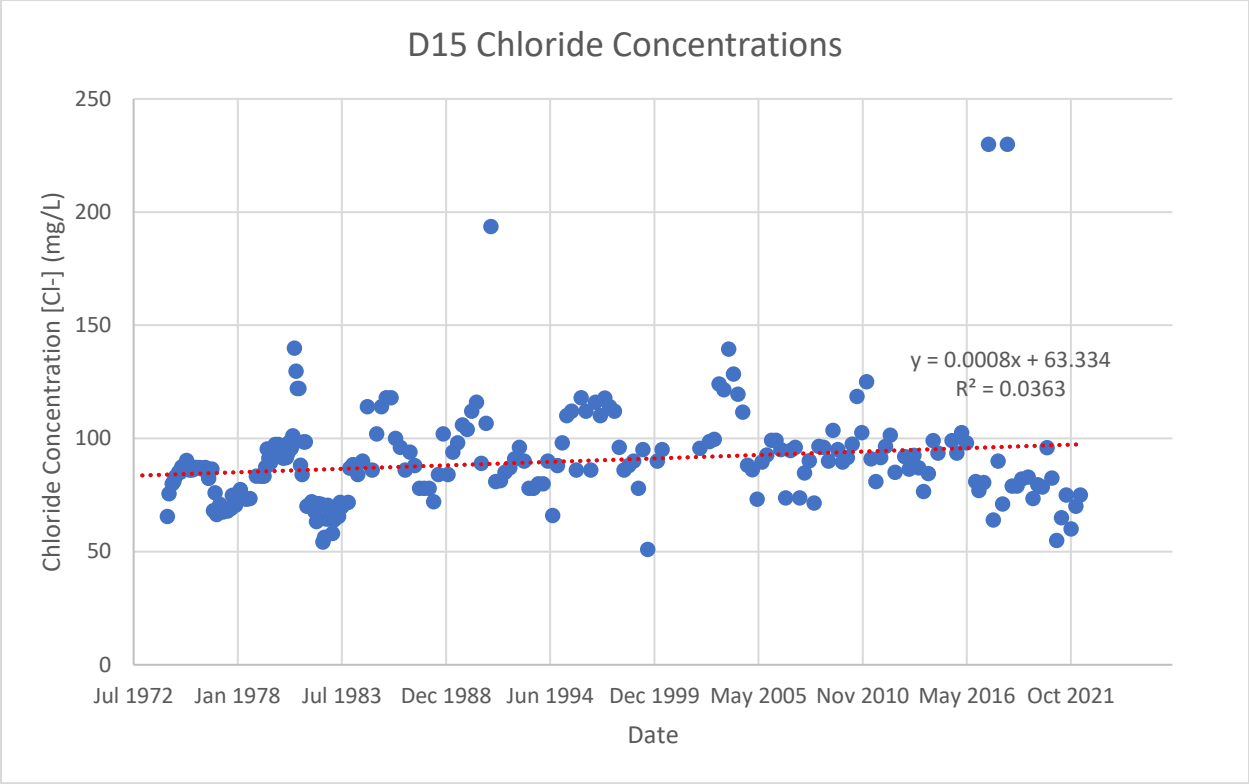


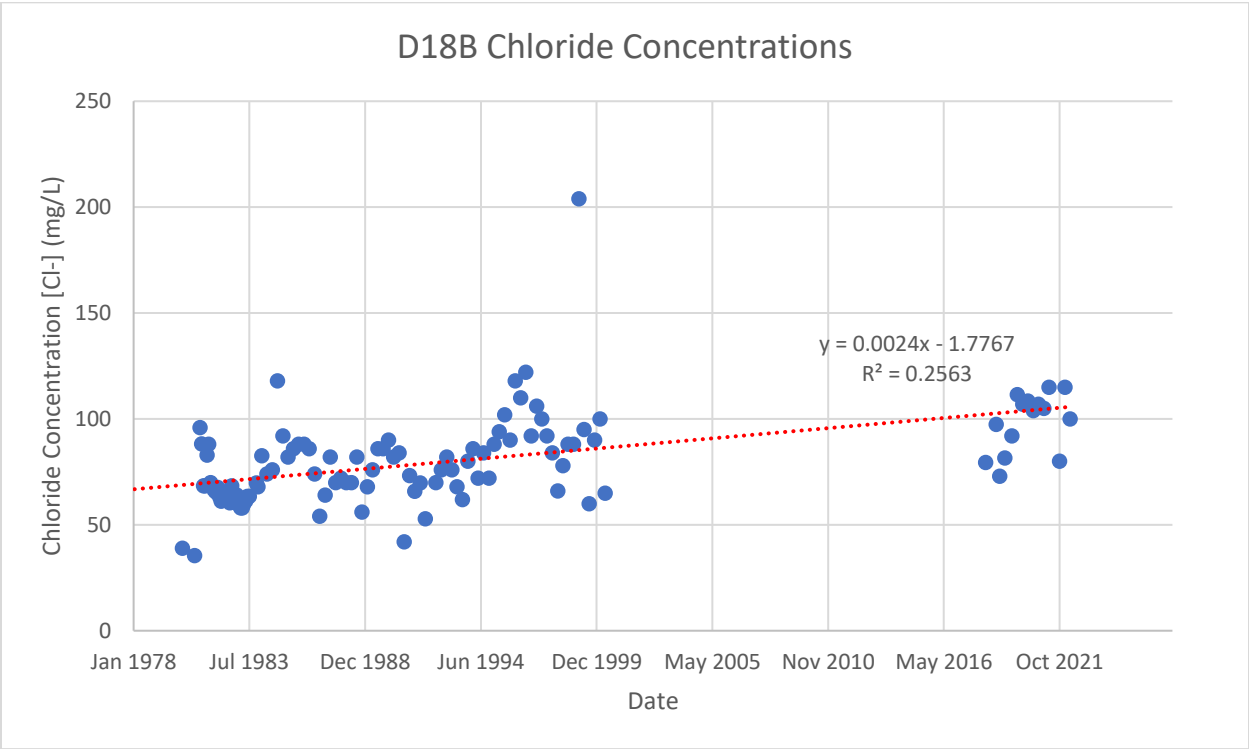
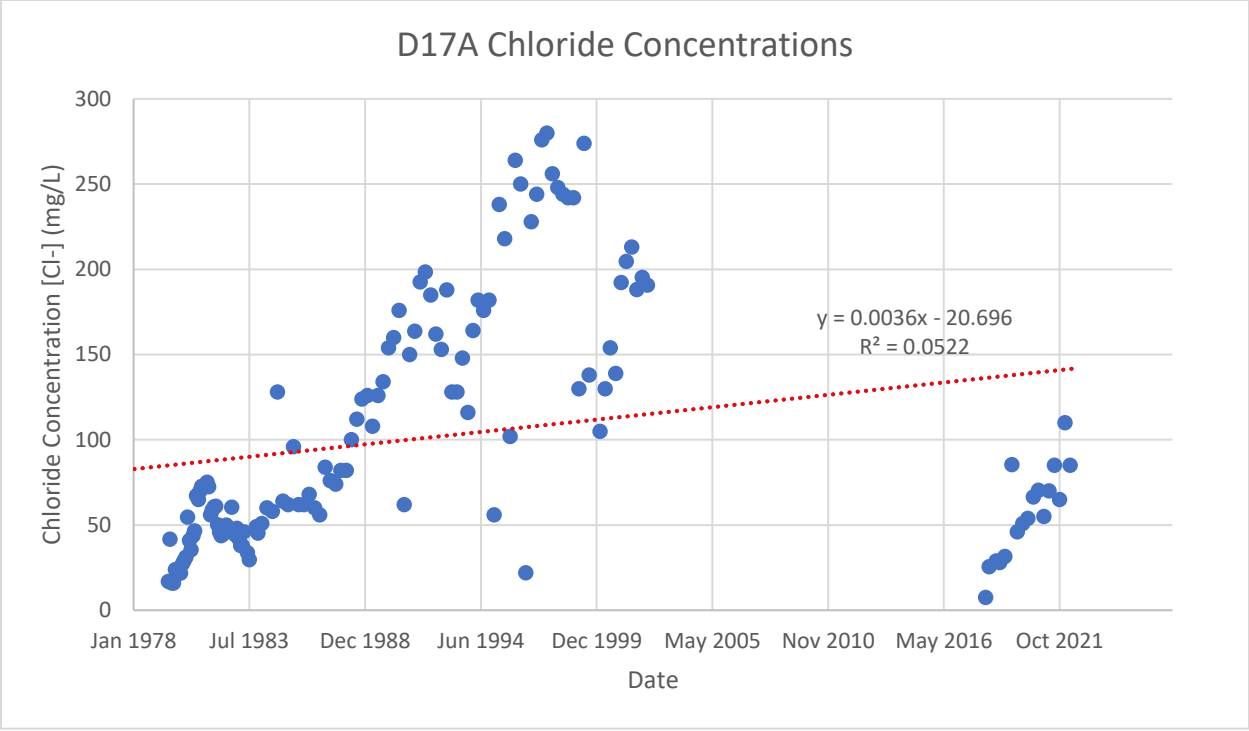


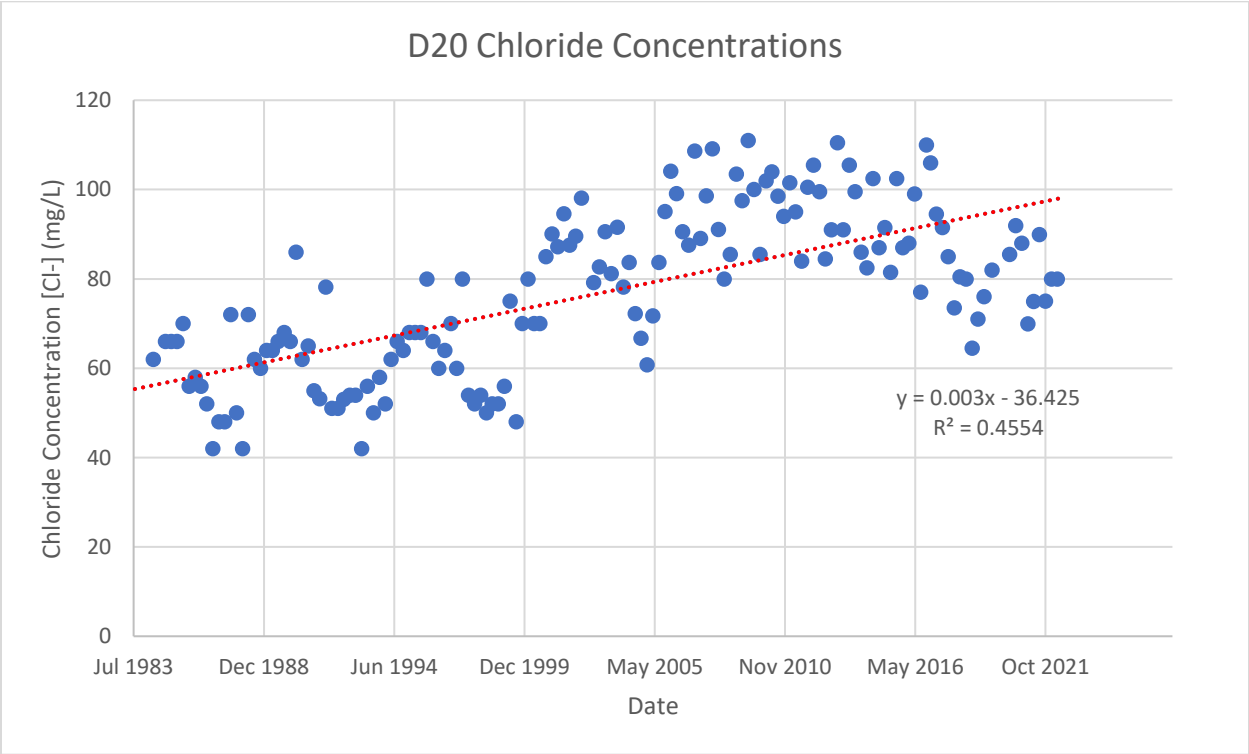
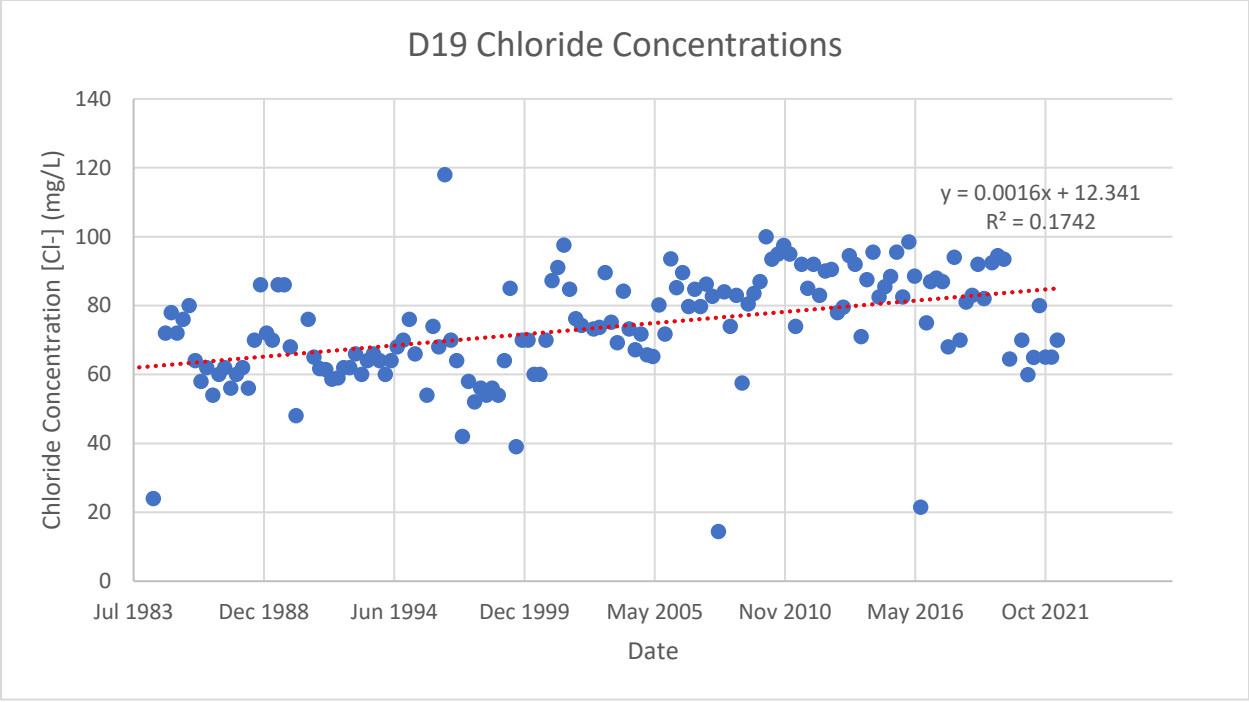
D13 was taken out of commission in May 2009 due to high chloride concentration levels.

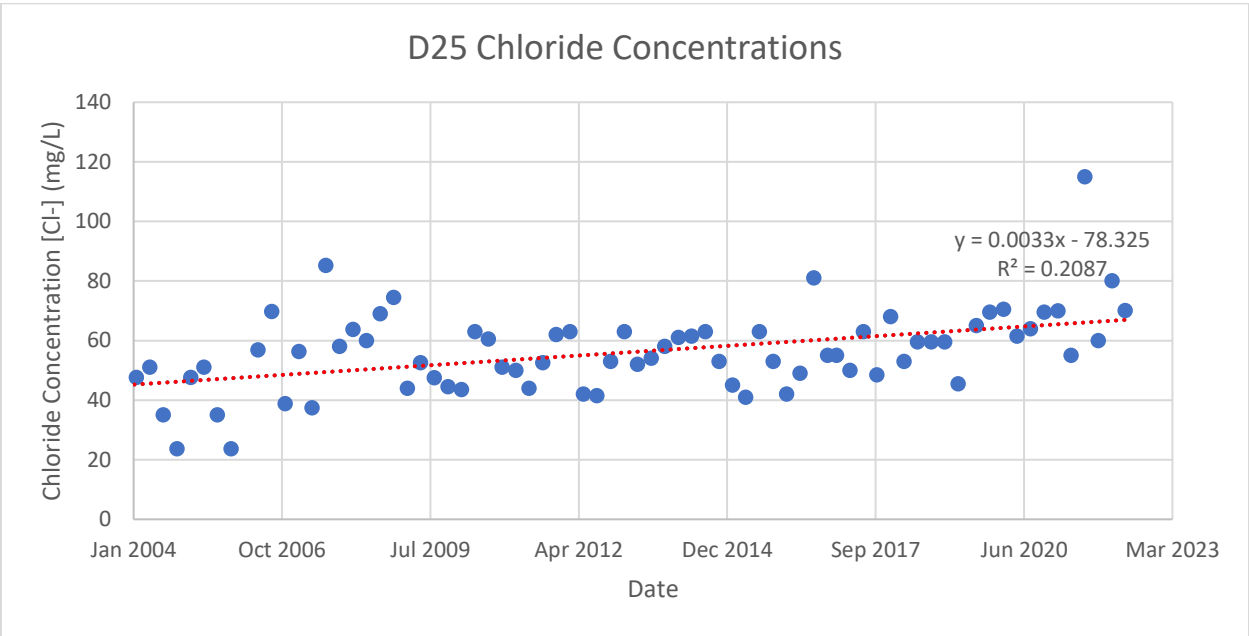
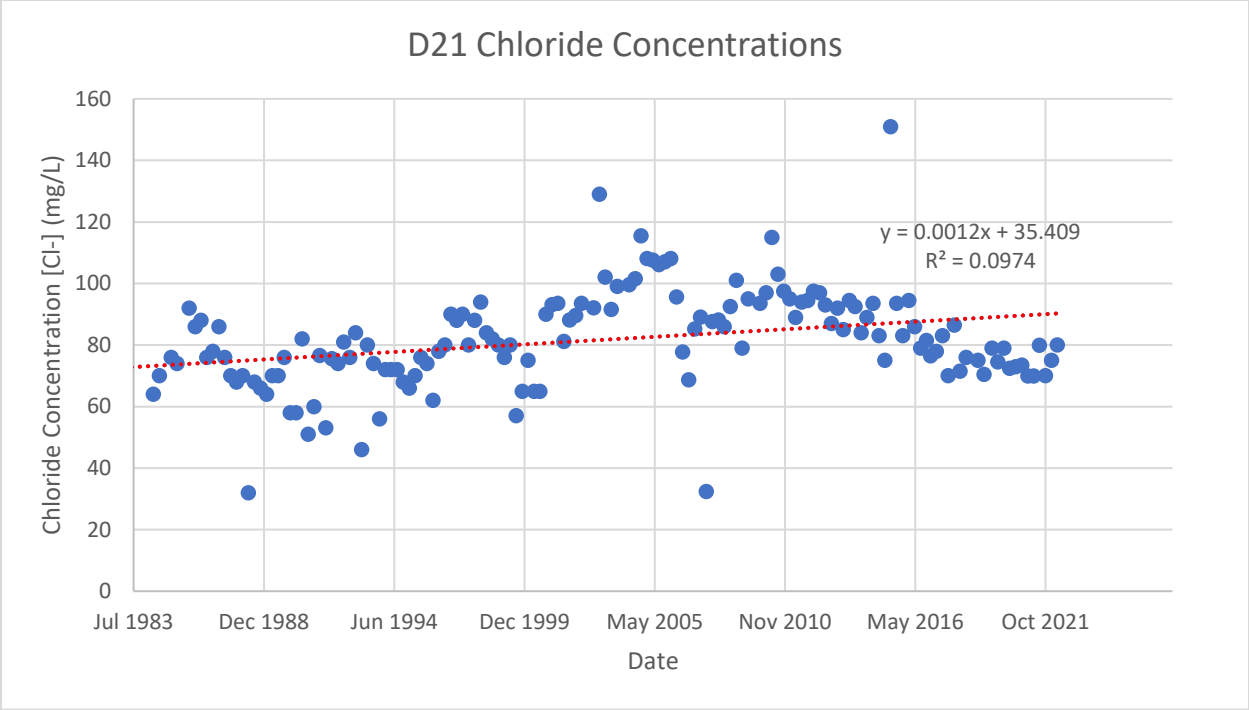


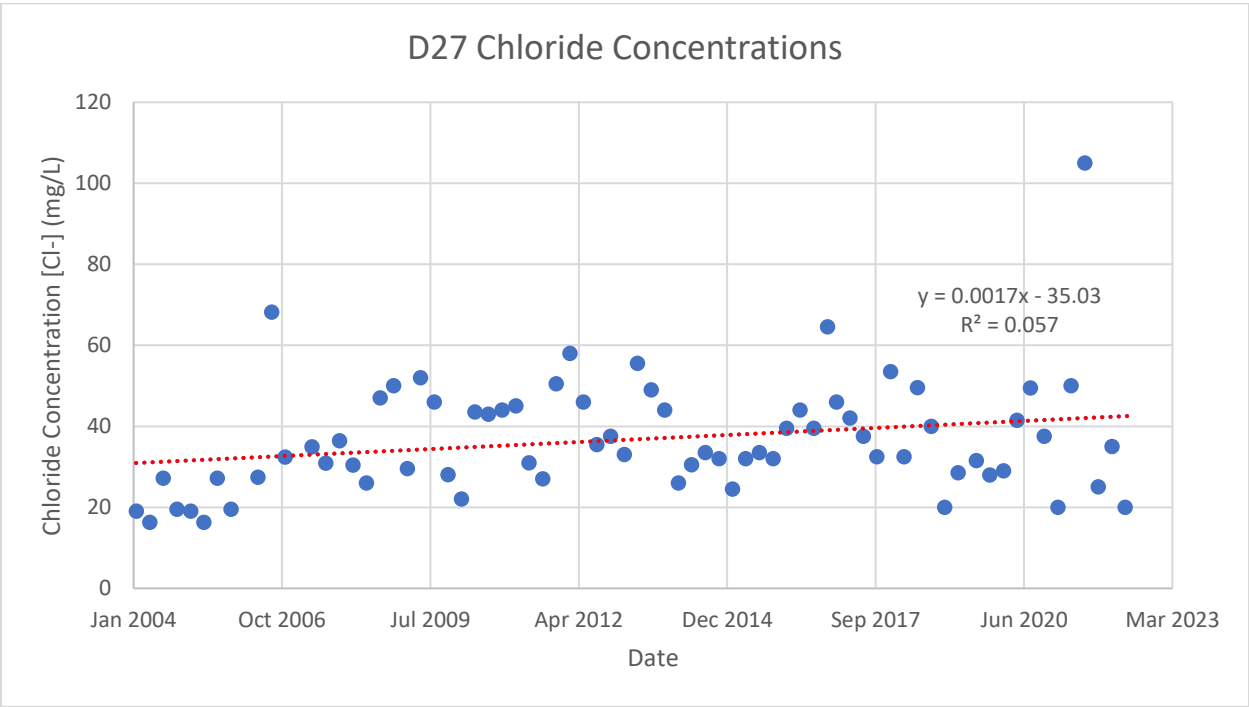
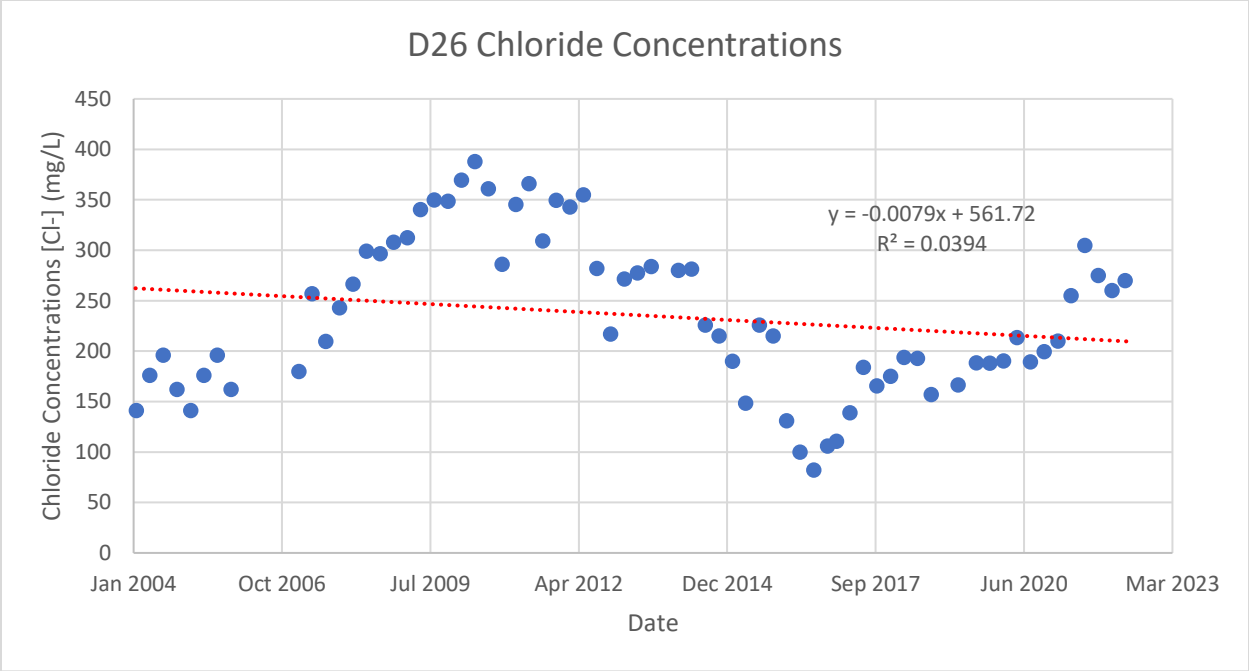


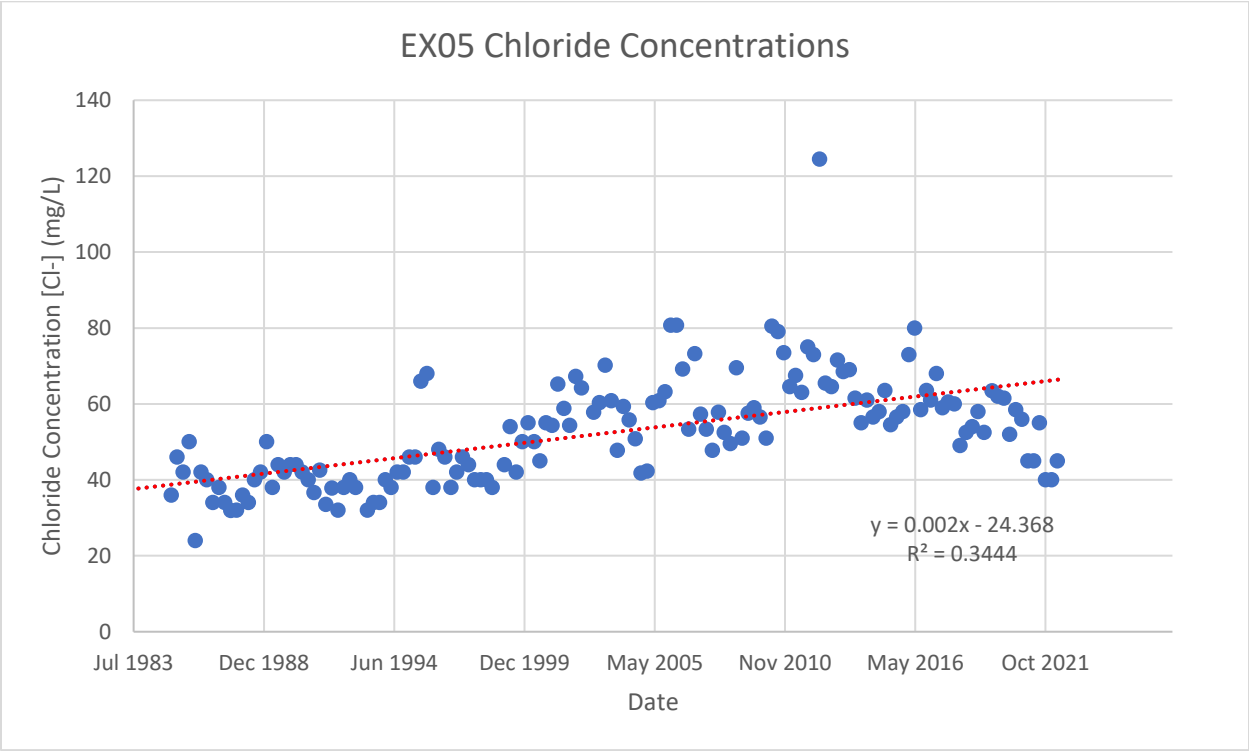
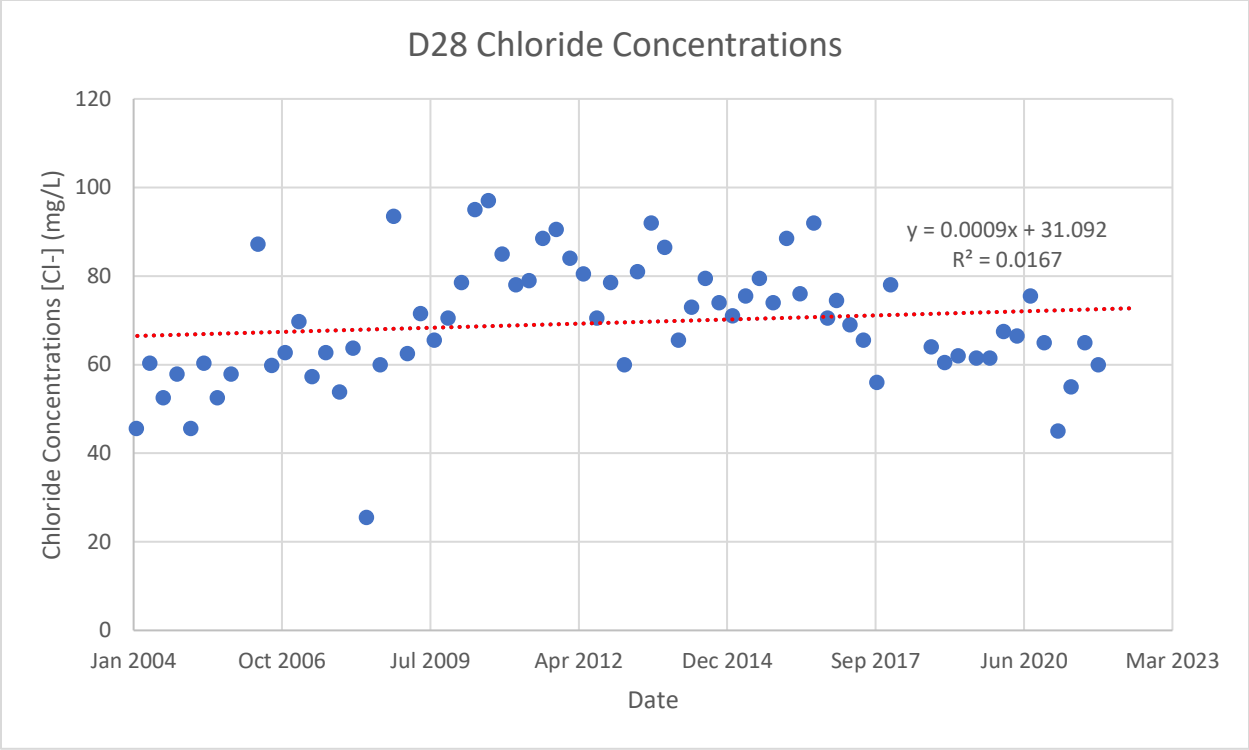




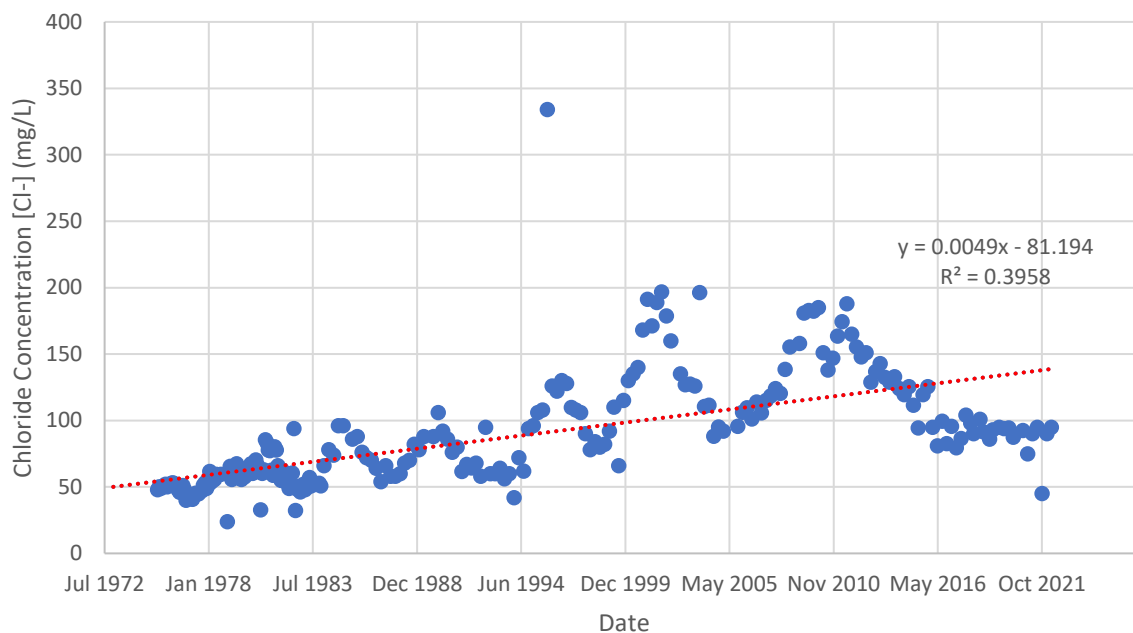




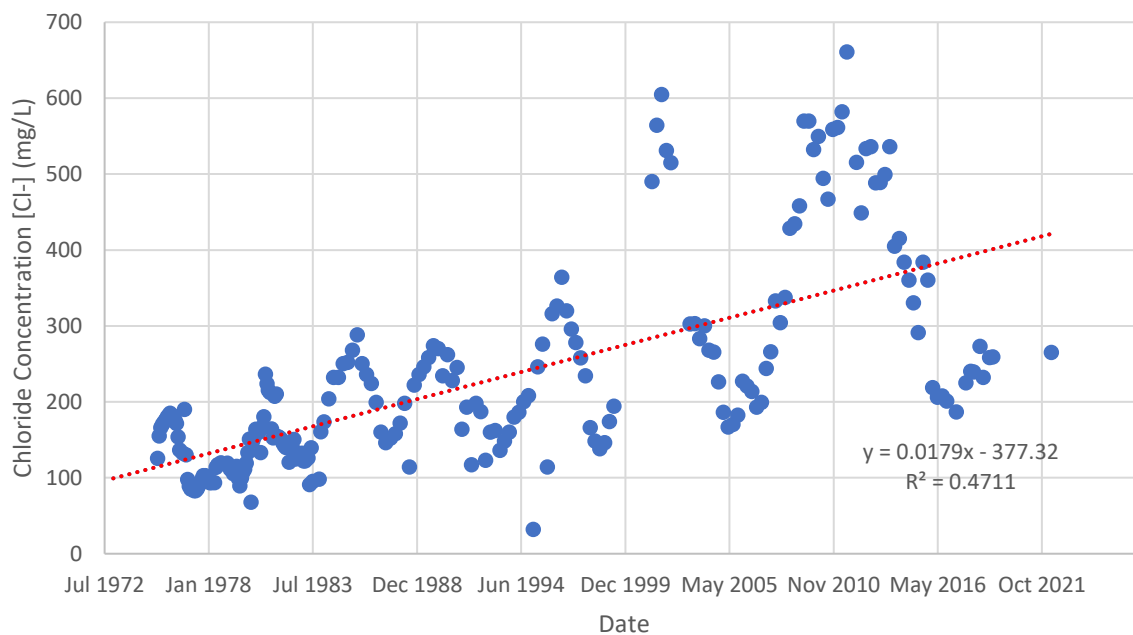




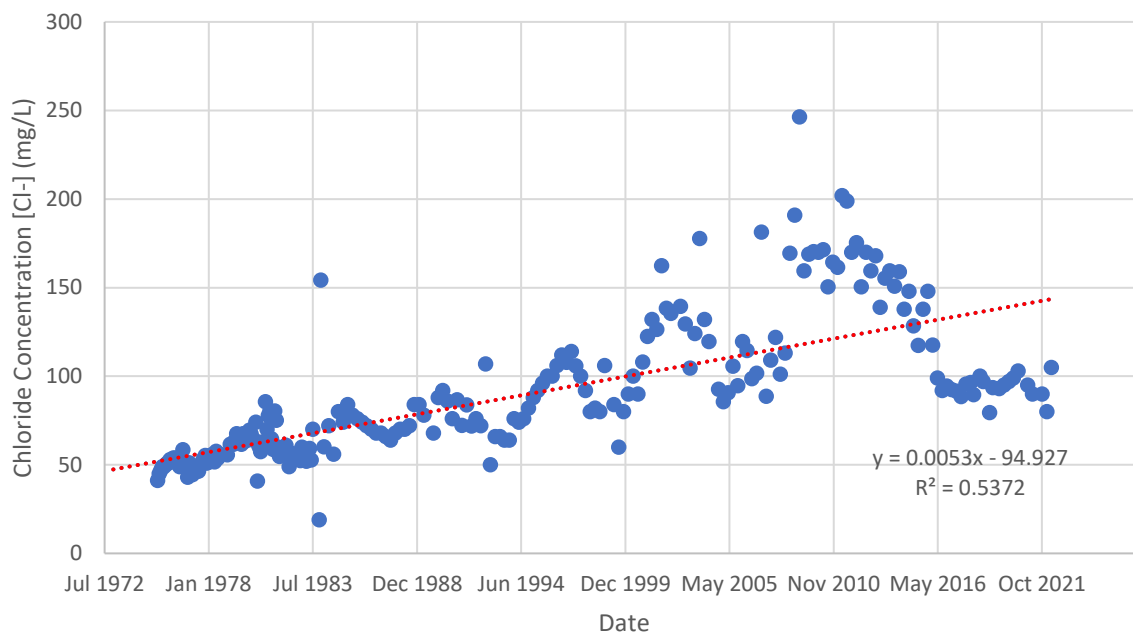
### F05 Chloride Concentrations



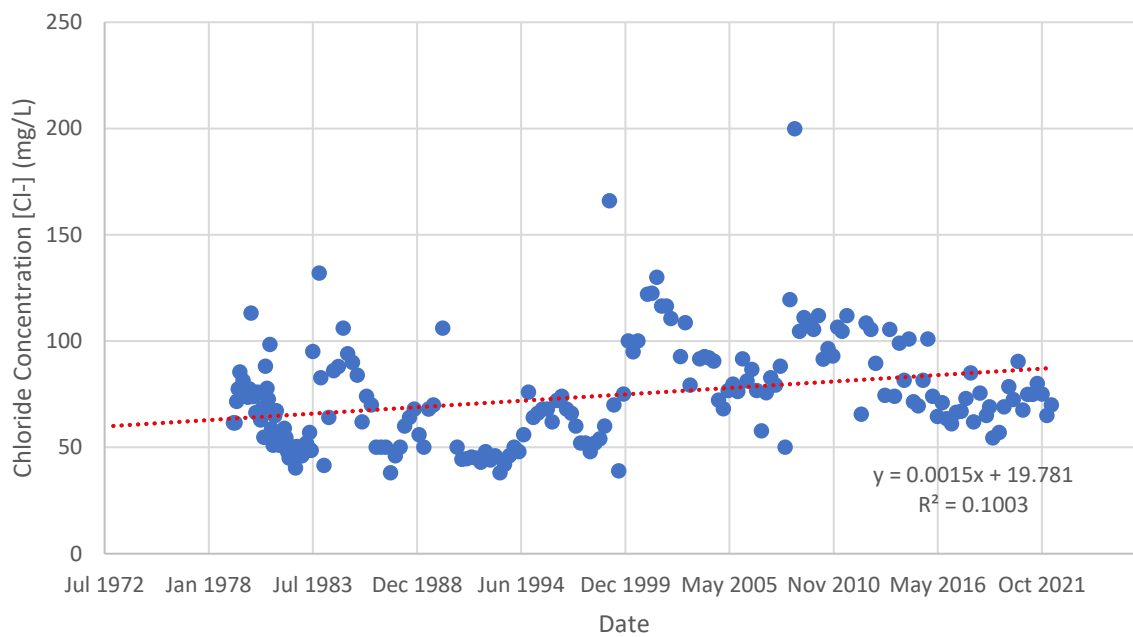
### F06 Chloride Concentrations



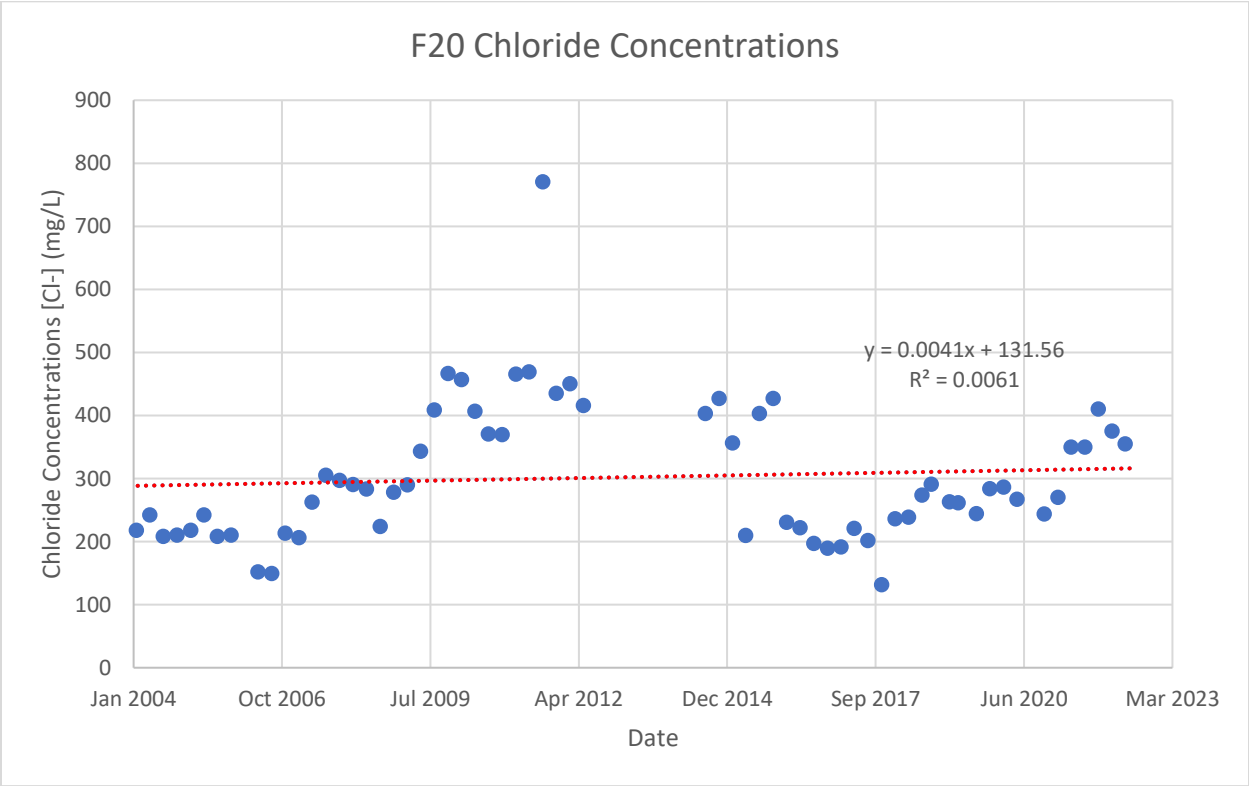
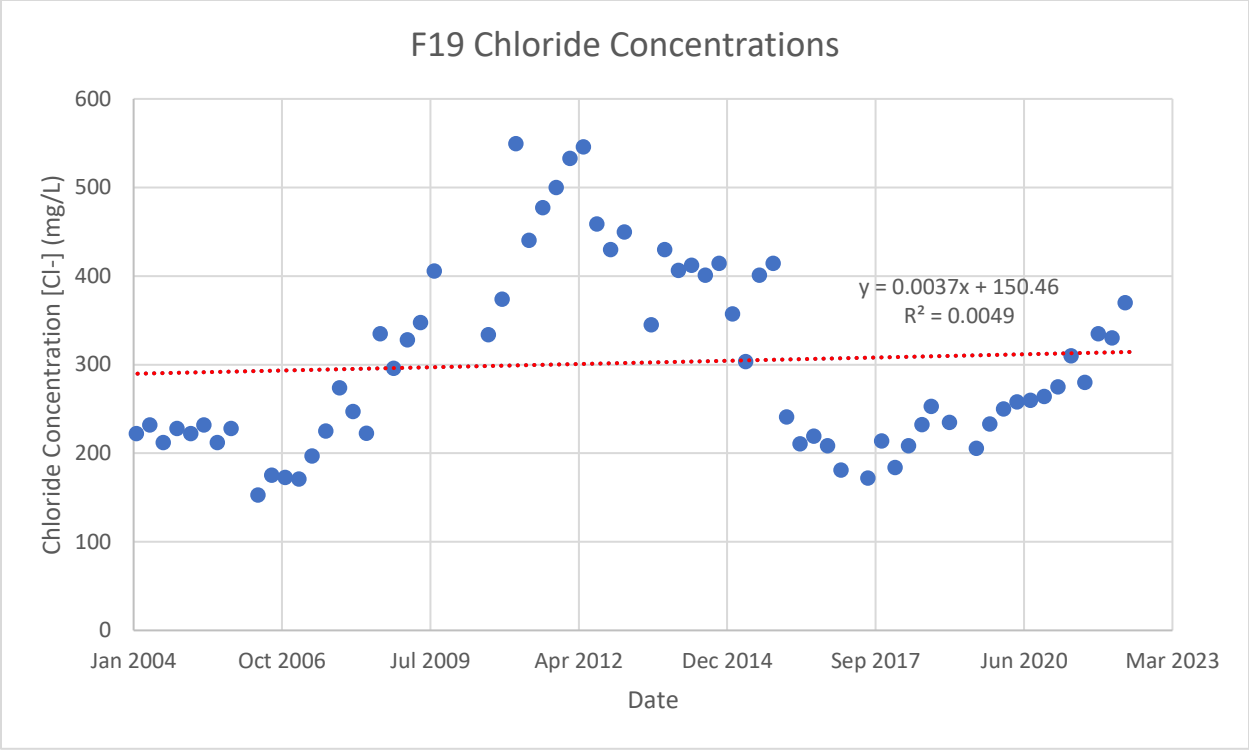
### F07 Chloride Concentrations



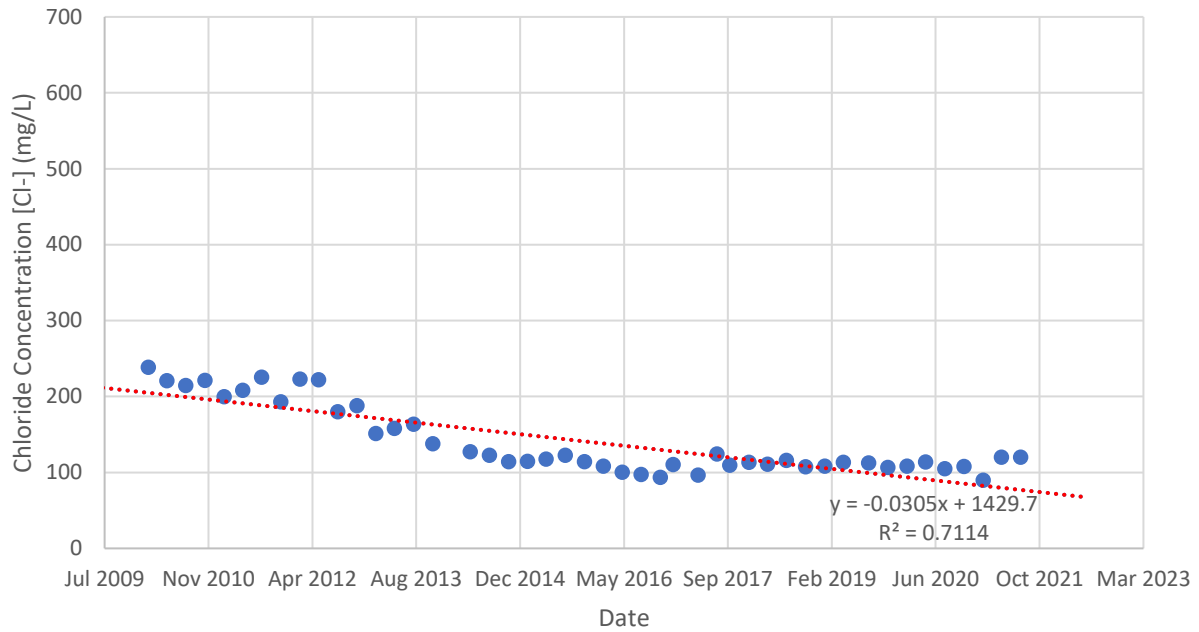
### F09 Chloride Concentrations



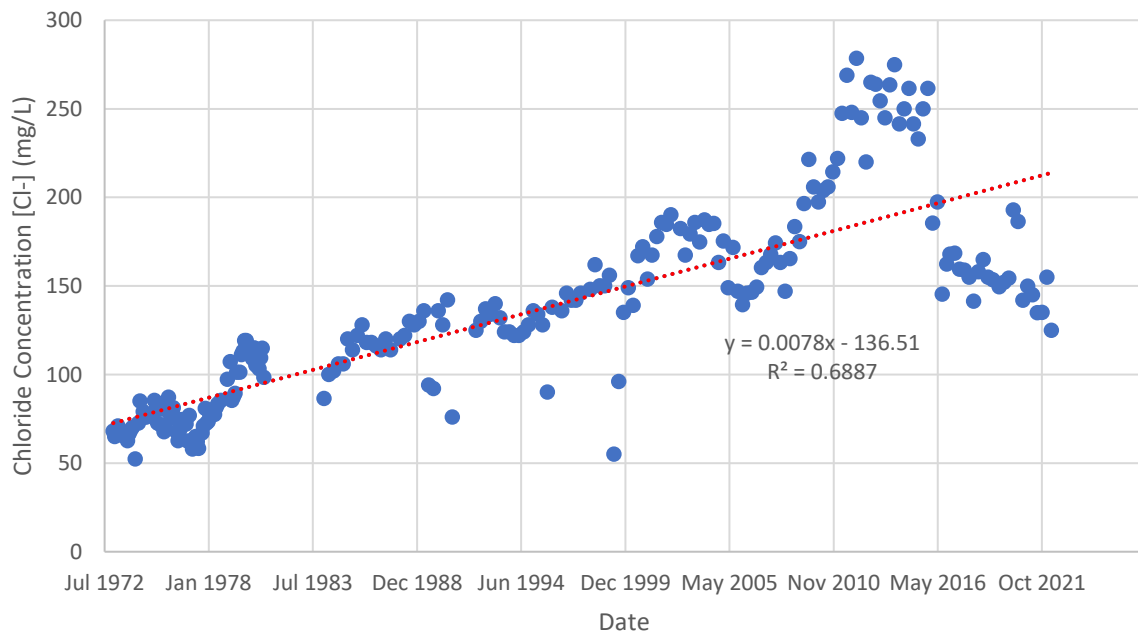


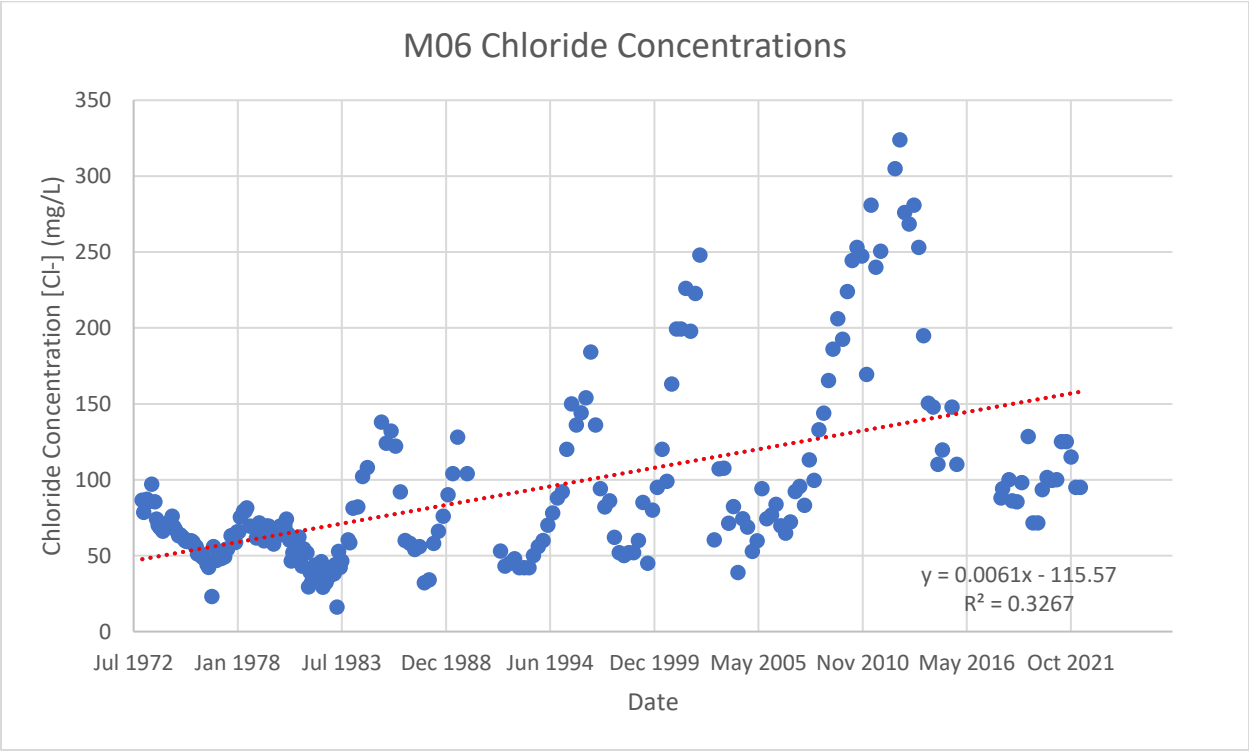
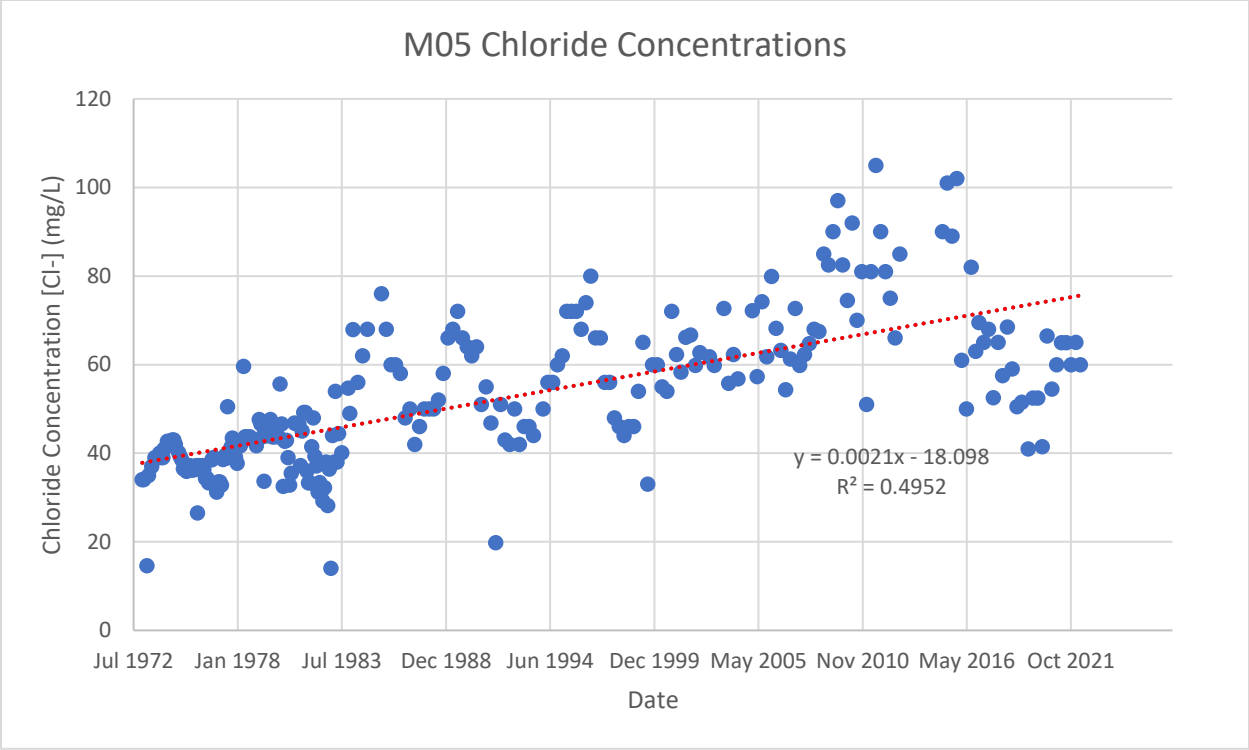


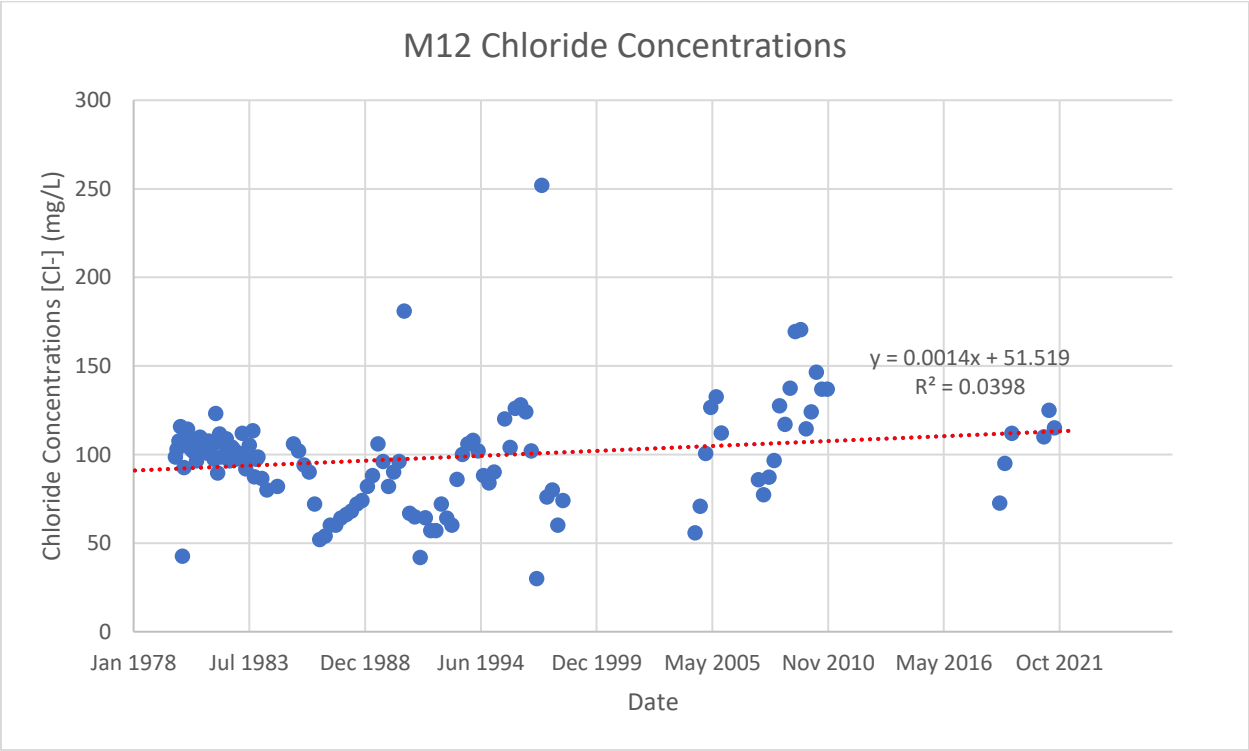
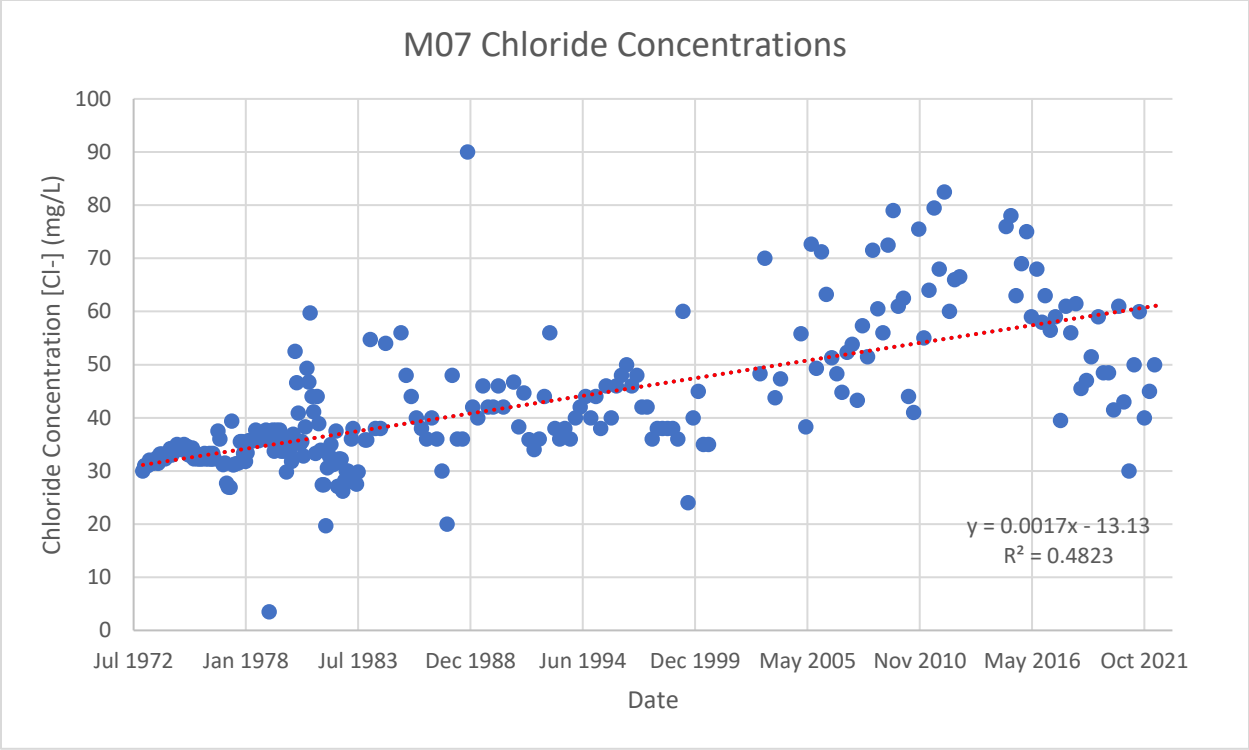
### G501 Chloride Concentrations

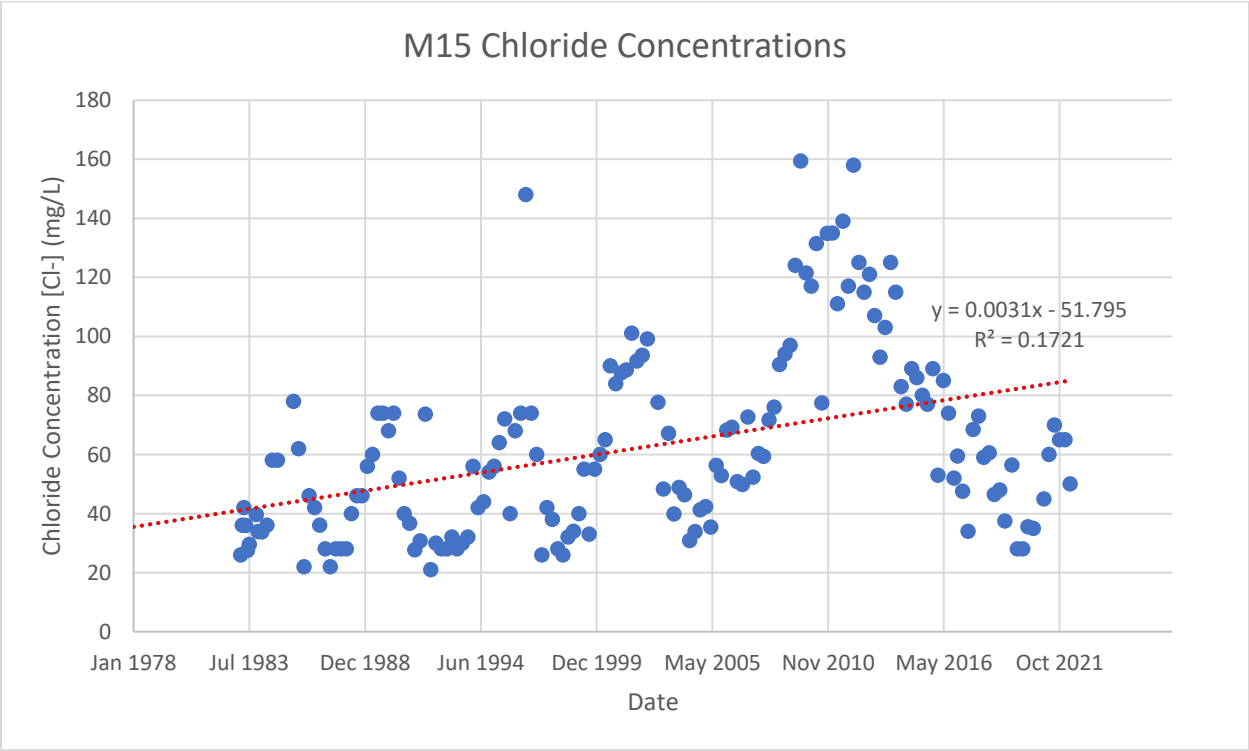
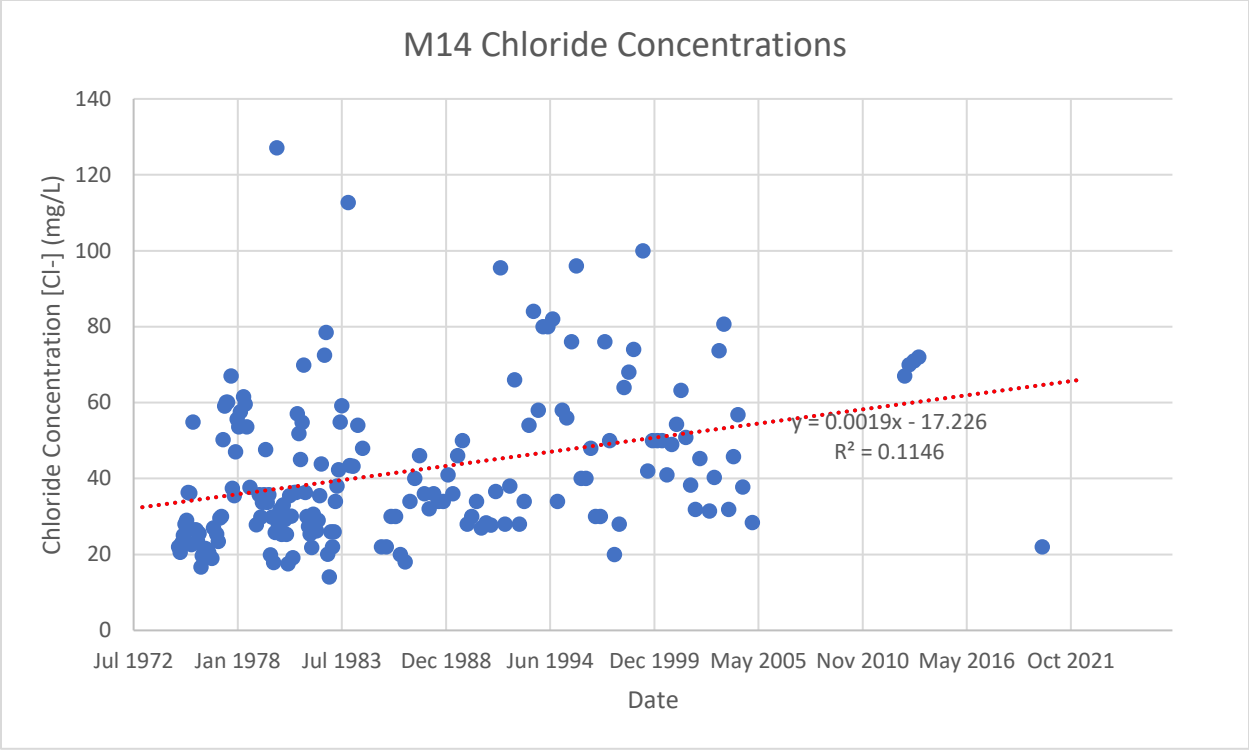


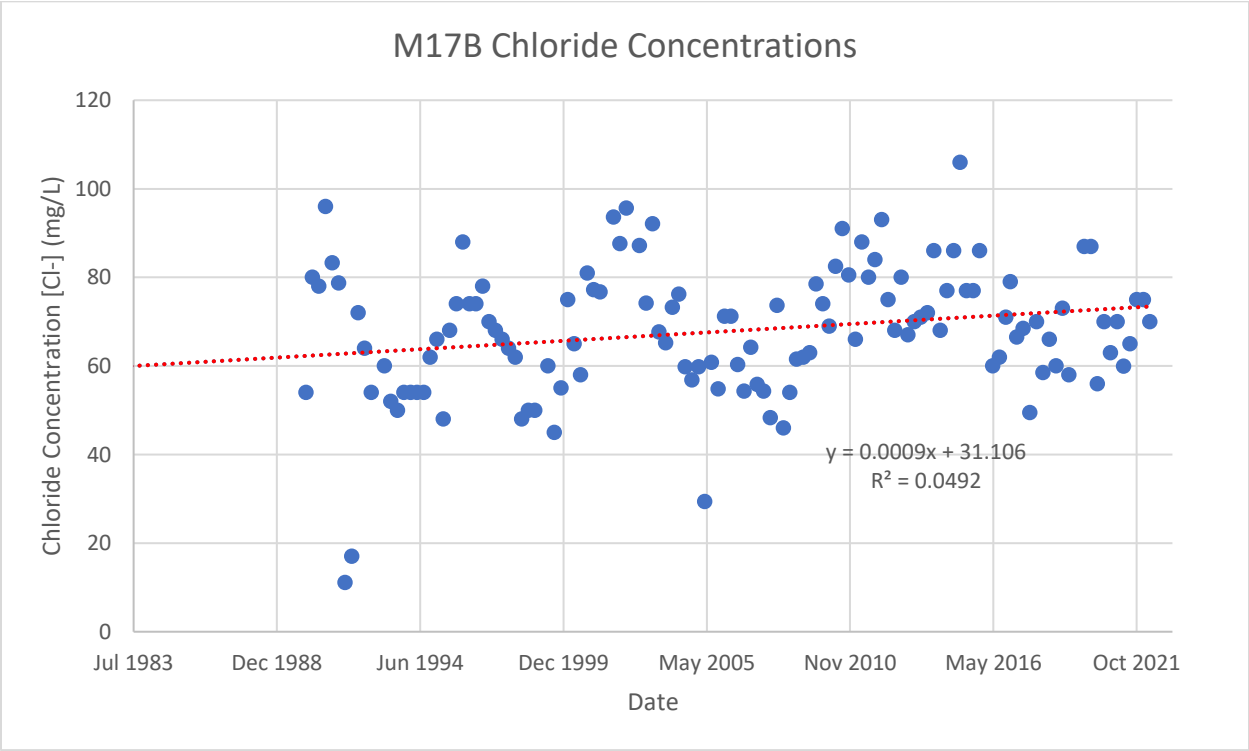
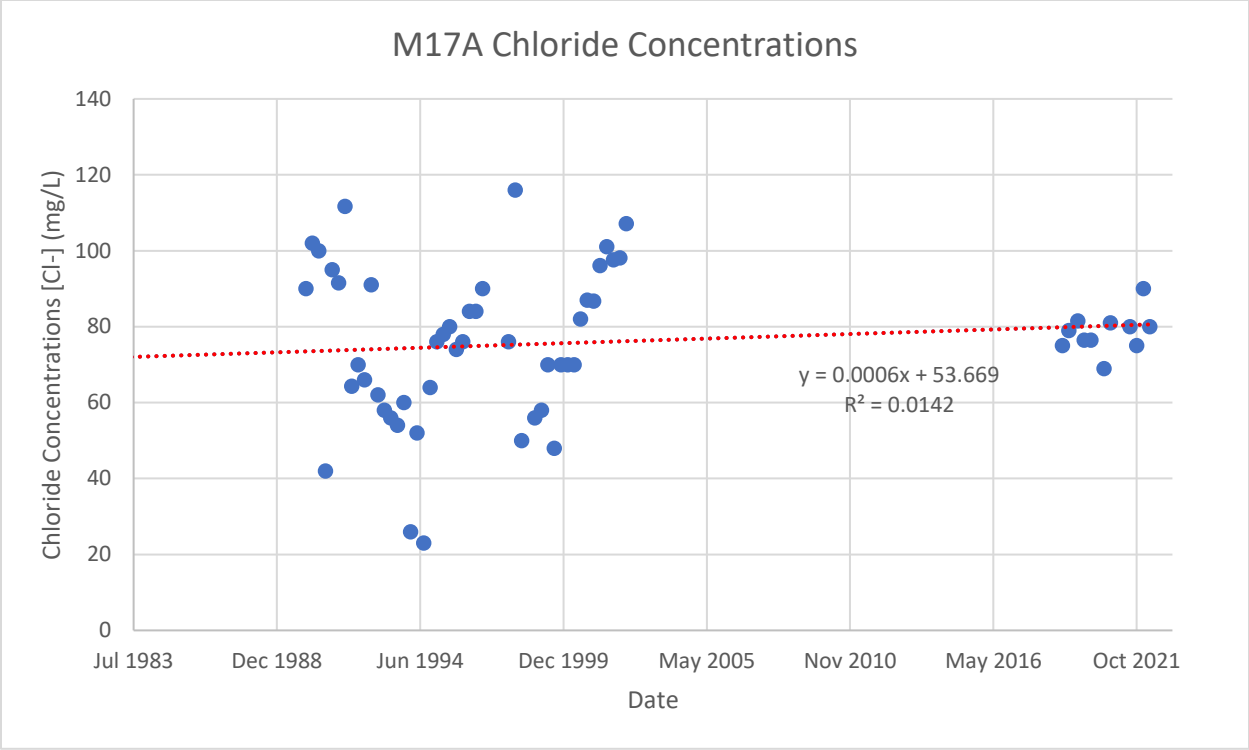
### H01 Chloride Concentrations

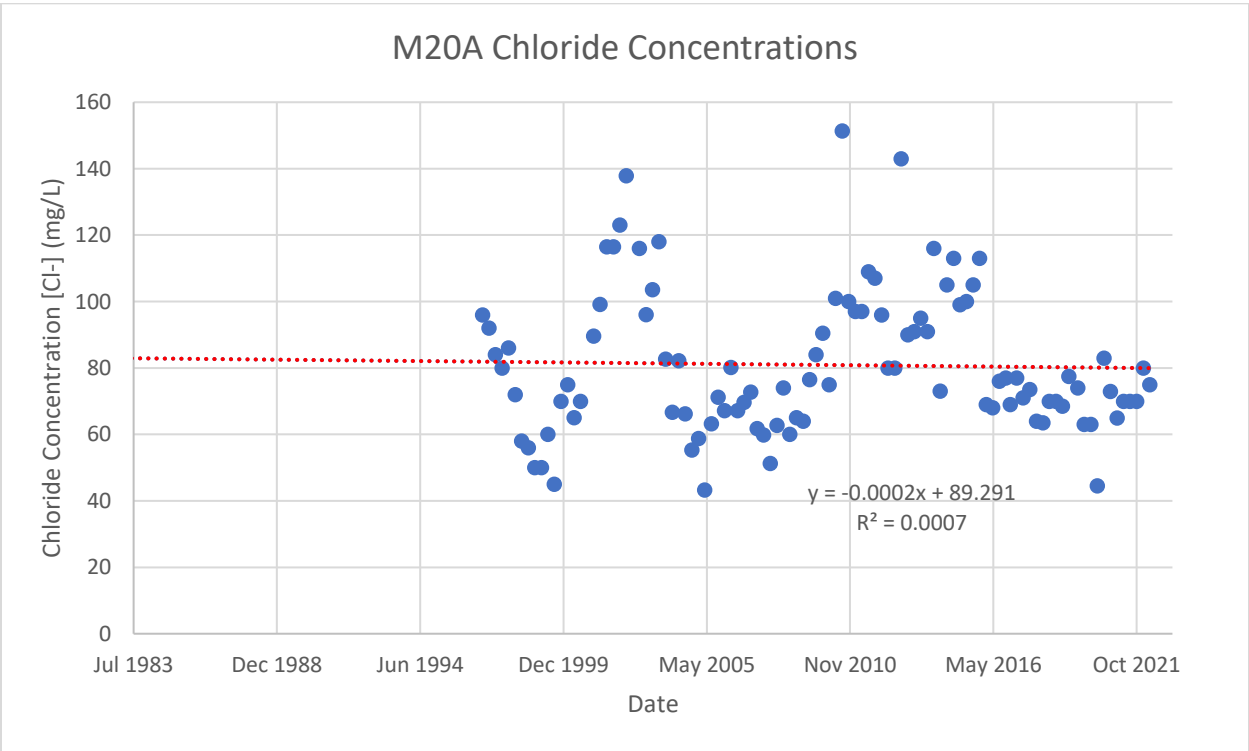
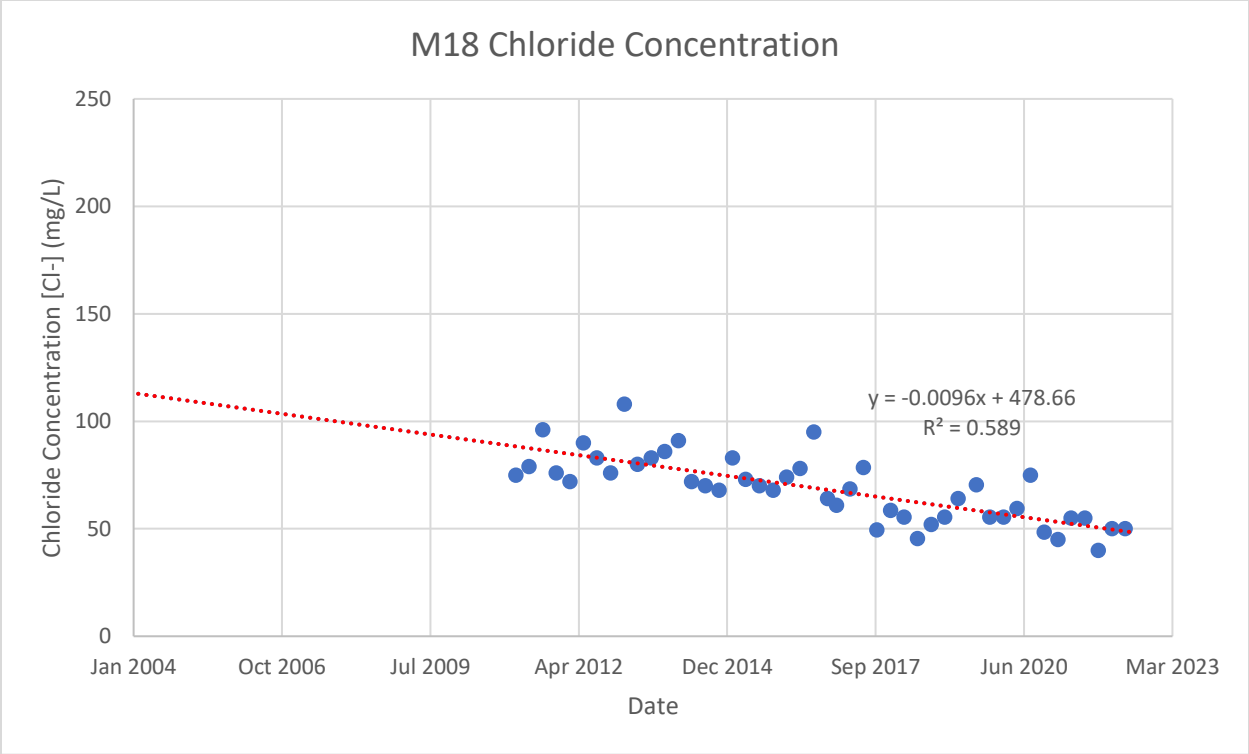


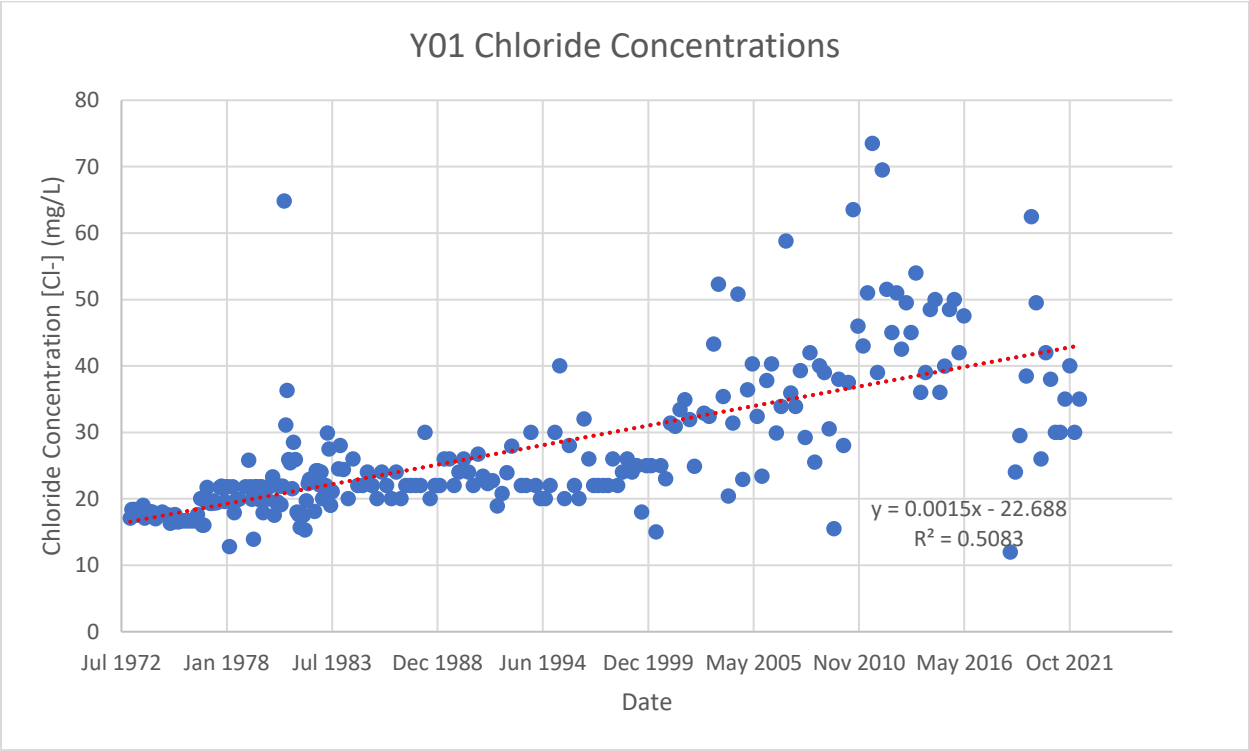
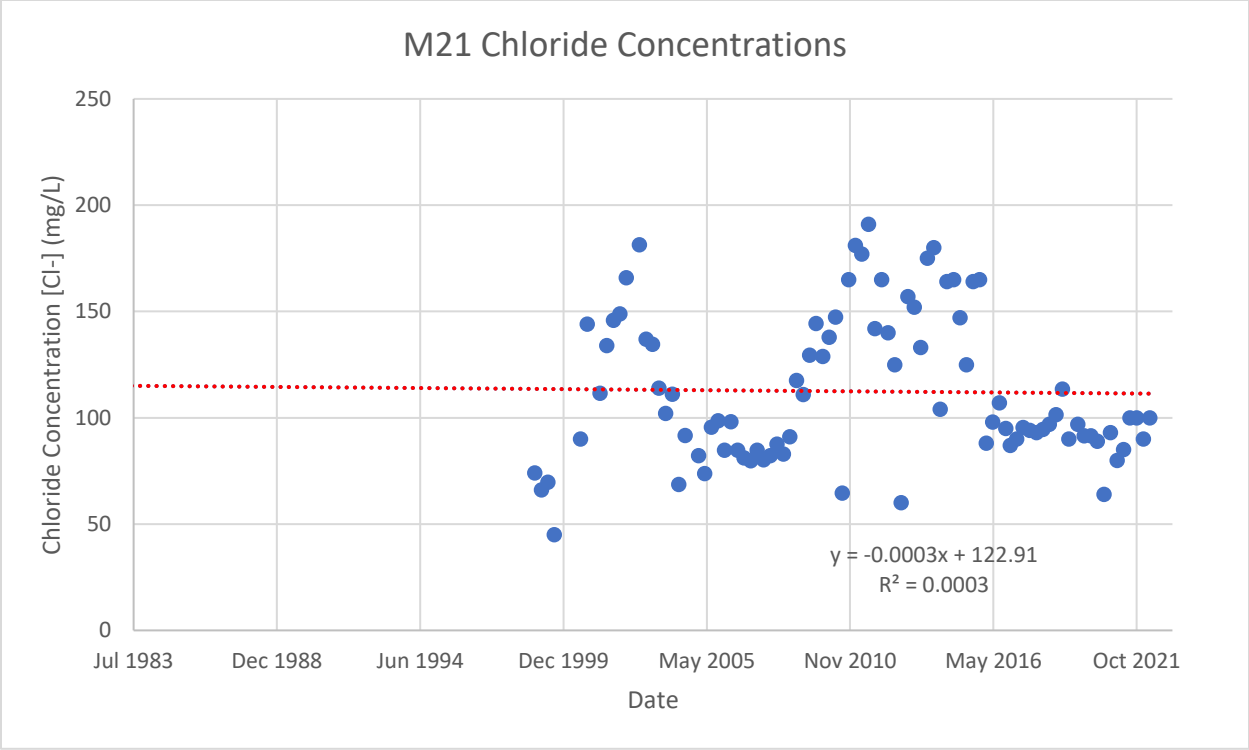




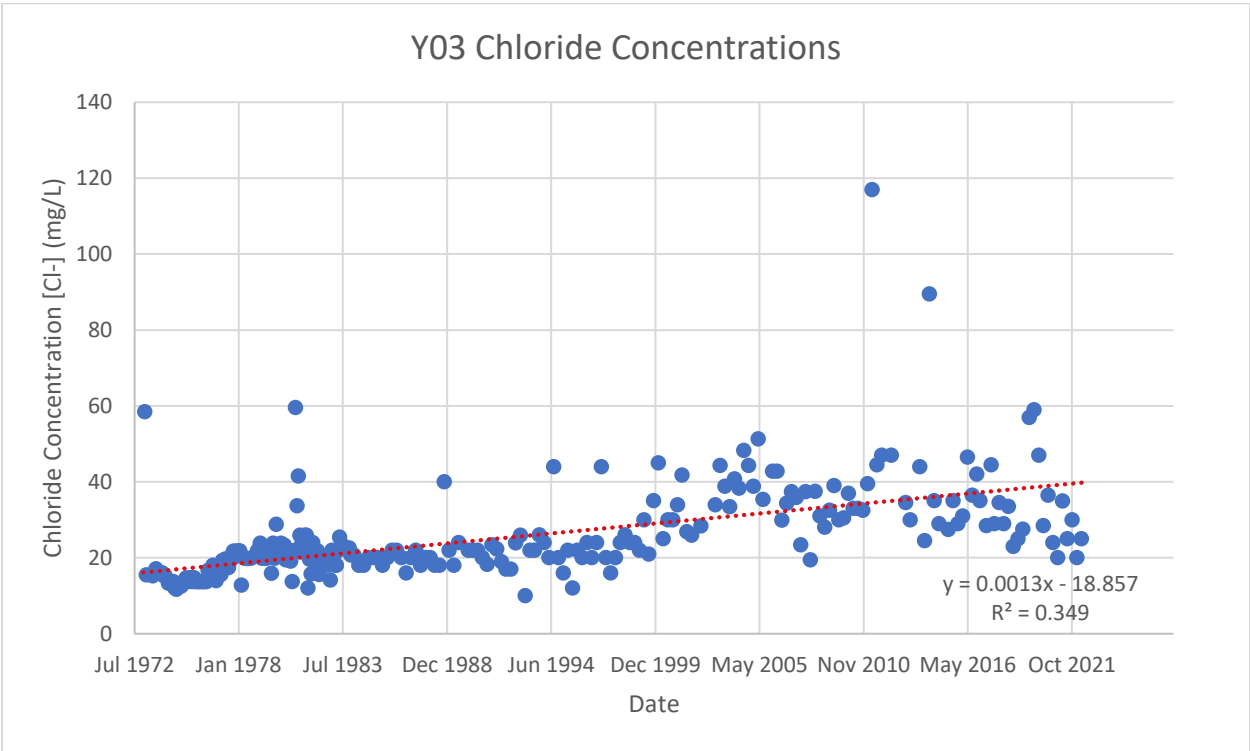
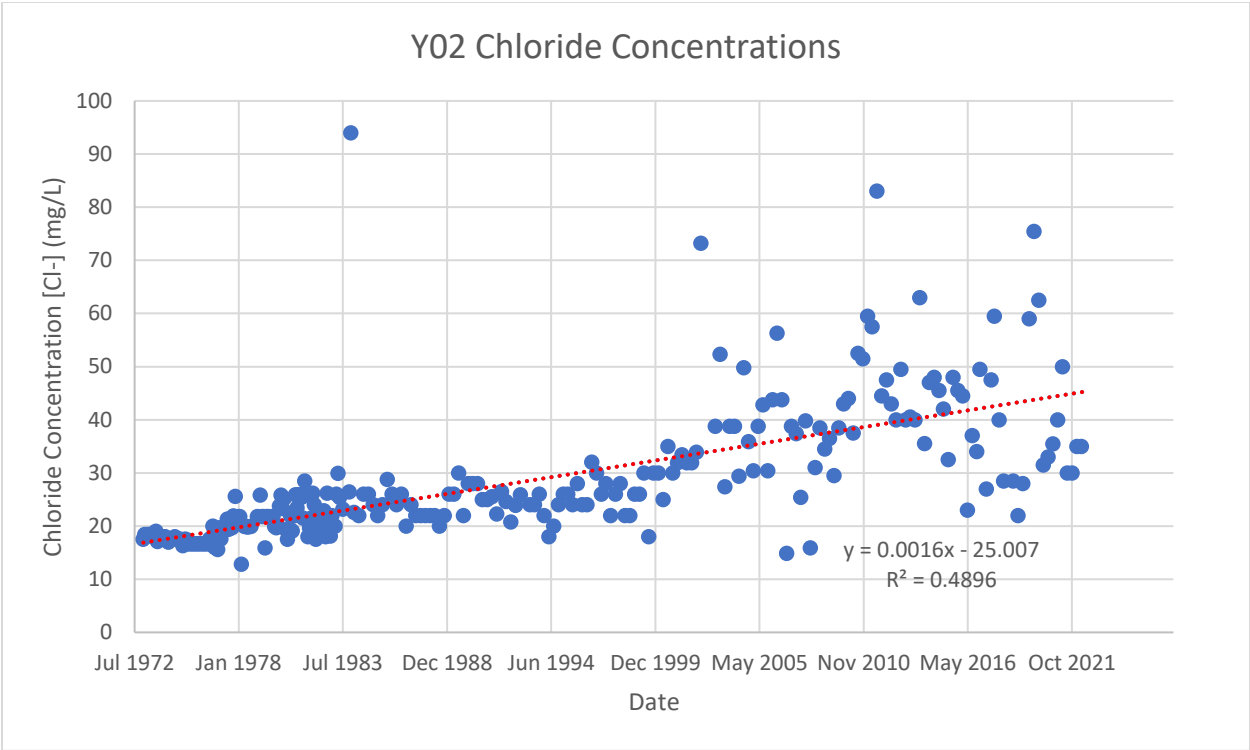


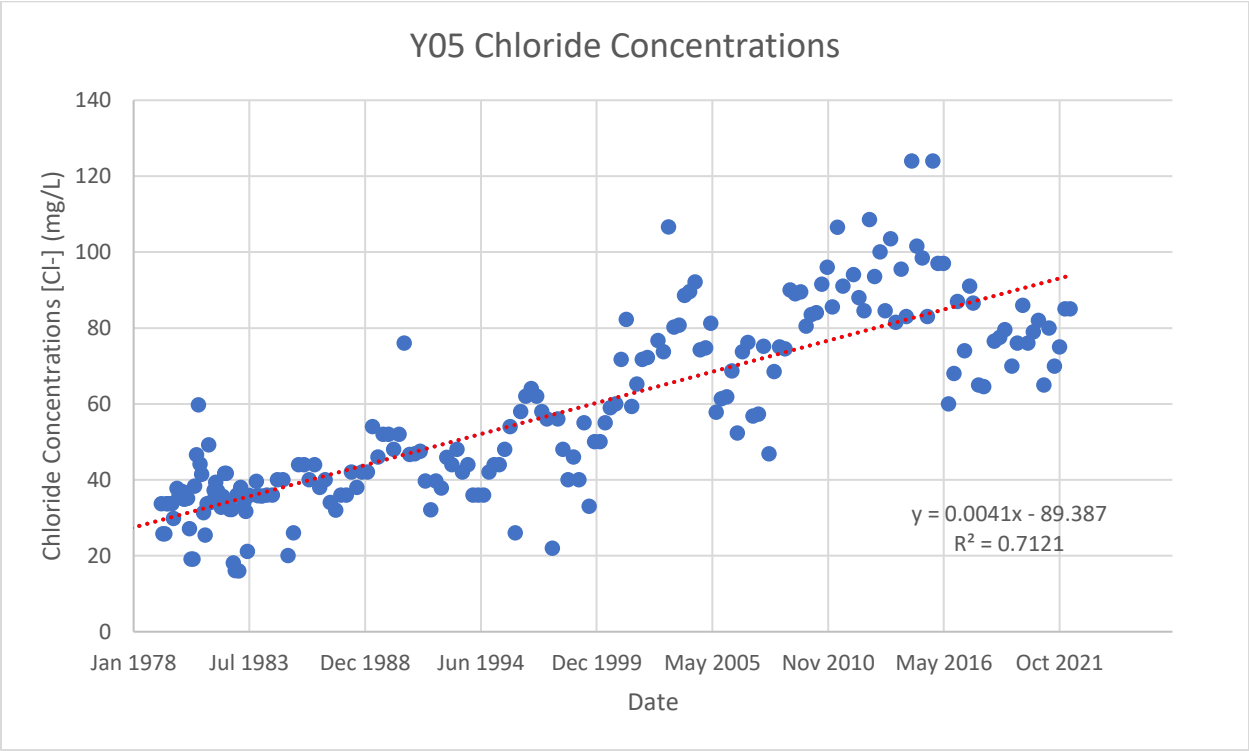
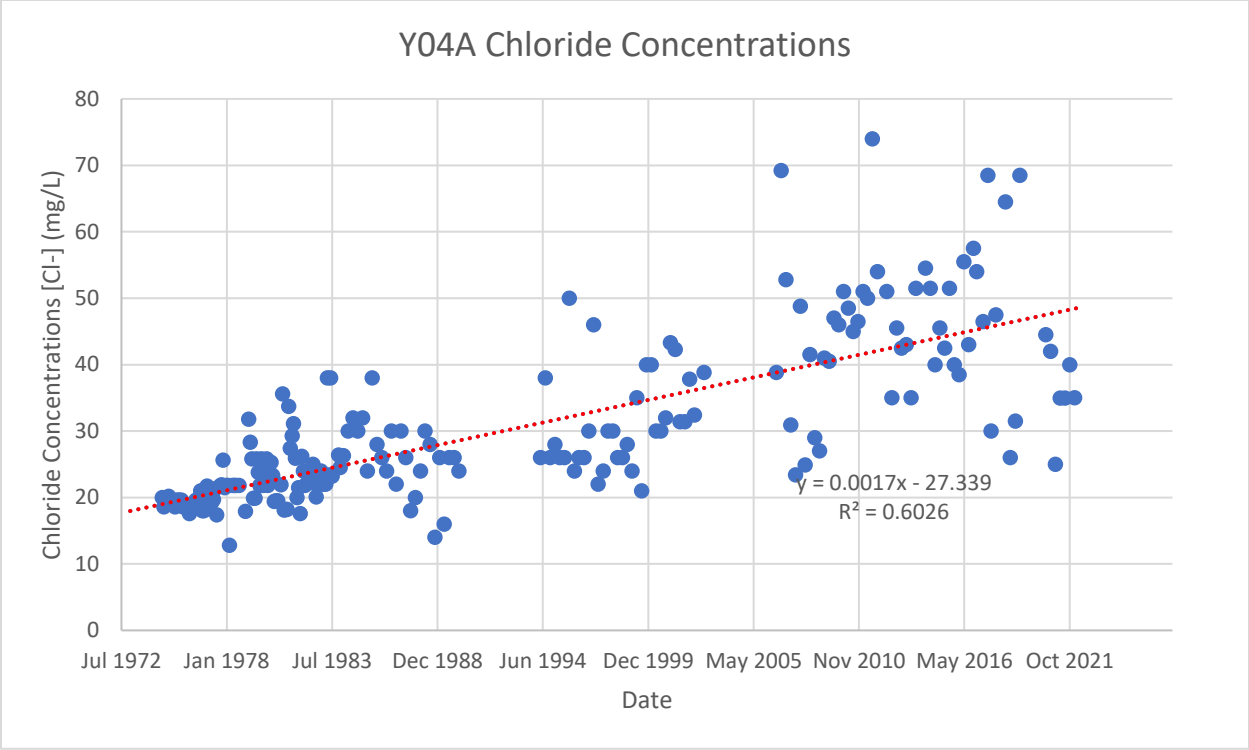


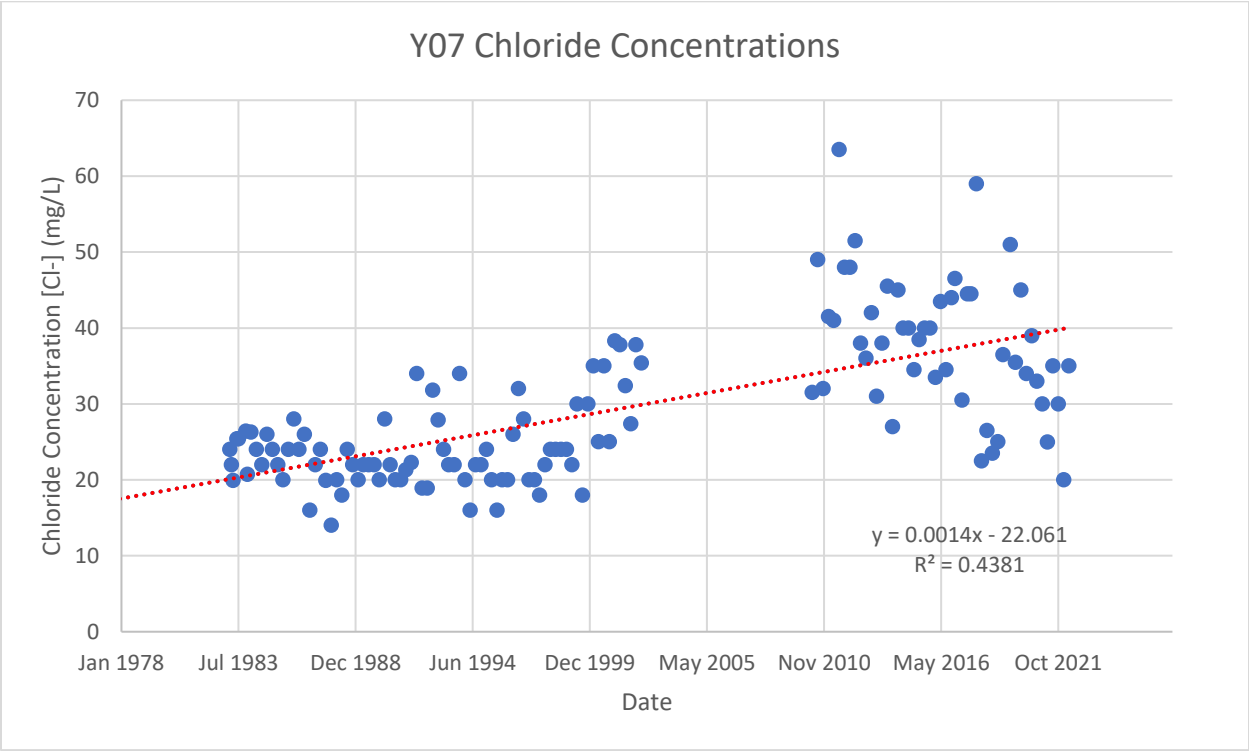
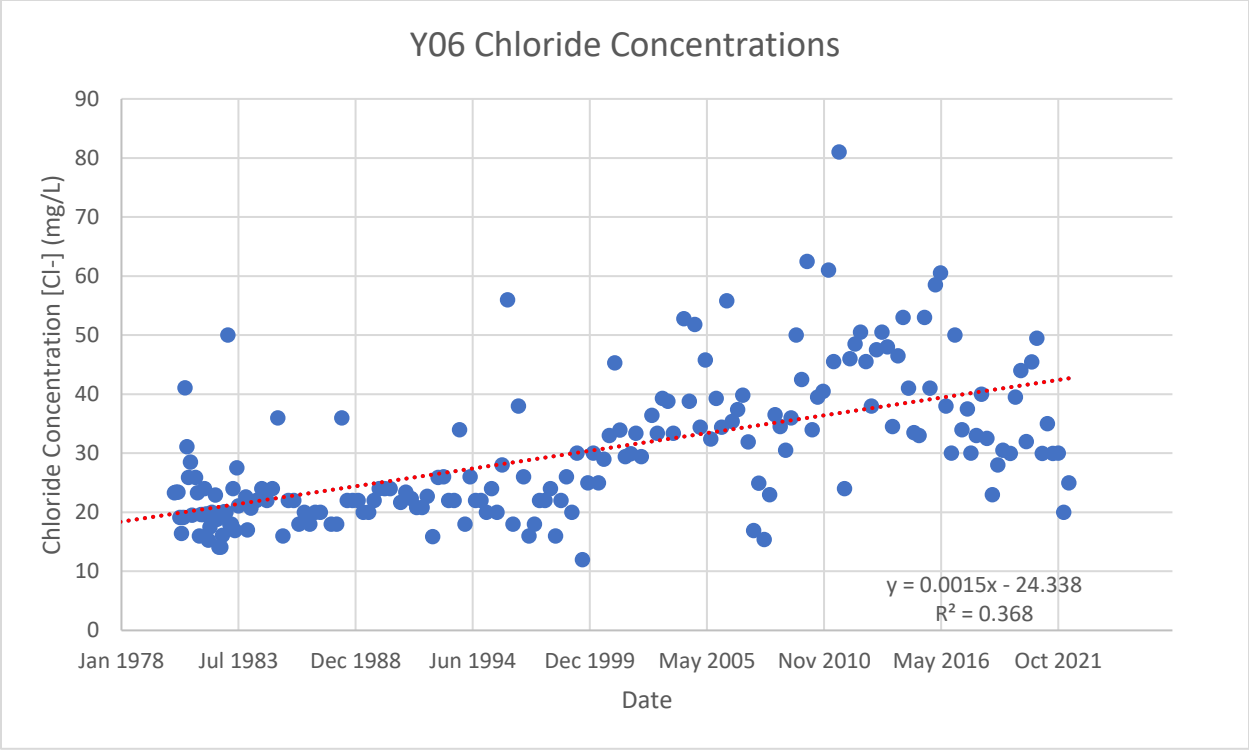


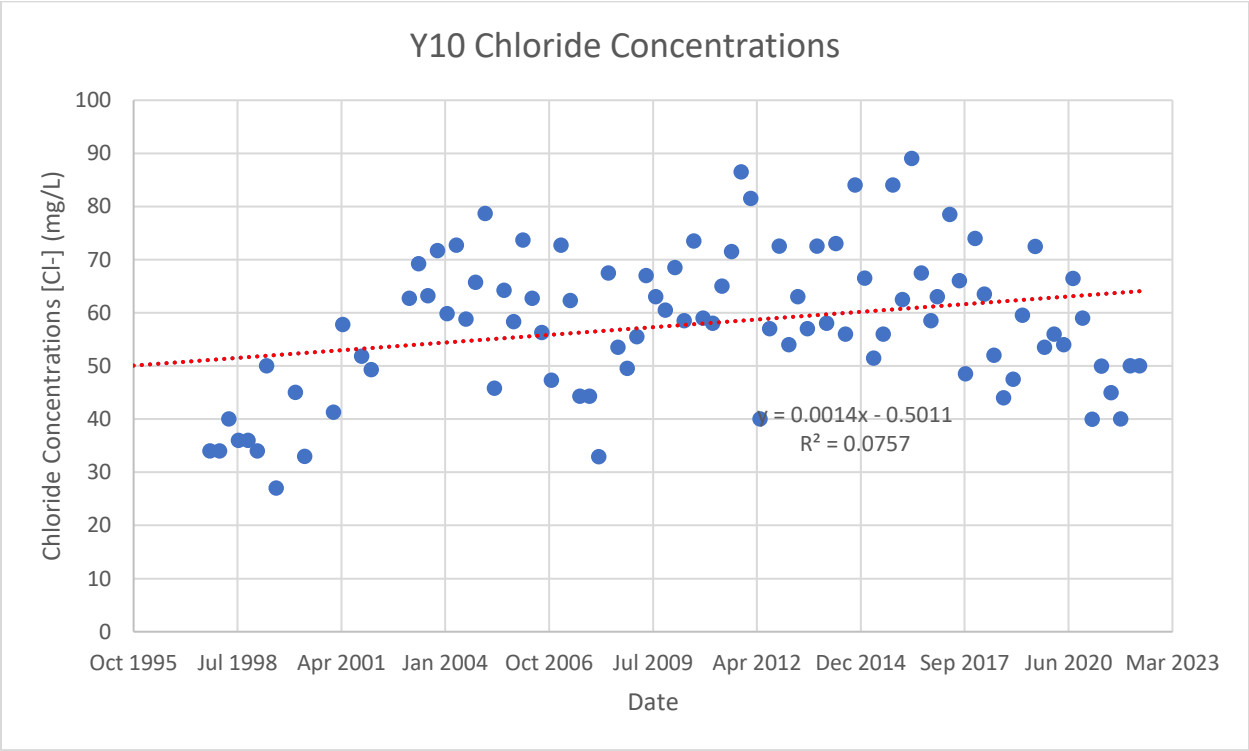
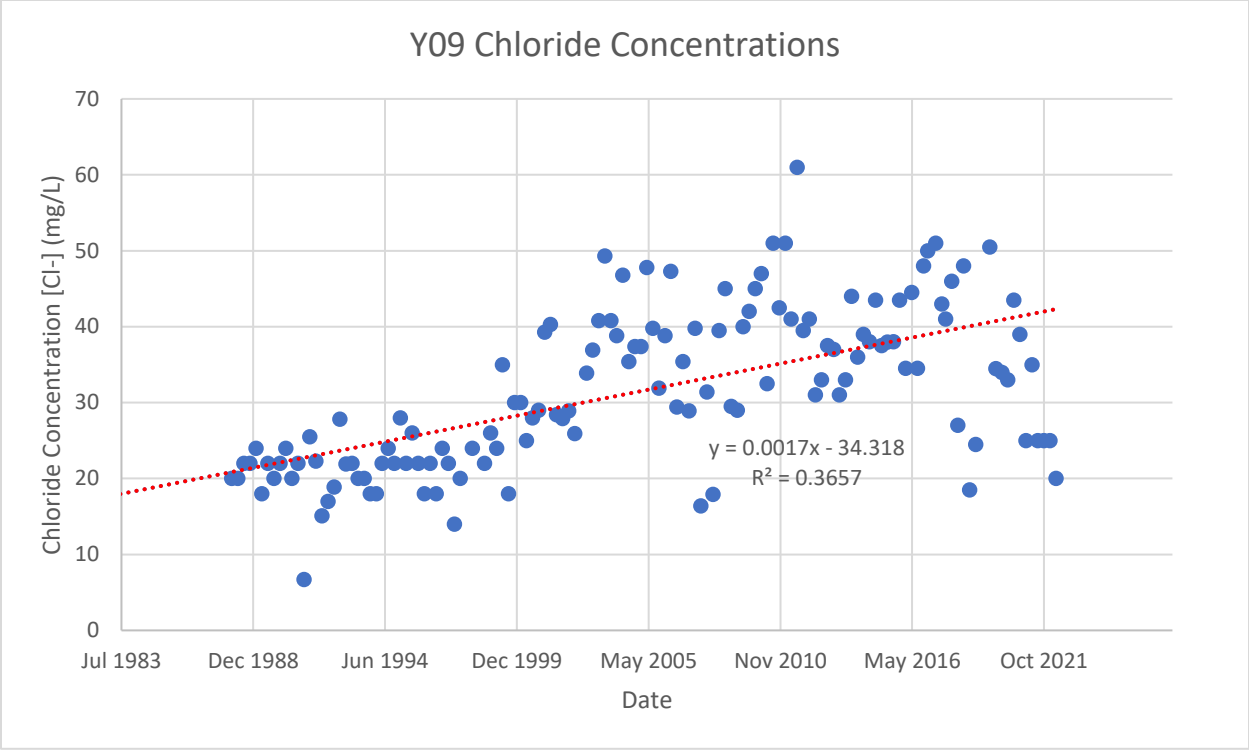


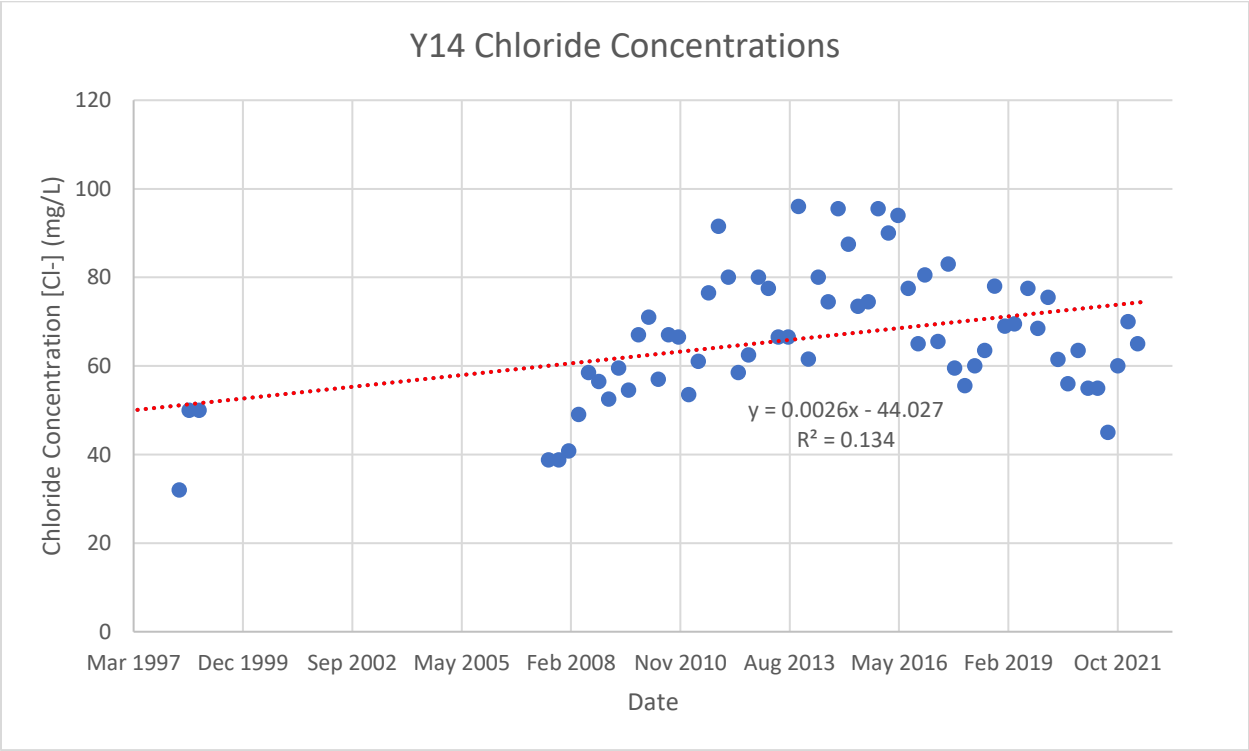
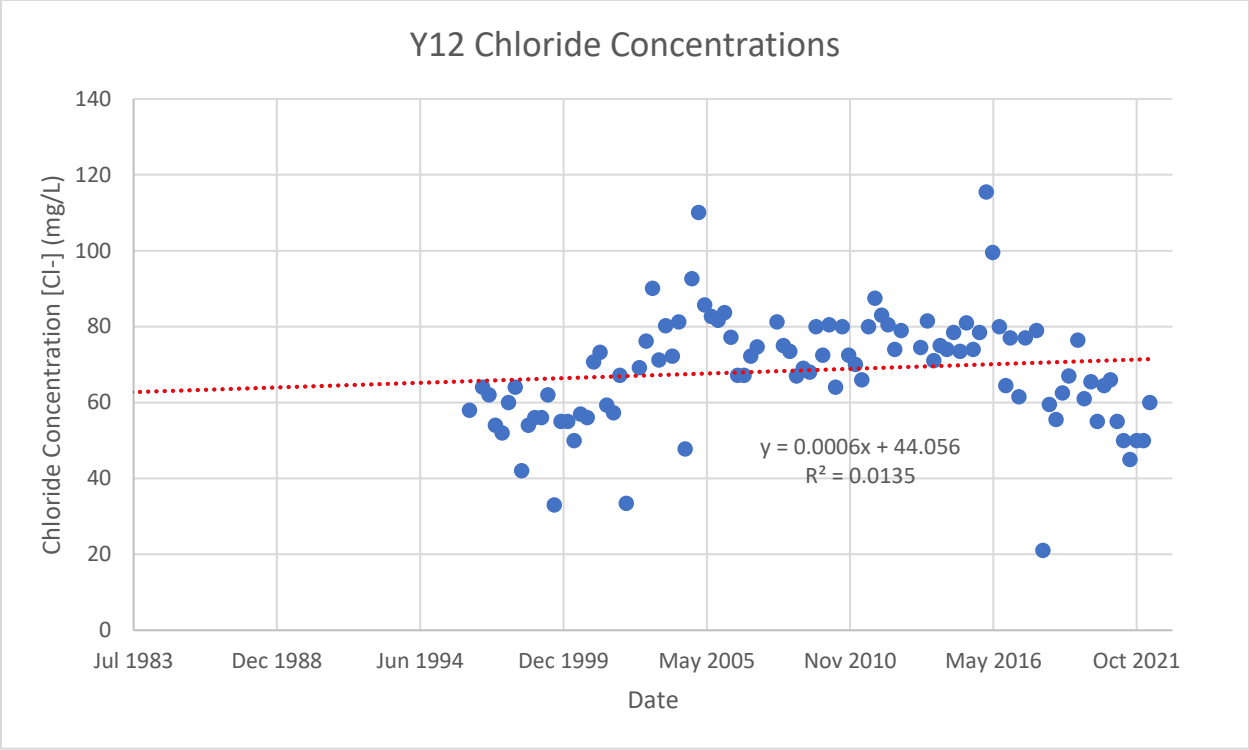


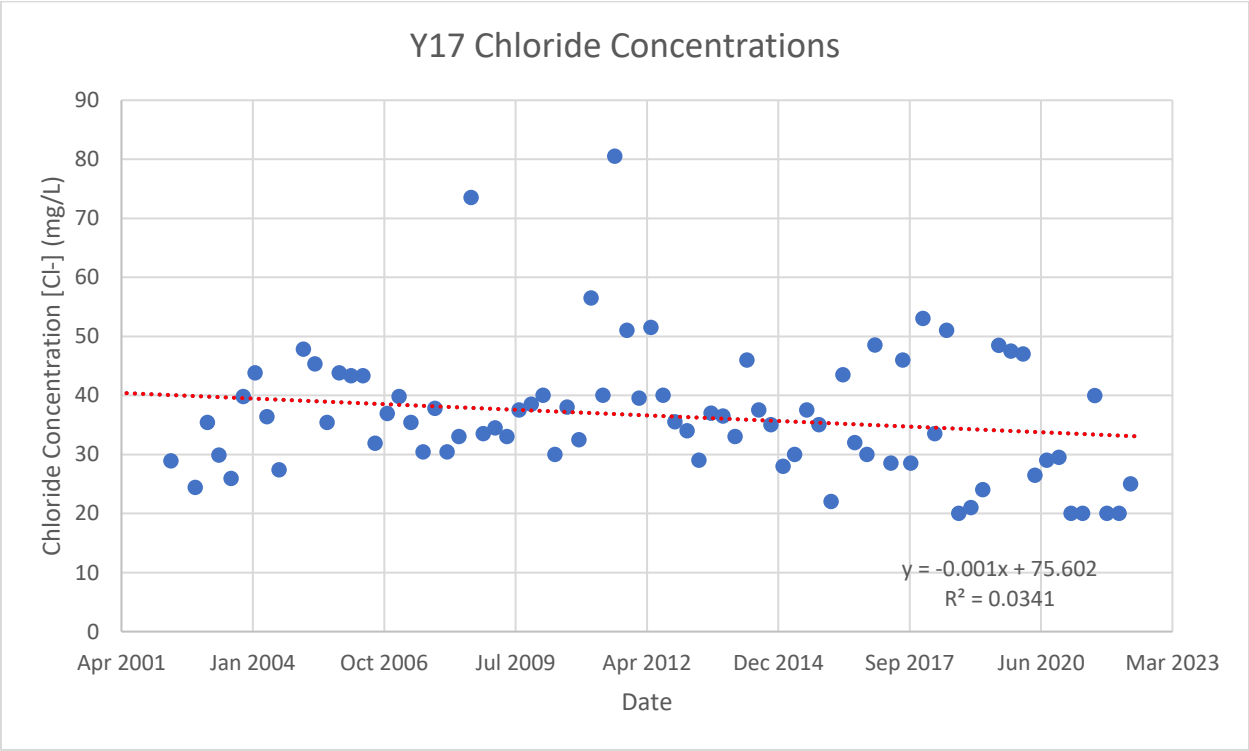
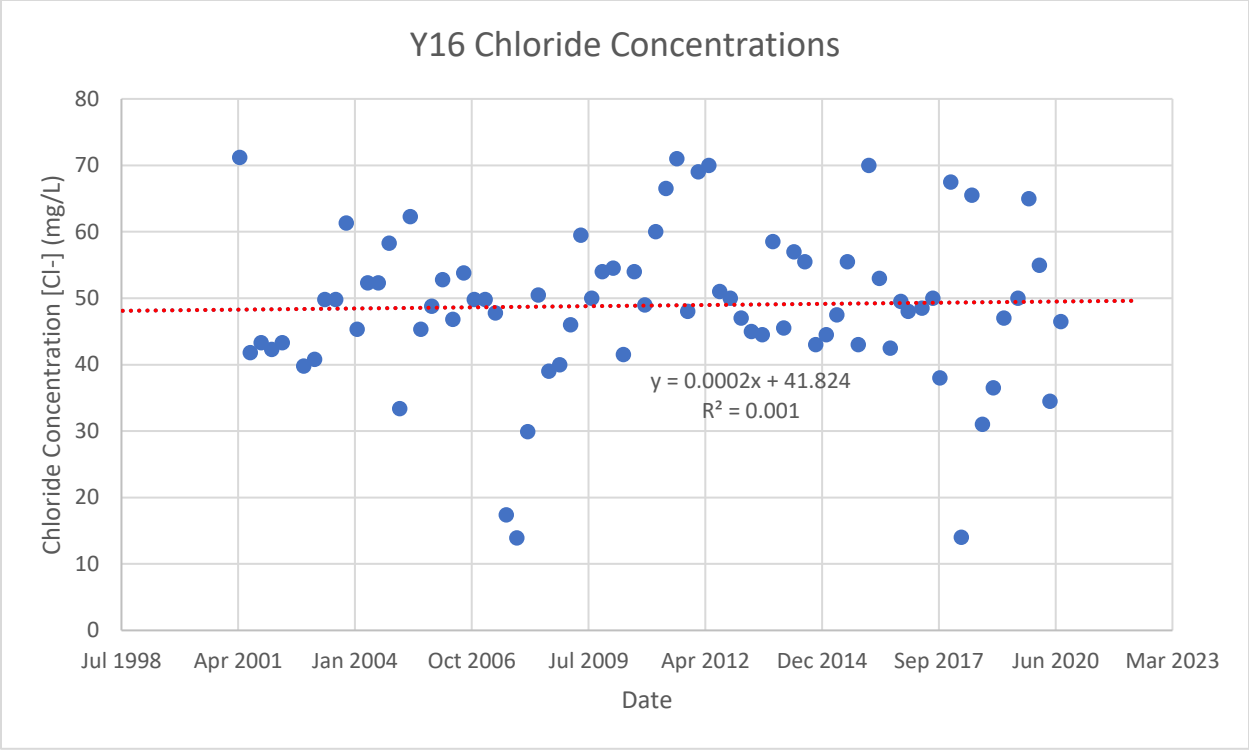


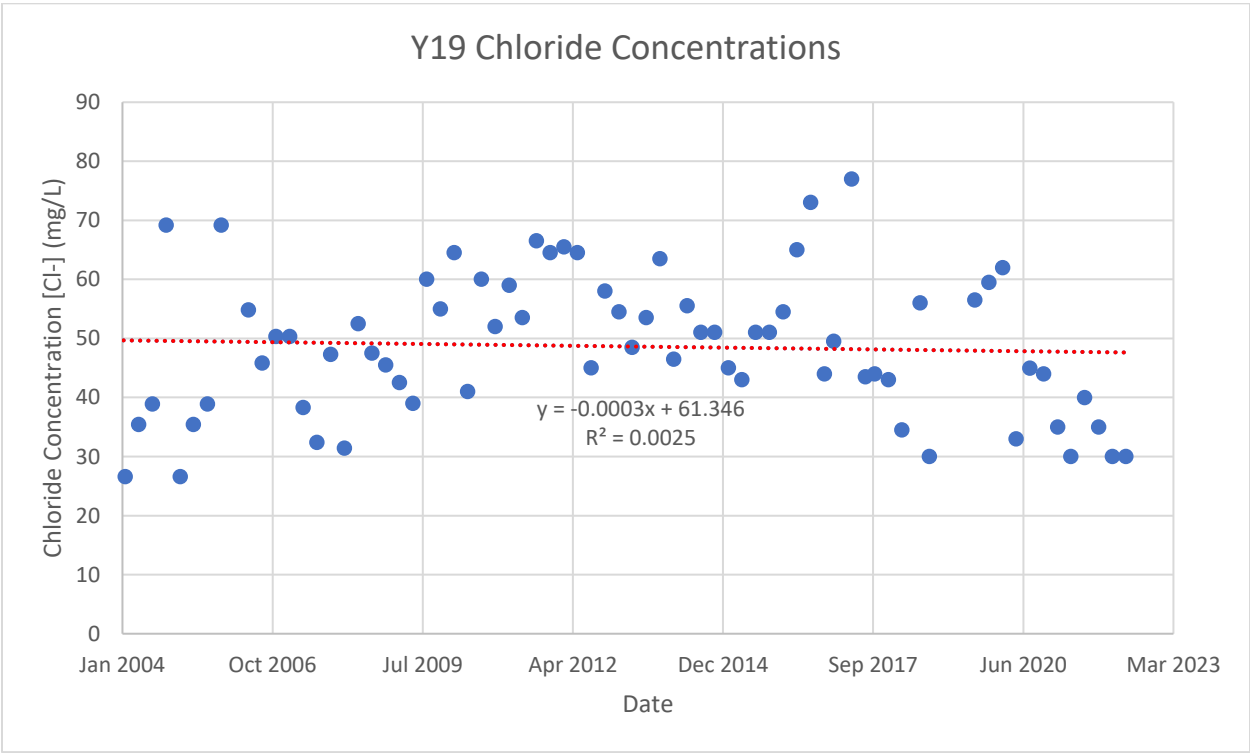
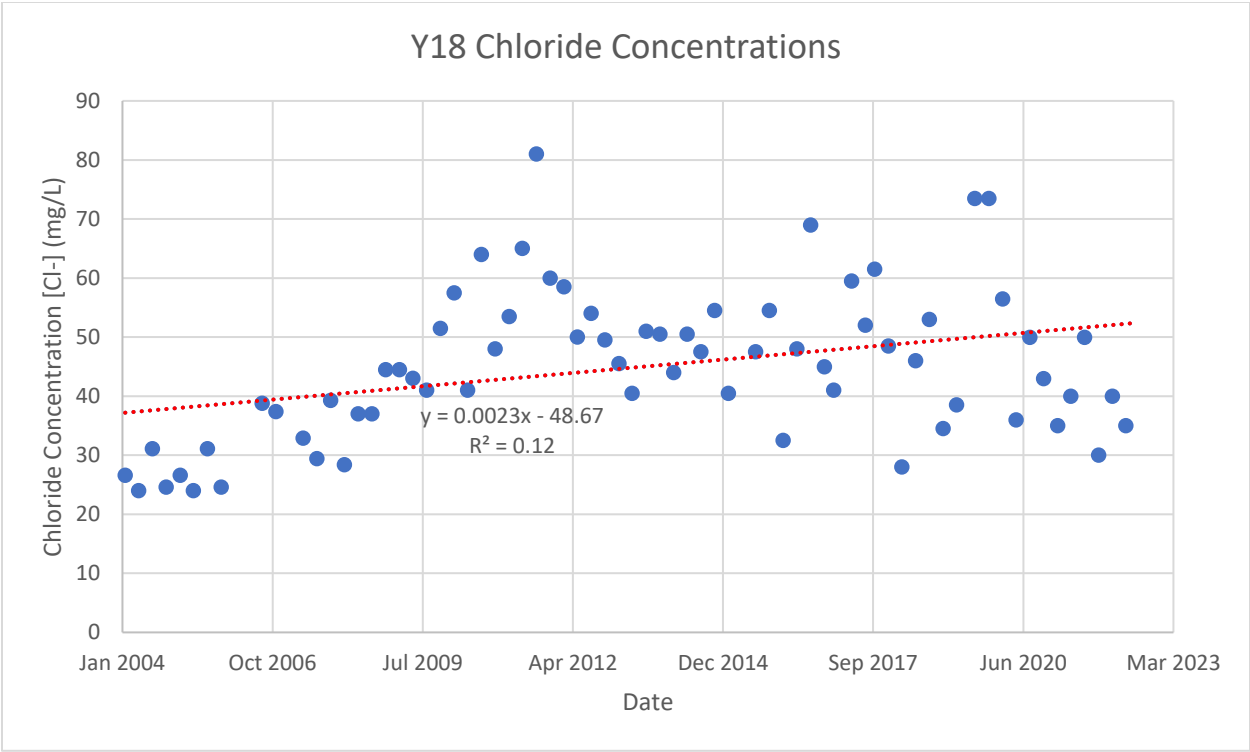


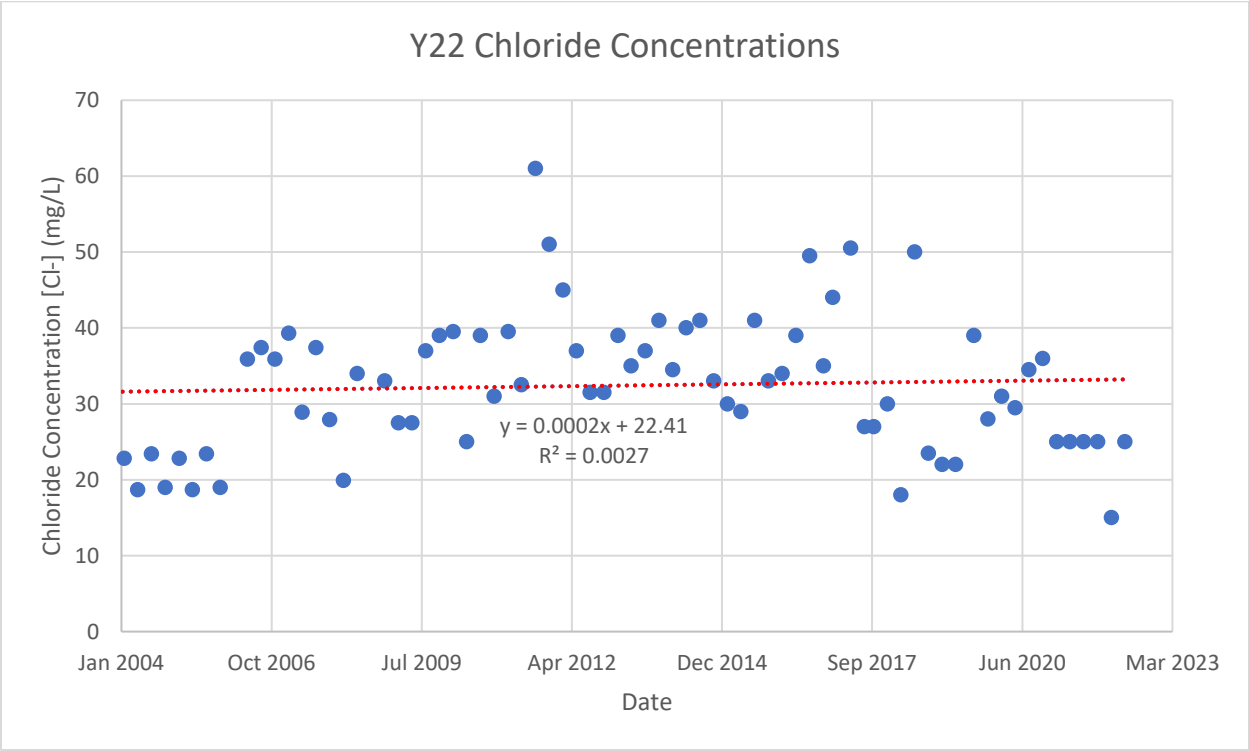
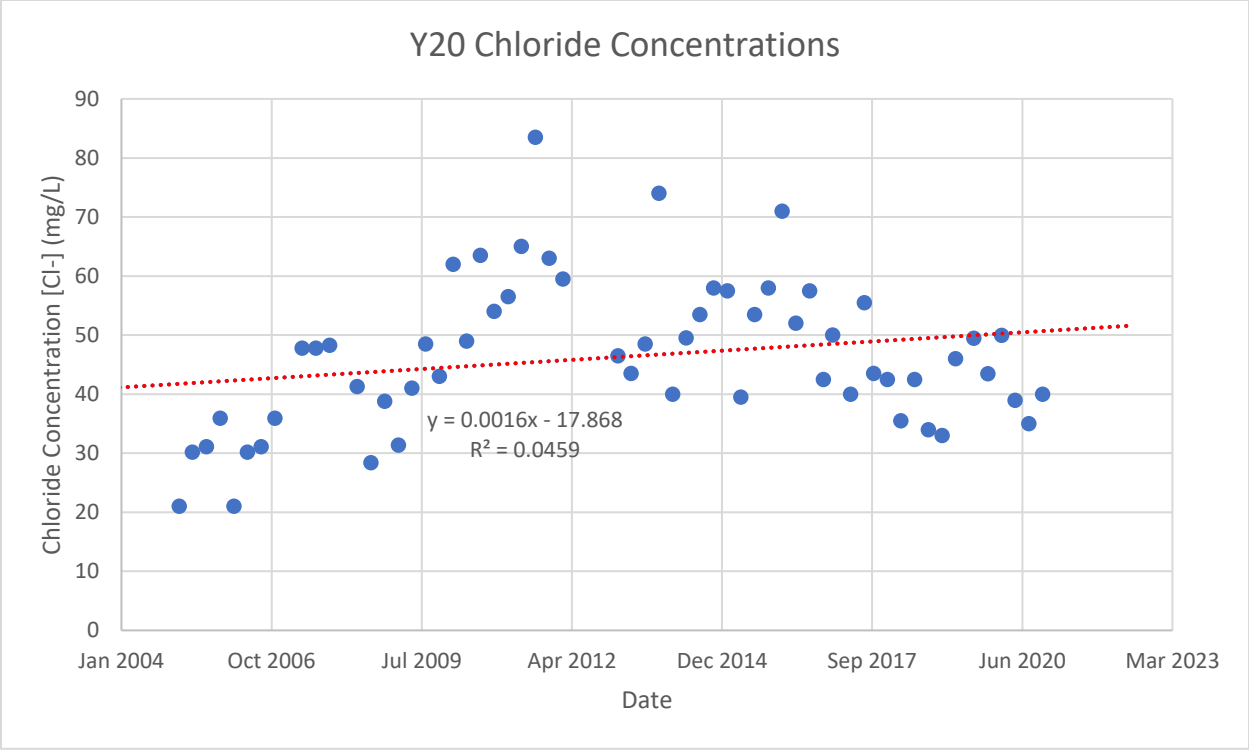




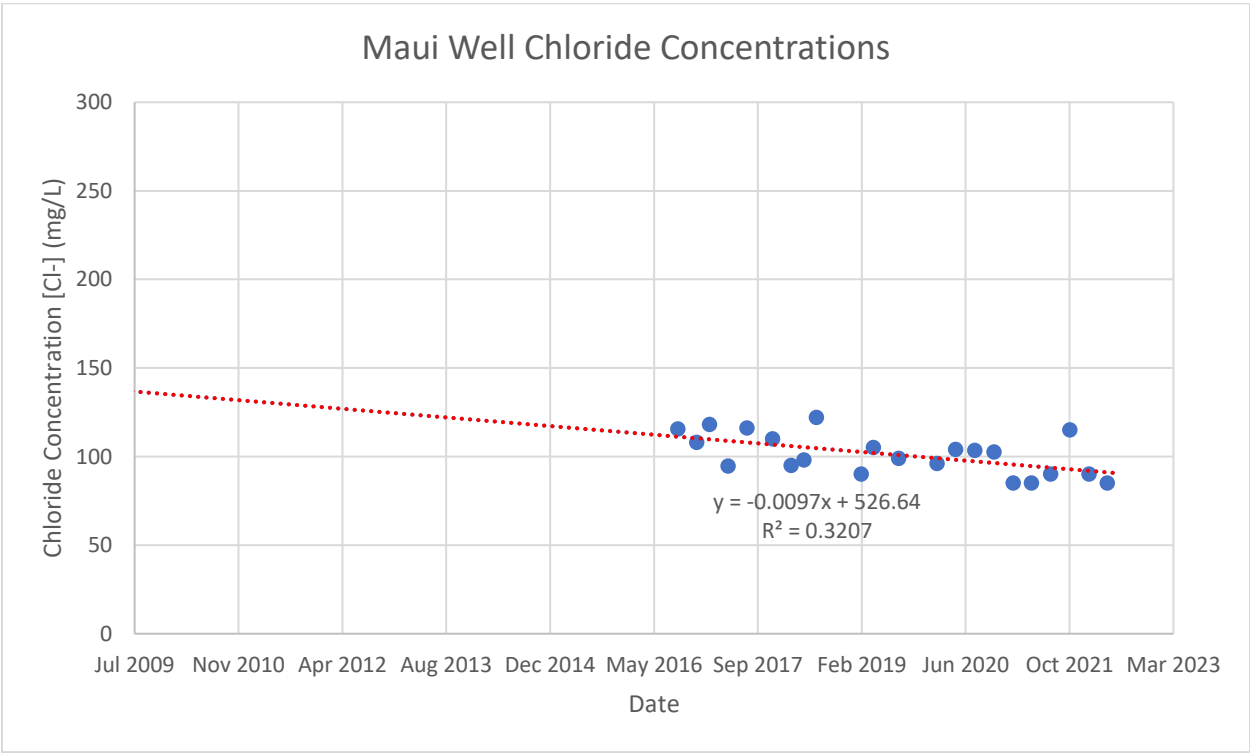
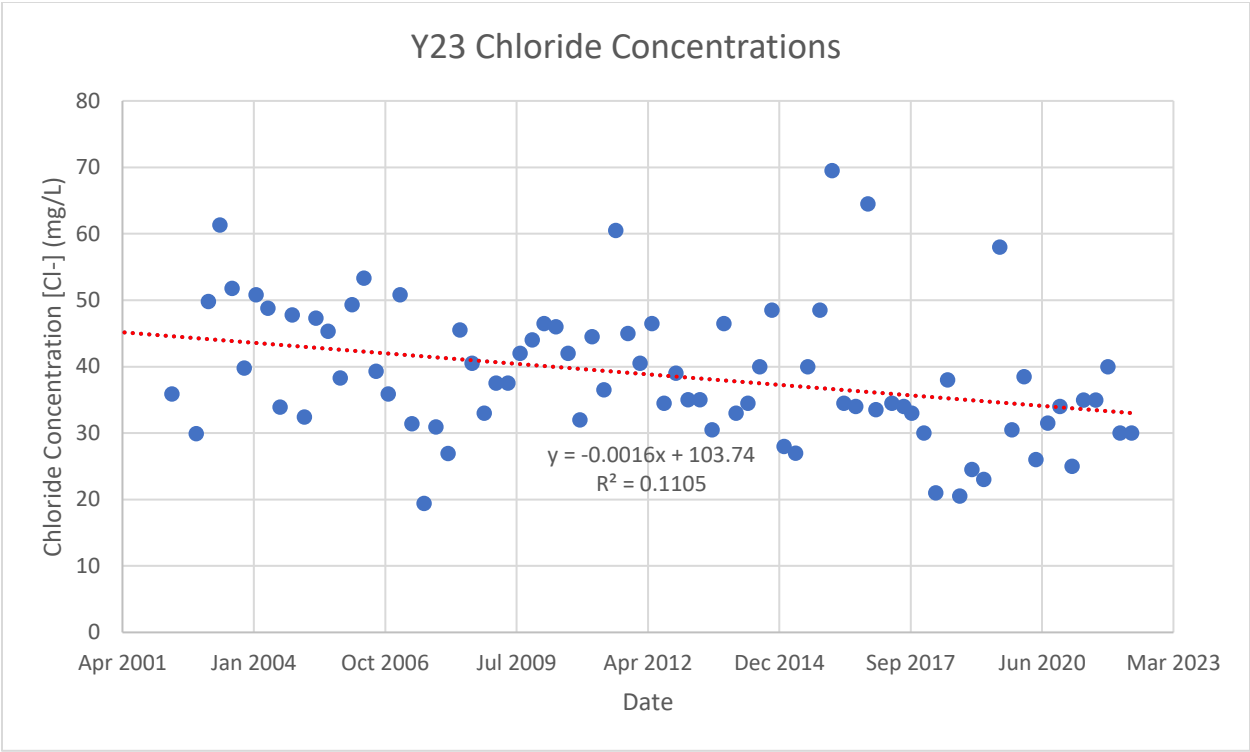






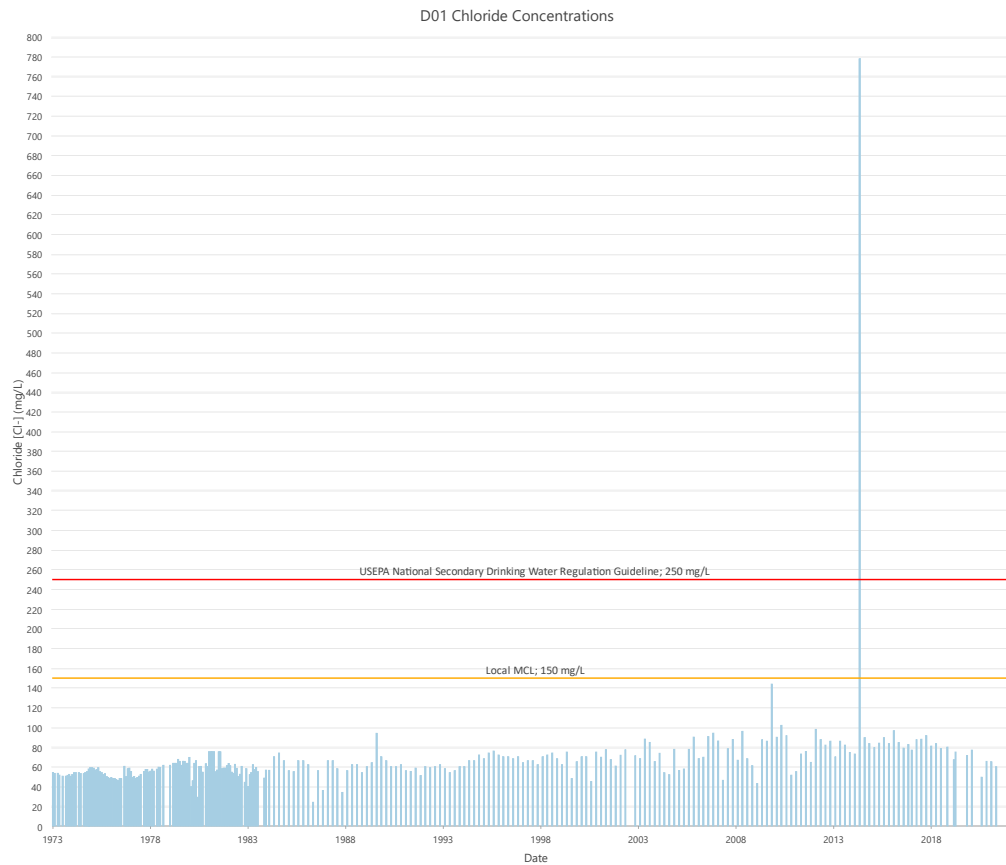


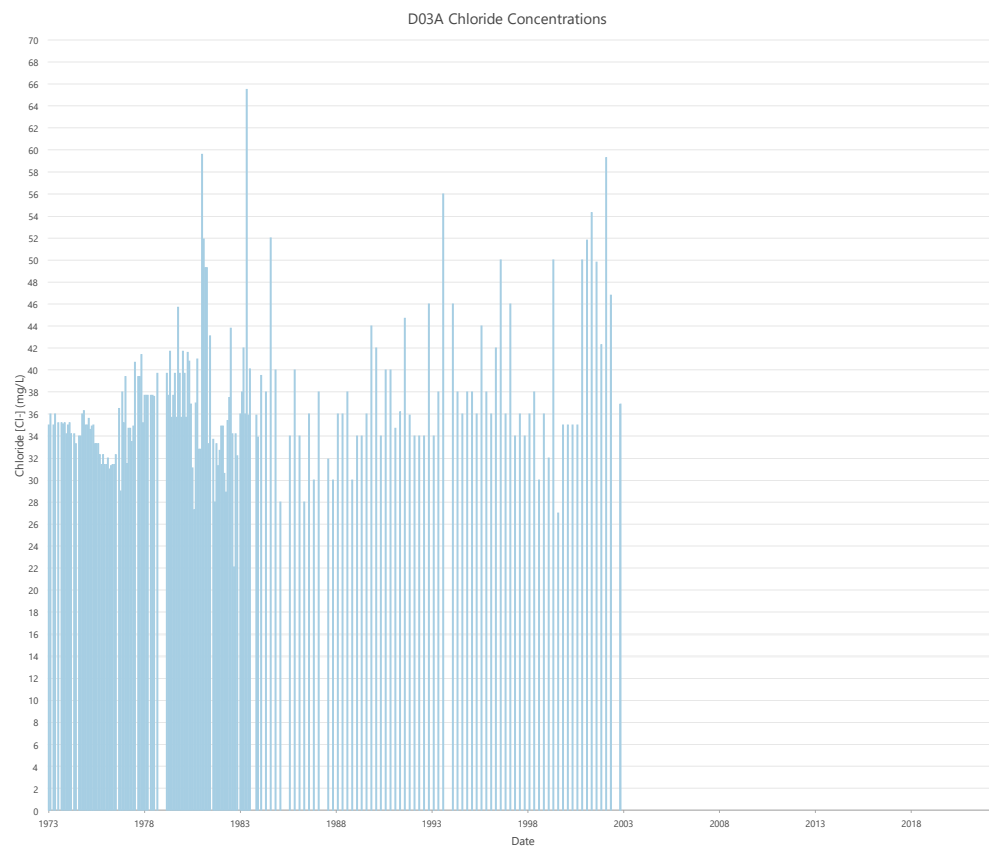
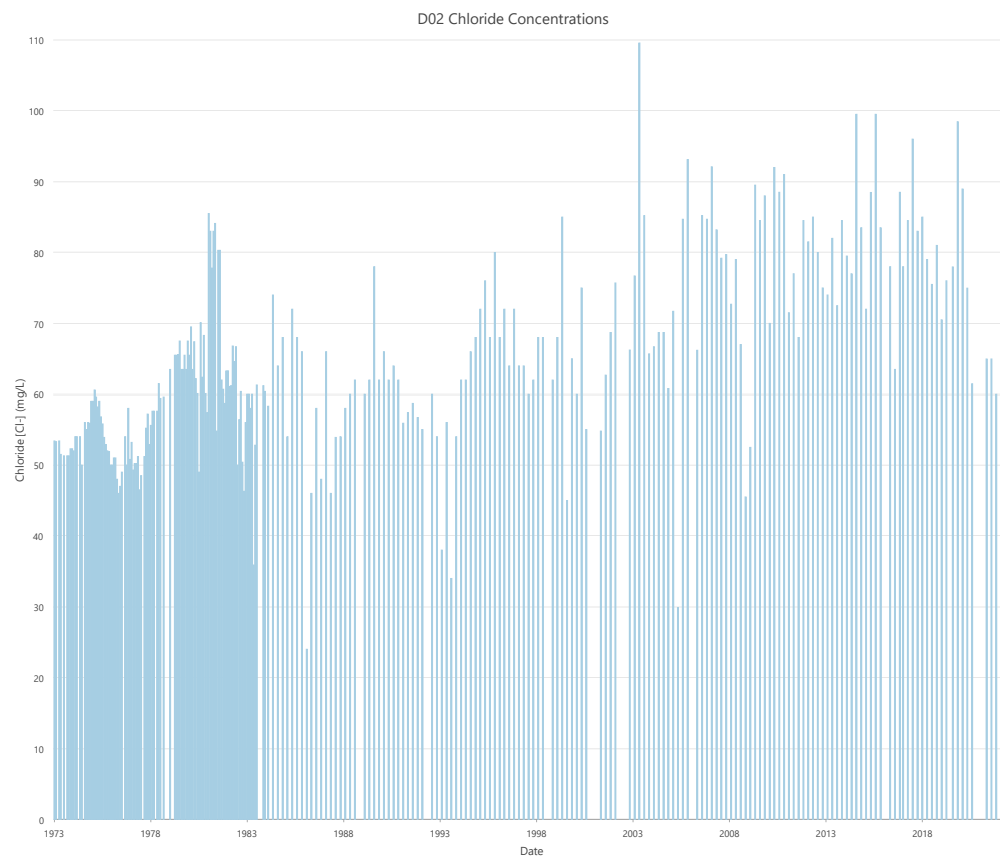


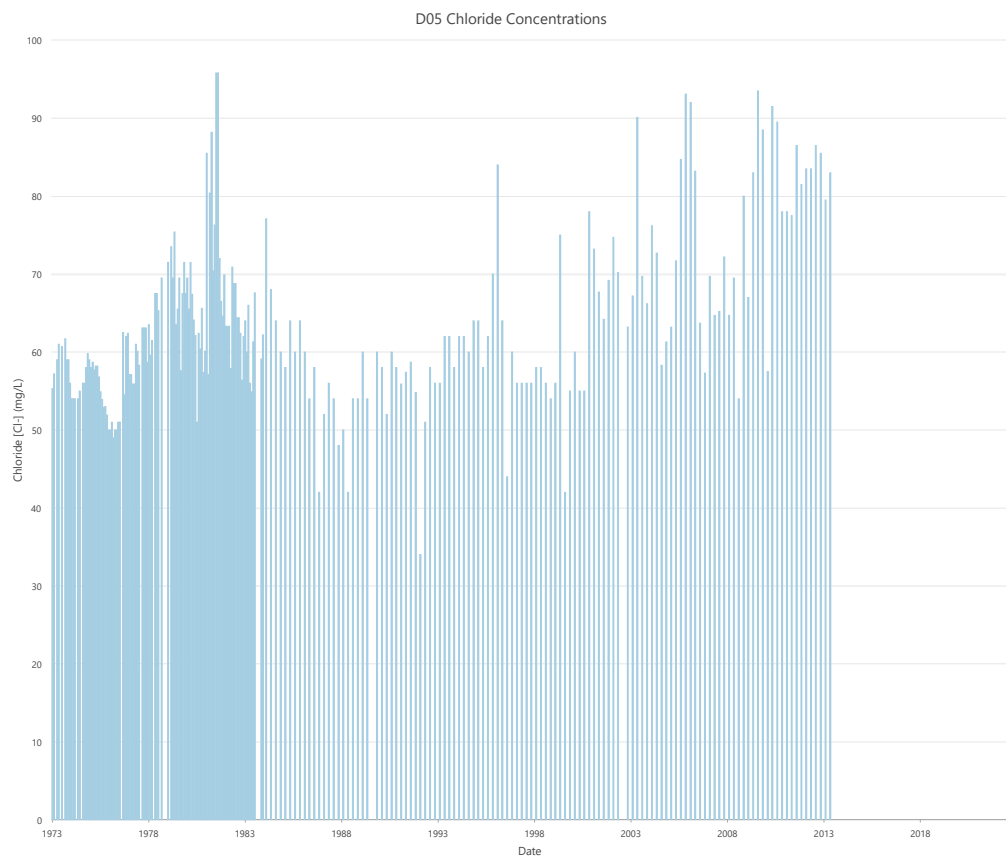
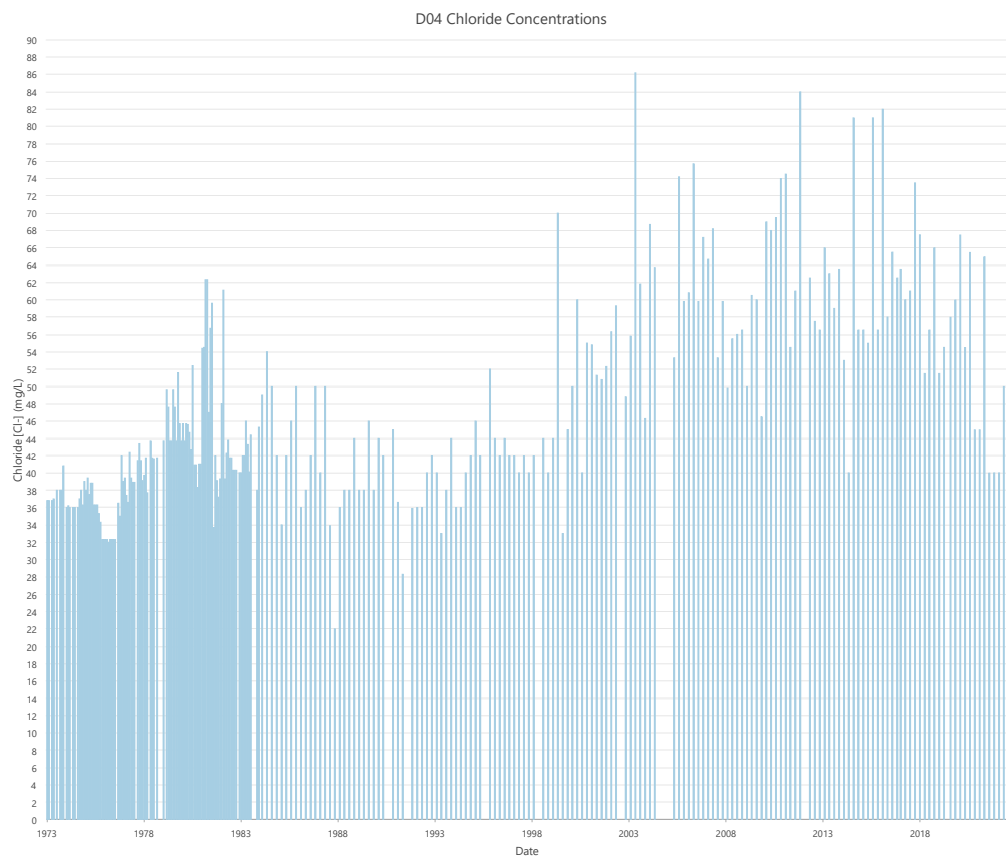


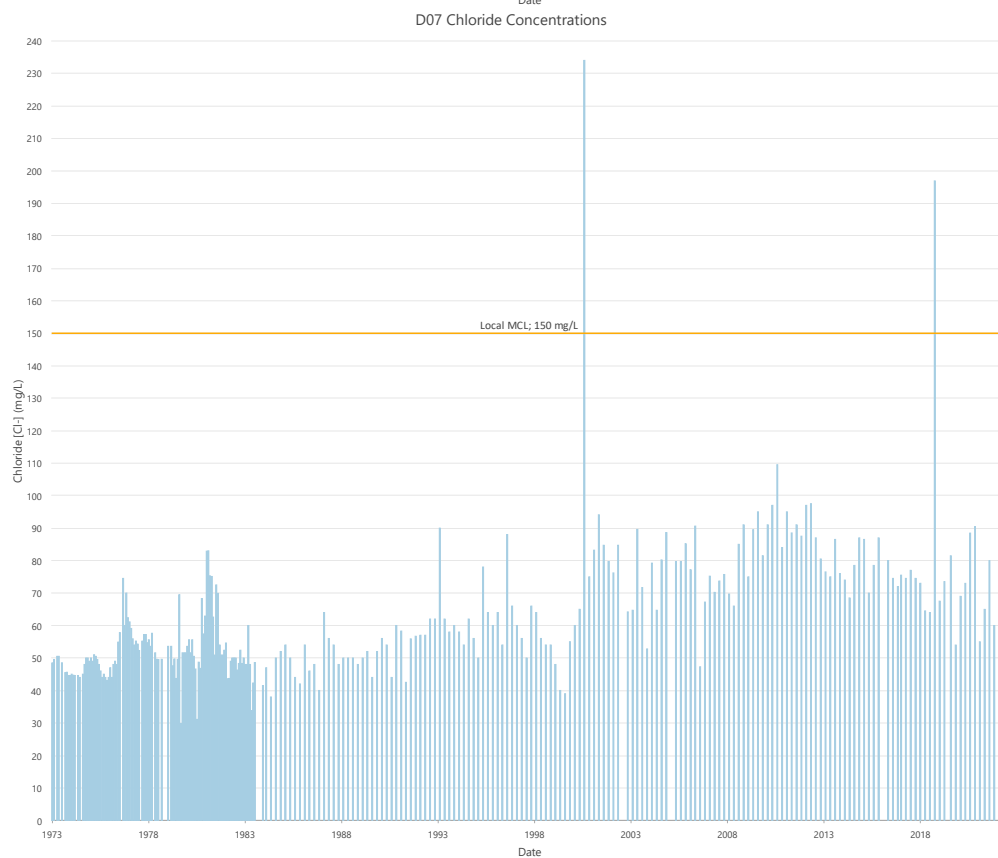
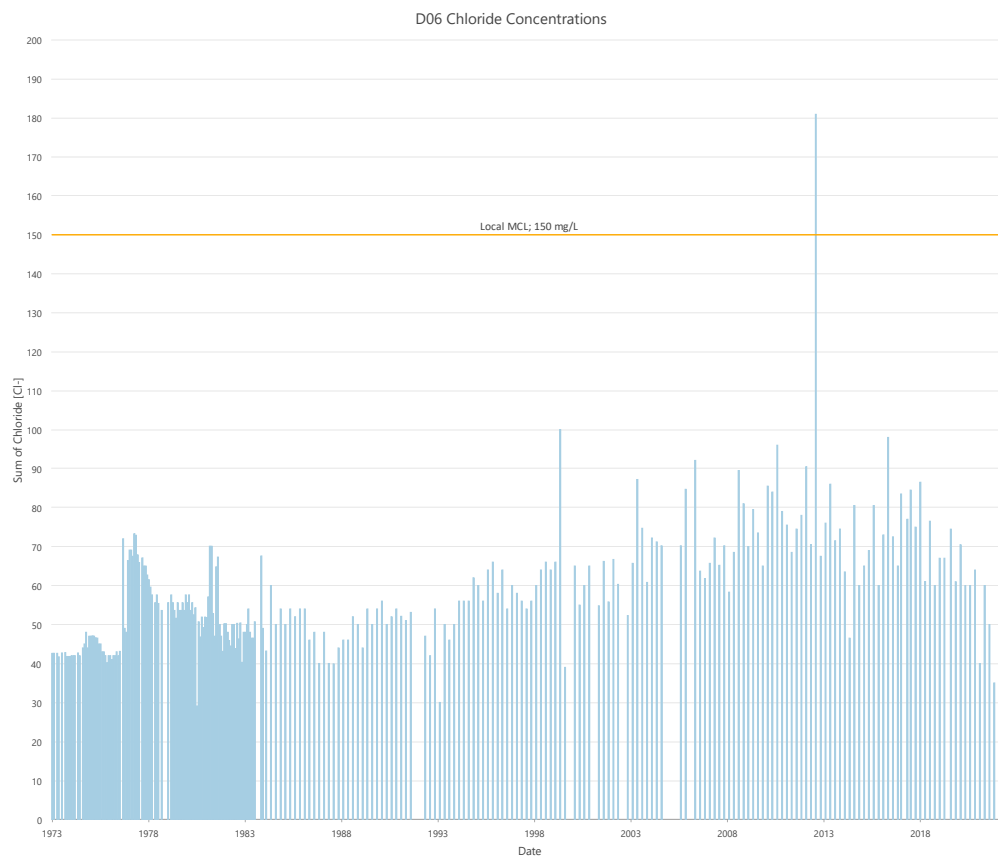
## Appendix C: Bar Graphs with Guidelines for the Chloride Concentrations of Individual Wells

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

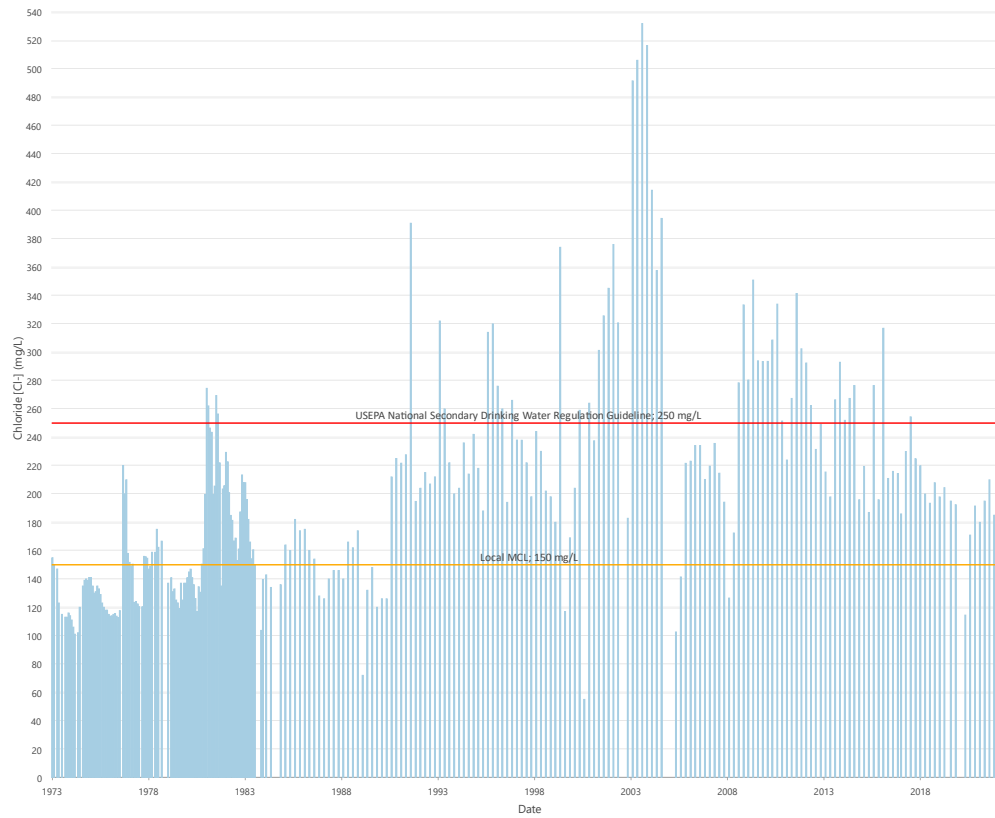




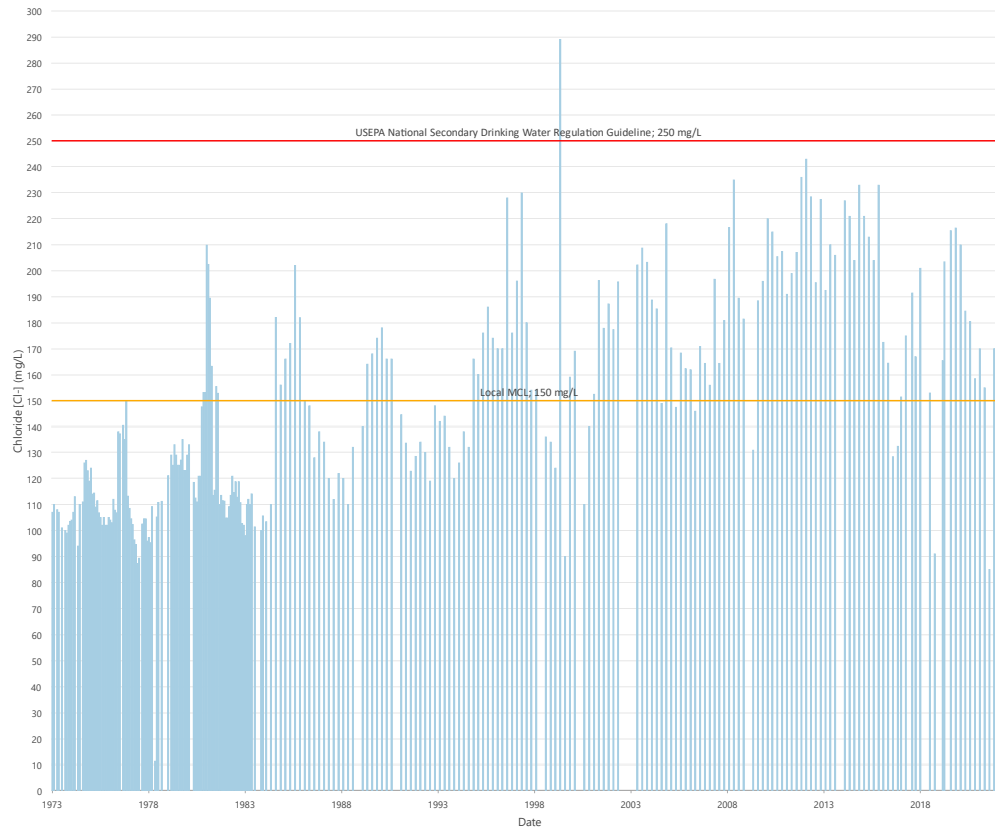


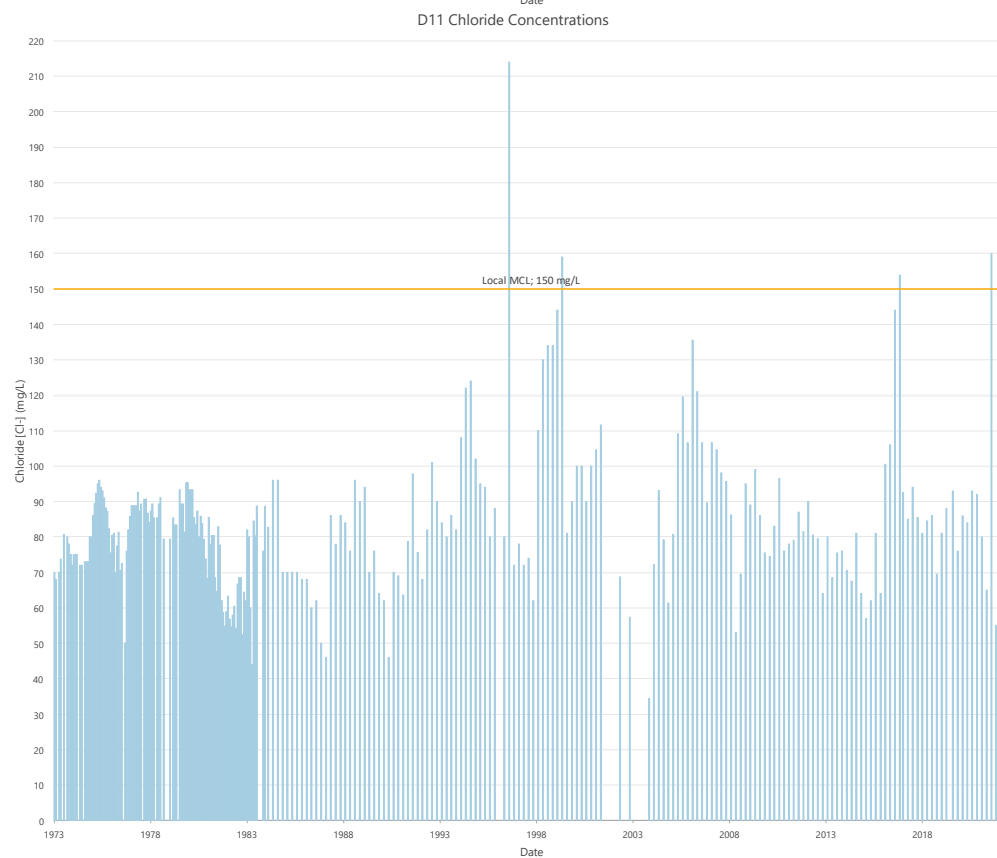
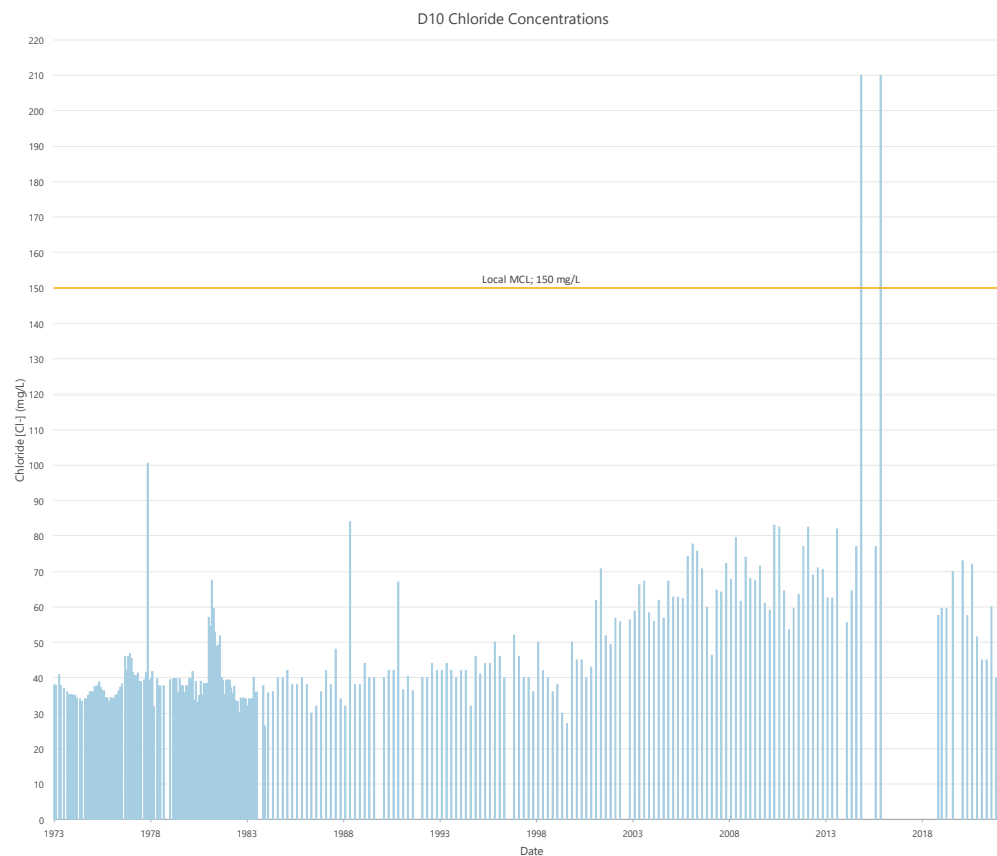


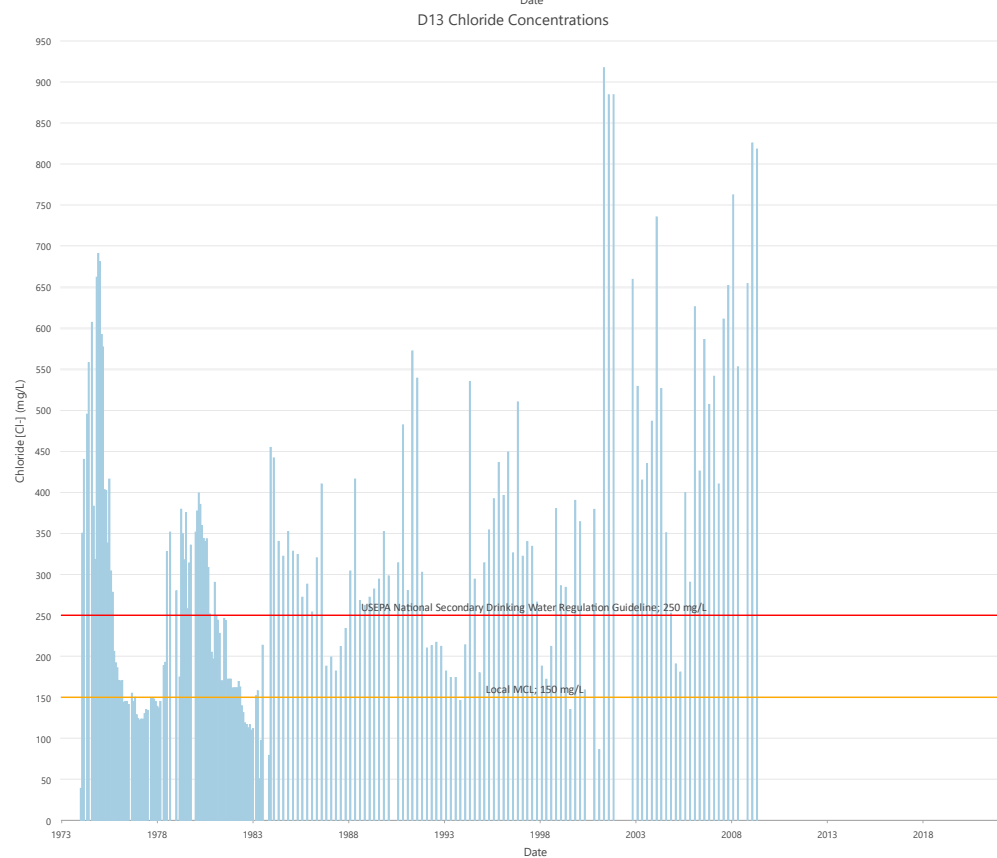
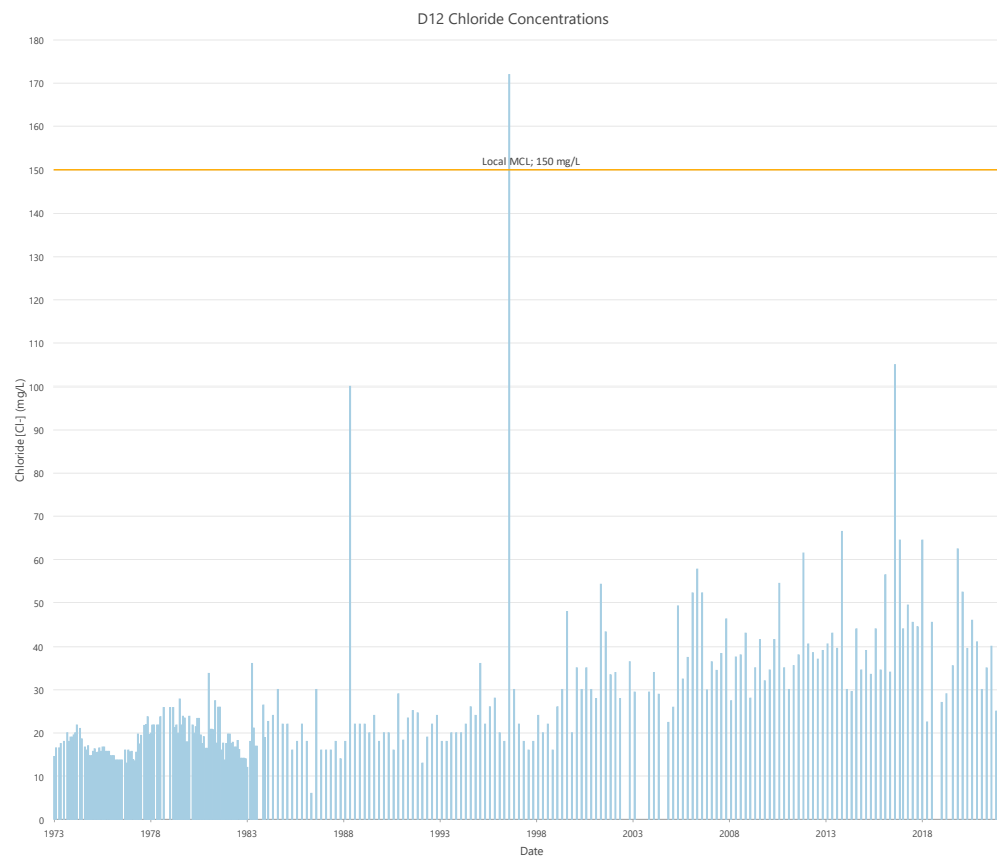
D08 Chloride Concentrations



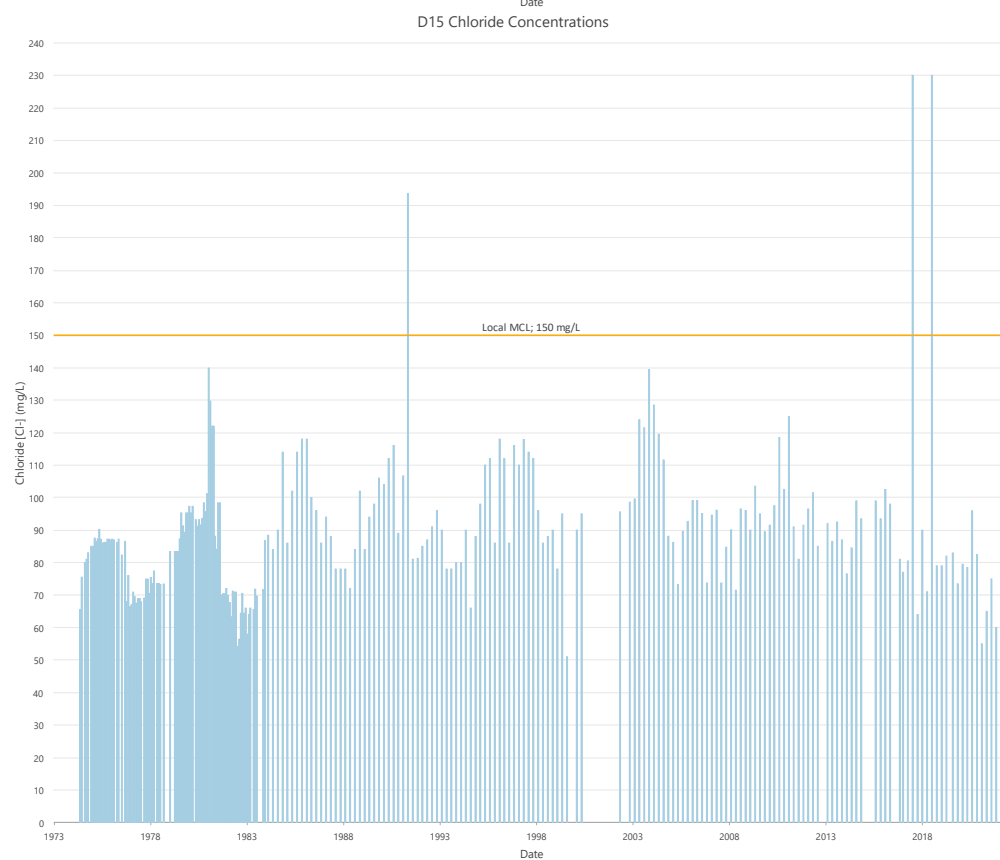
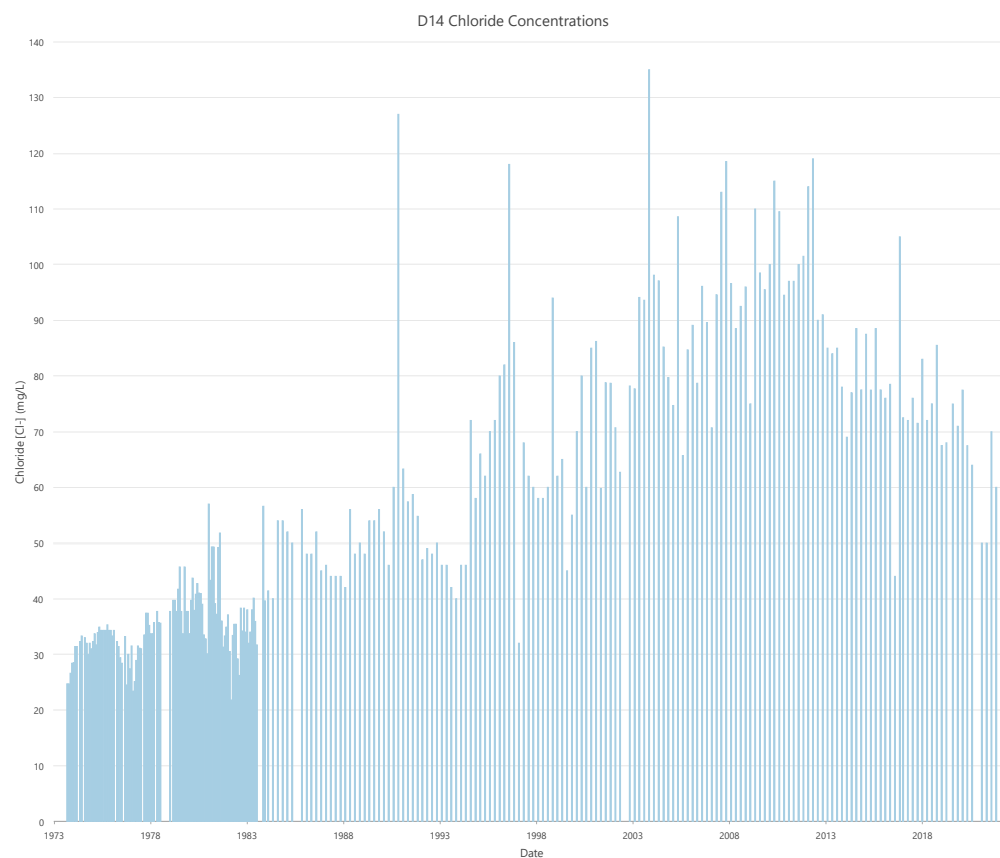
D09 Chloride Concentrations

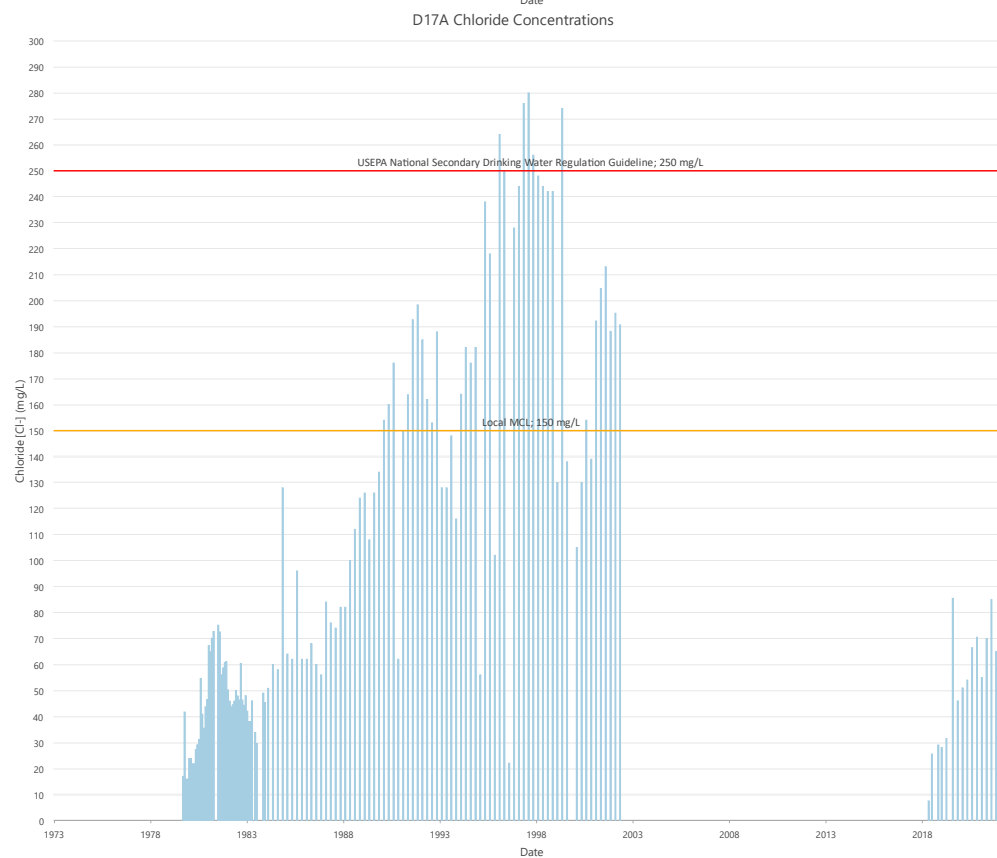
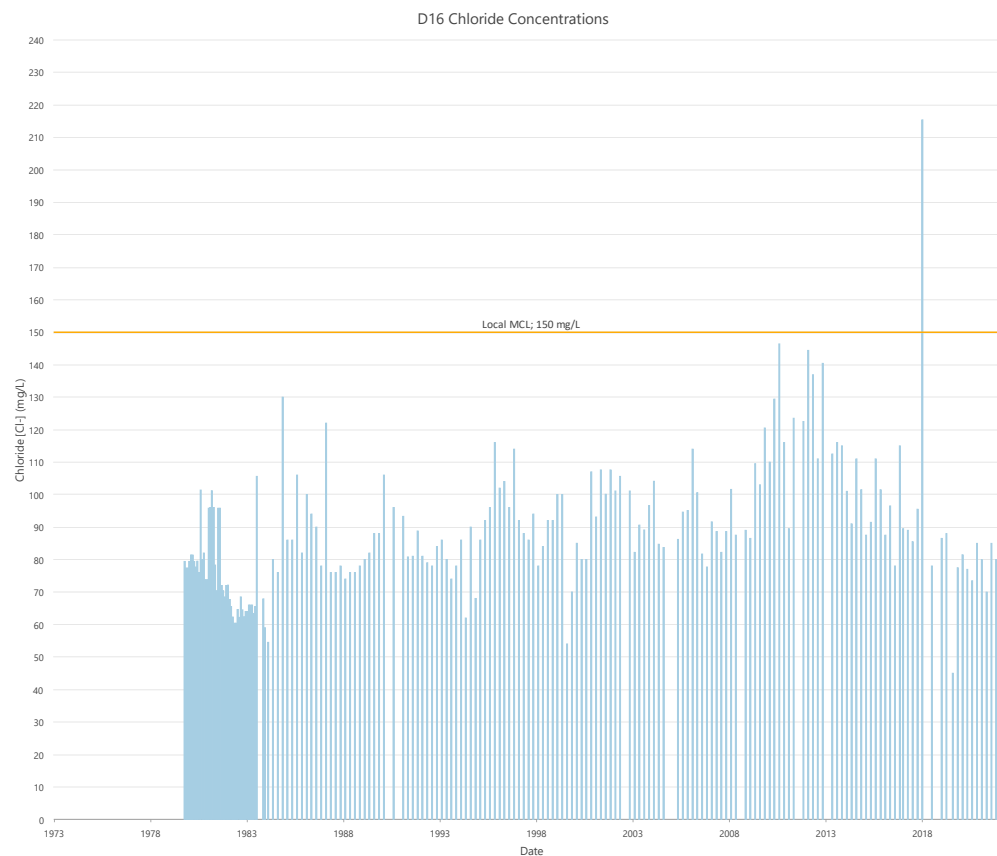


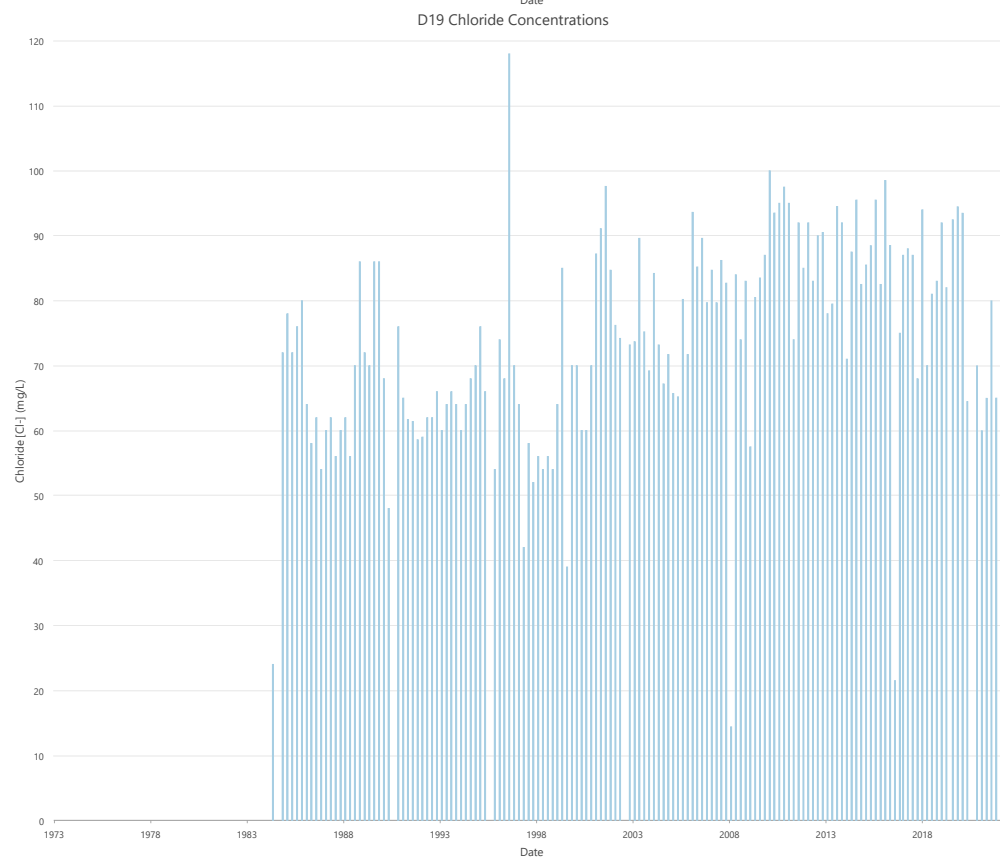
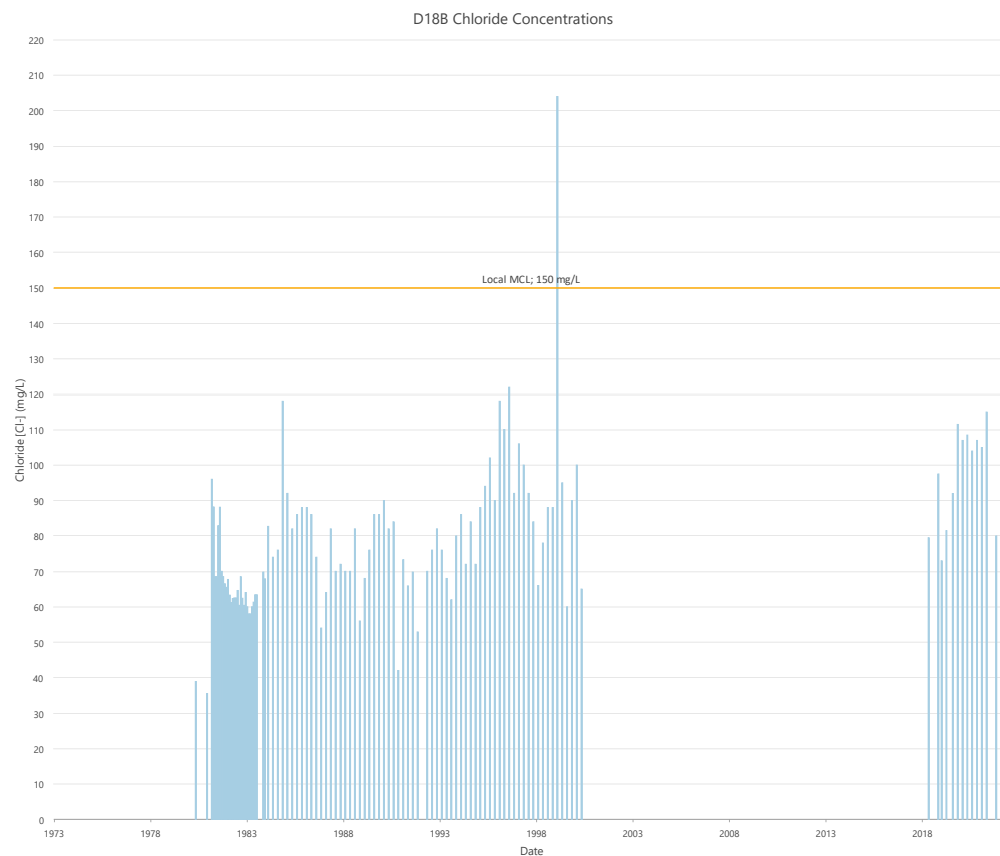


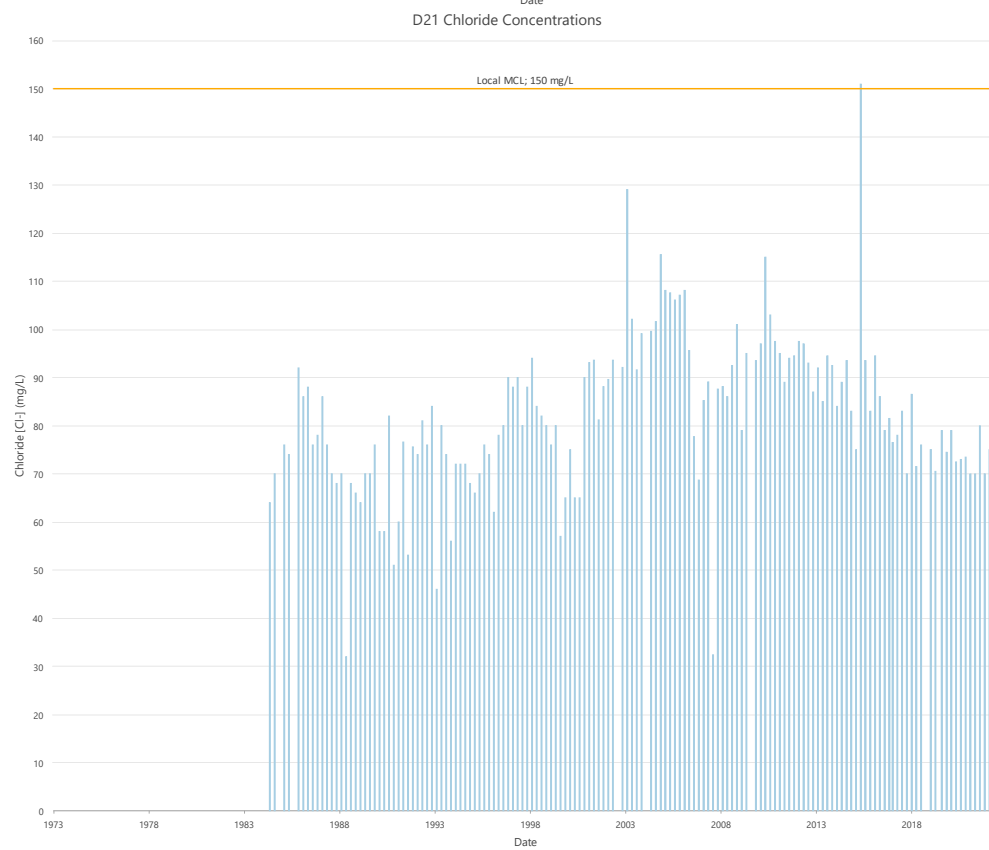
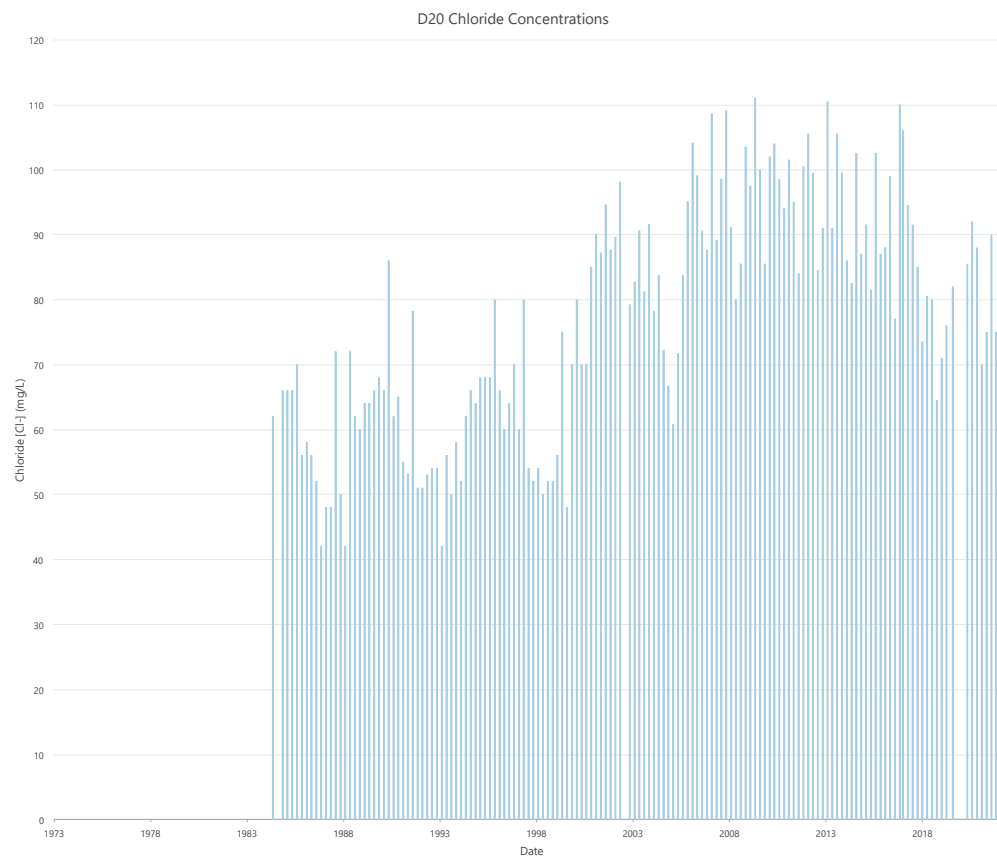


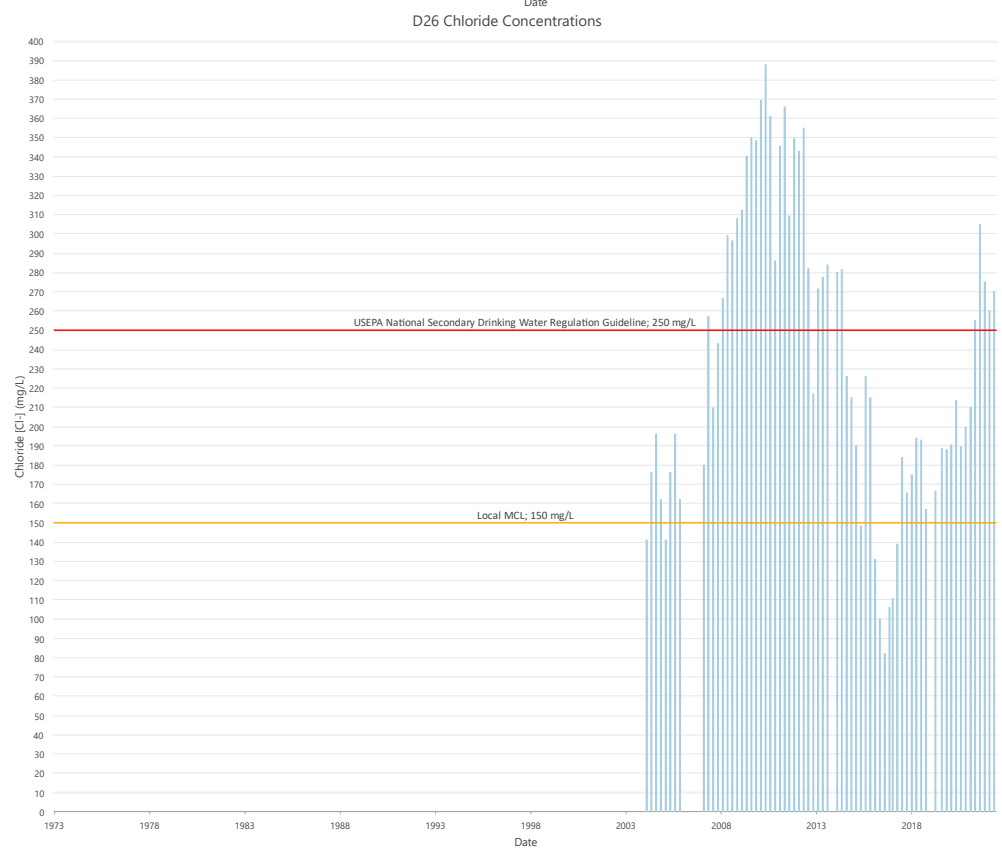
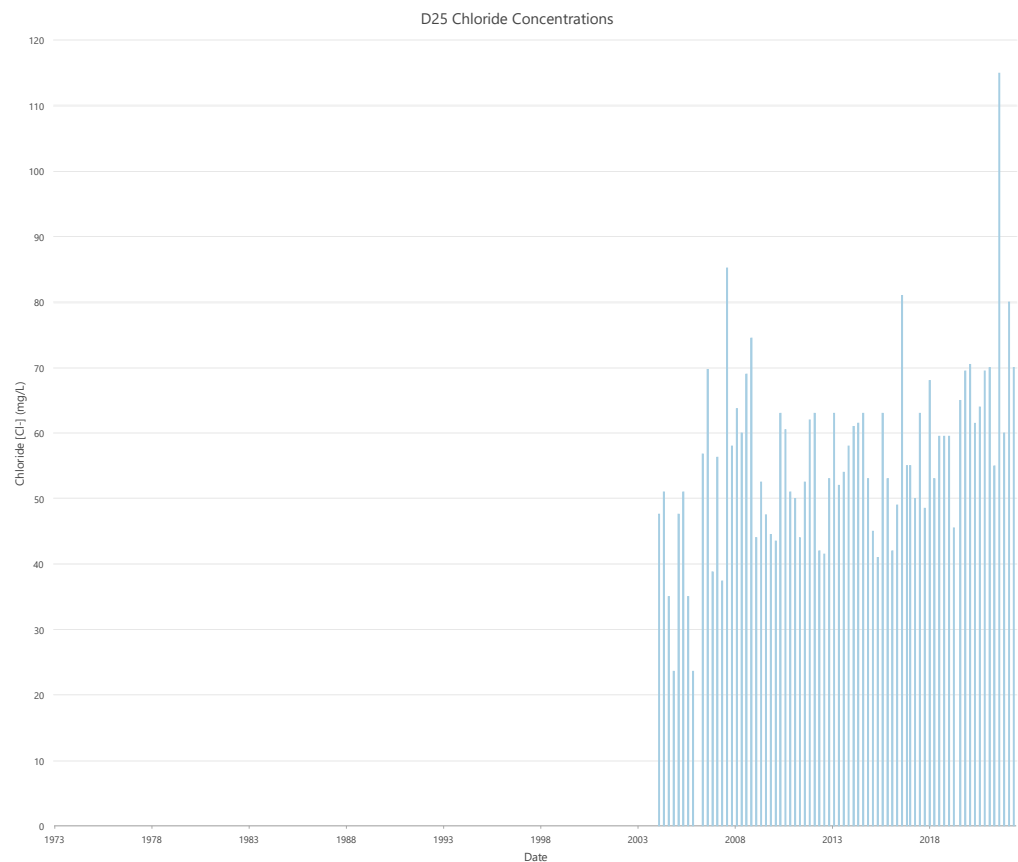


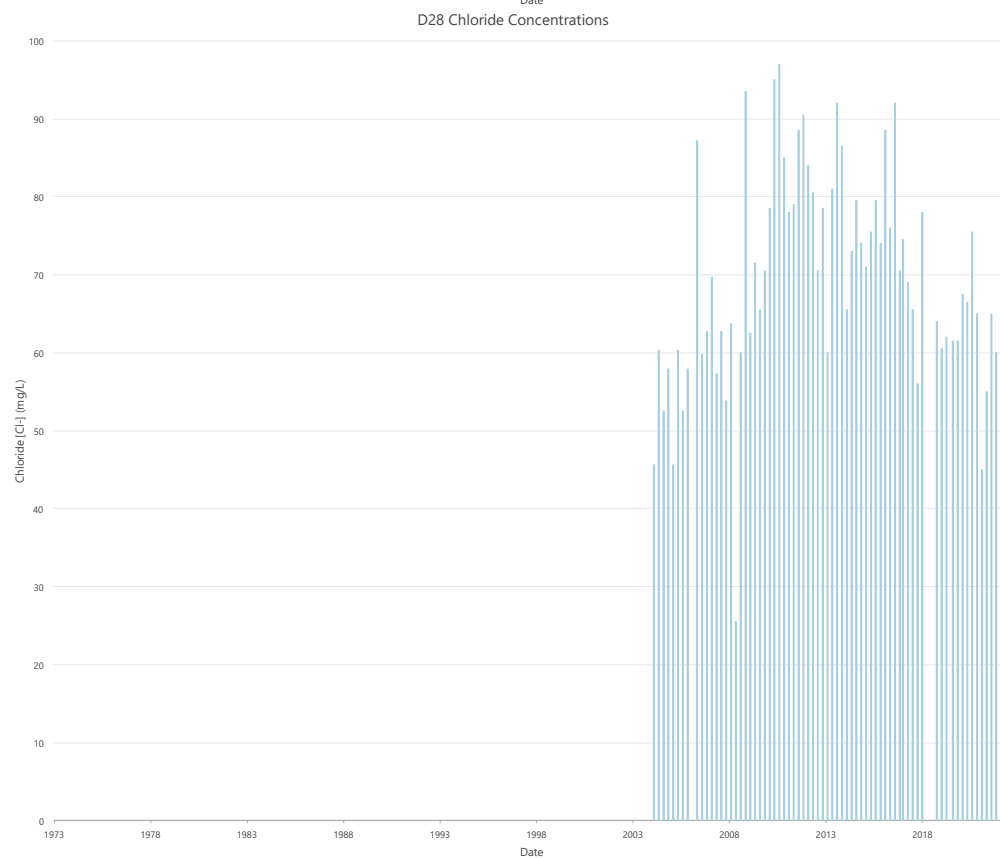
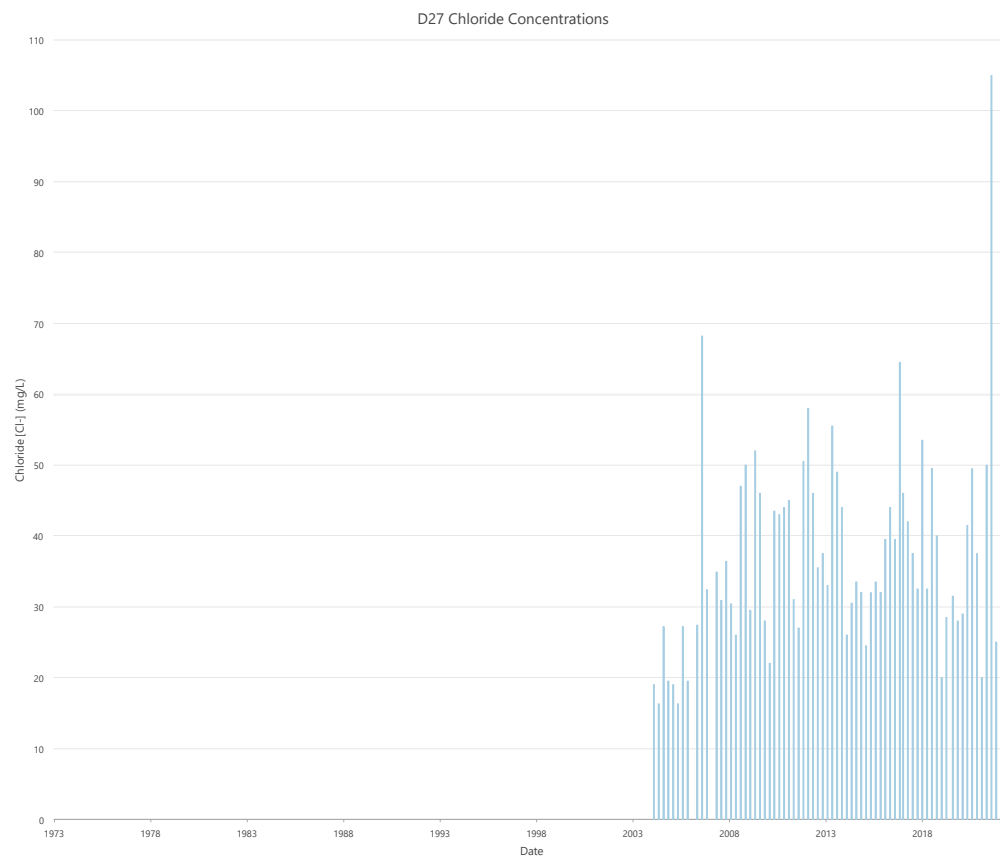


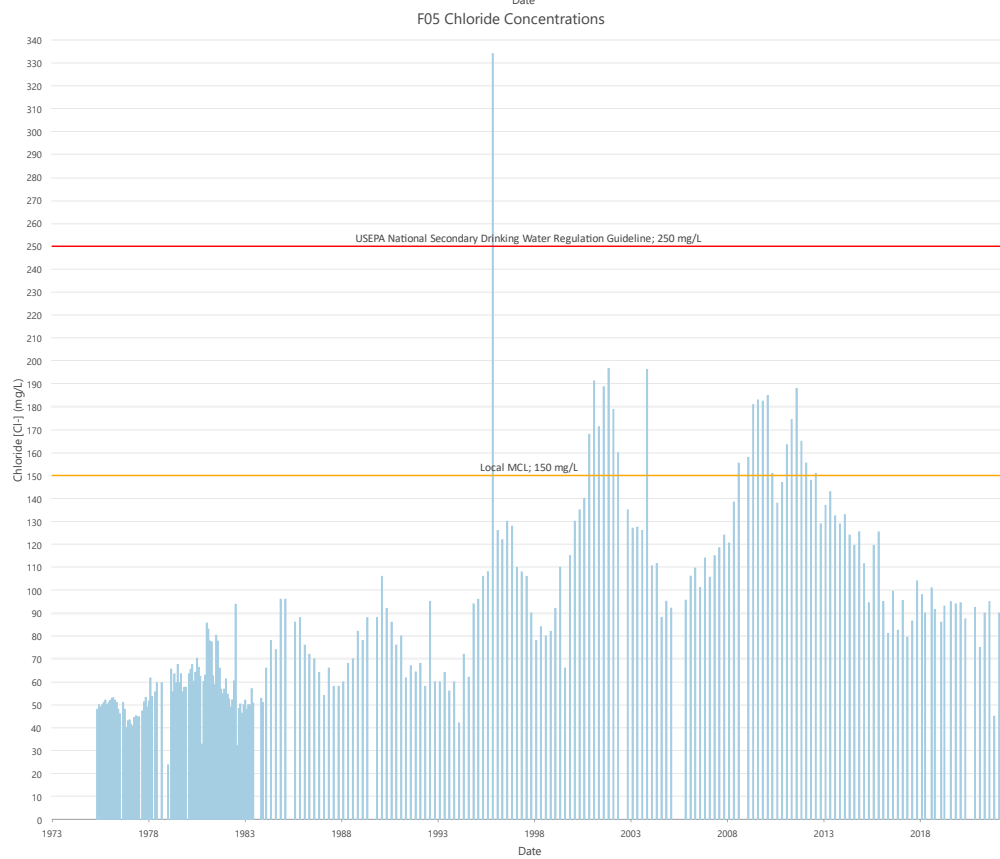
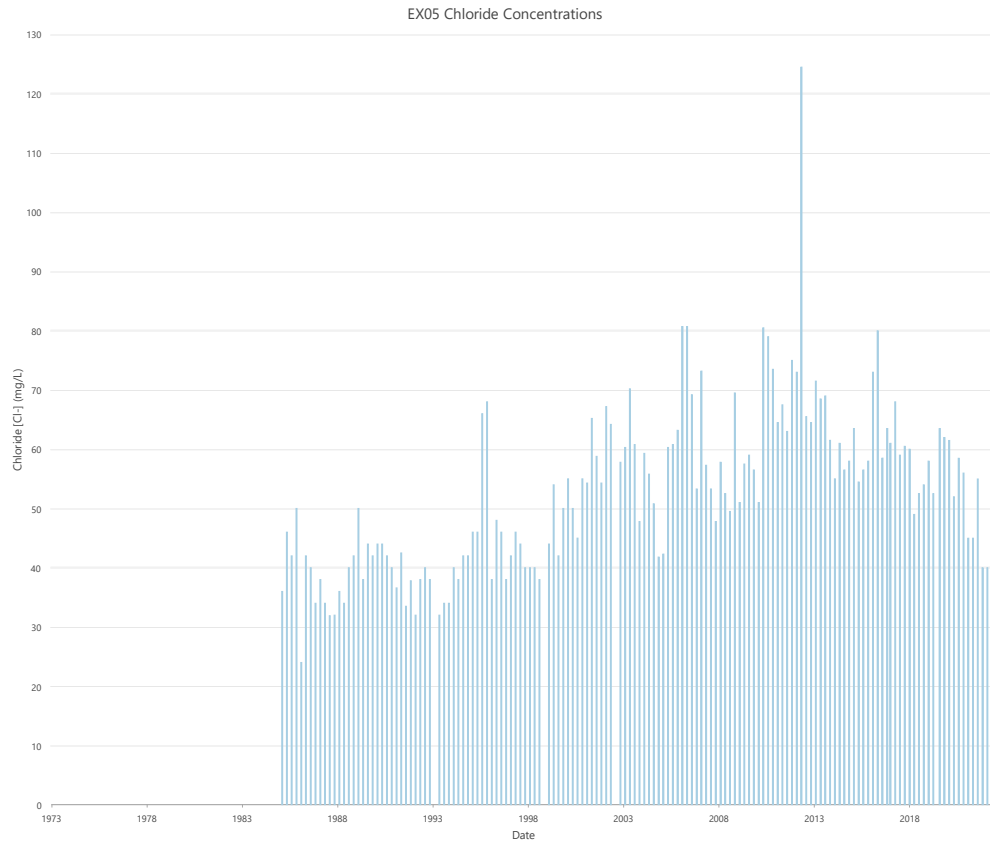


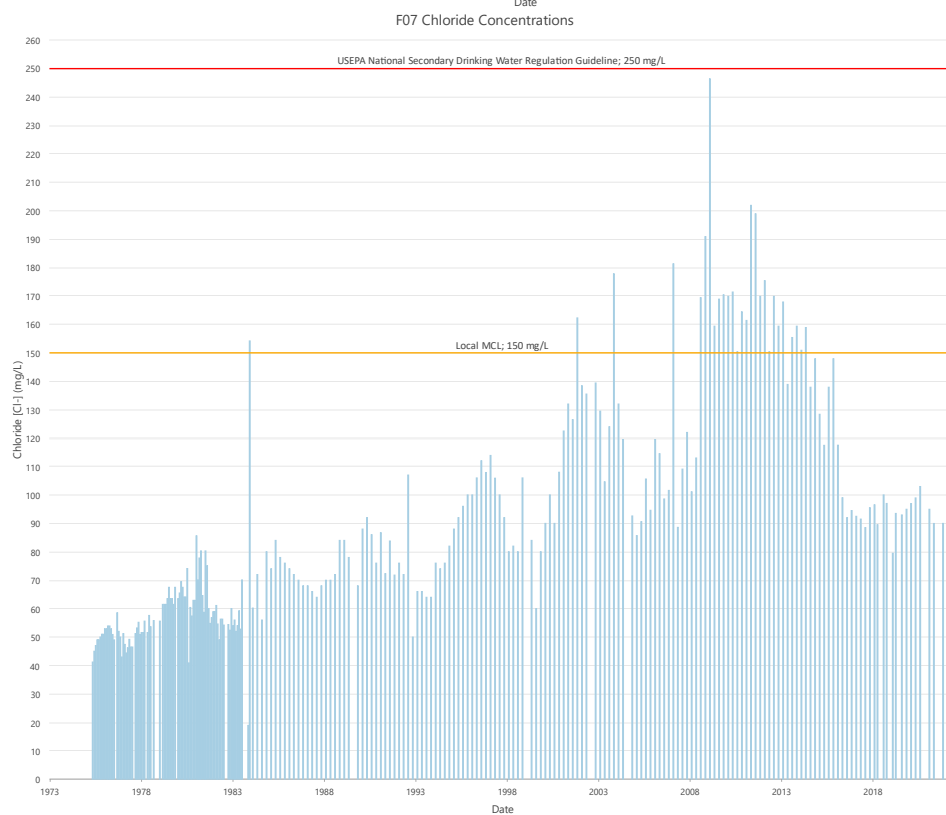
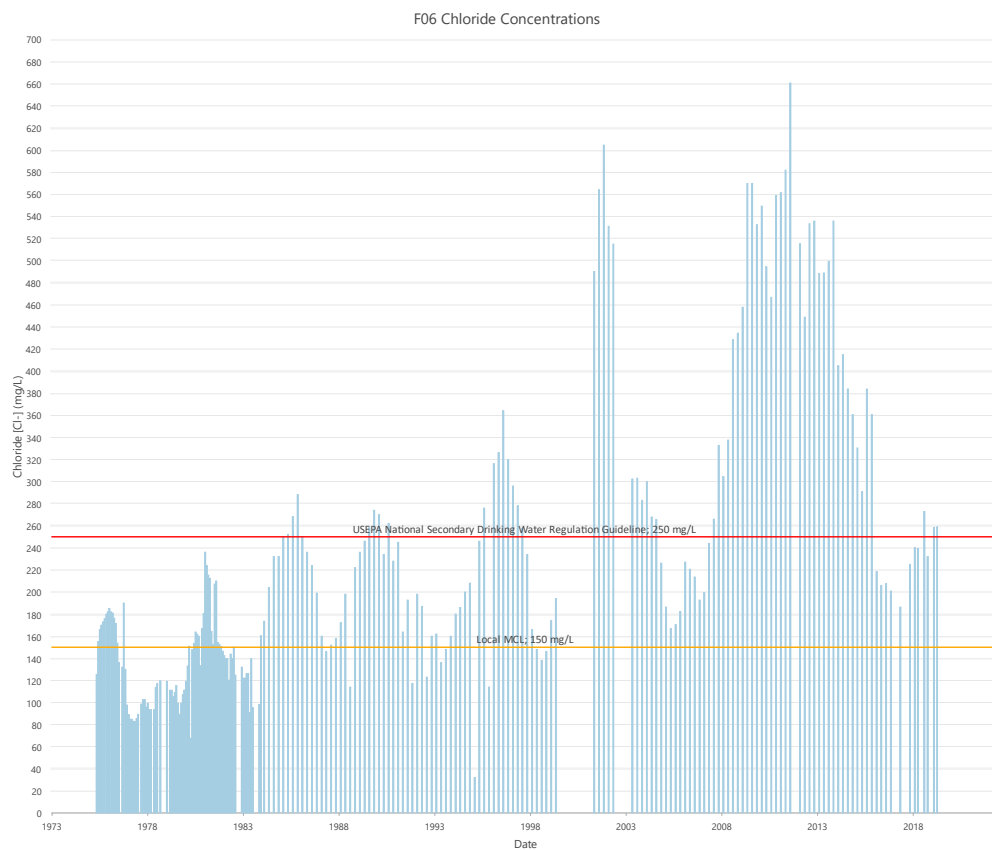




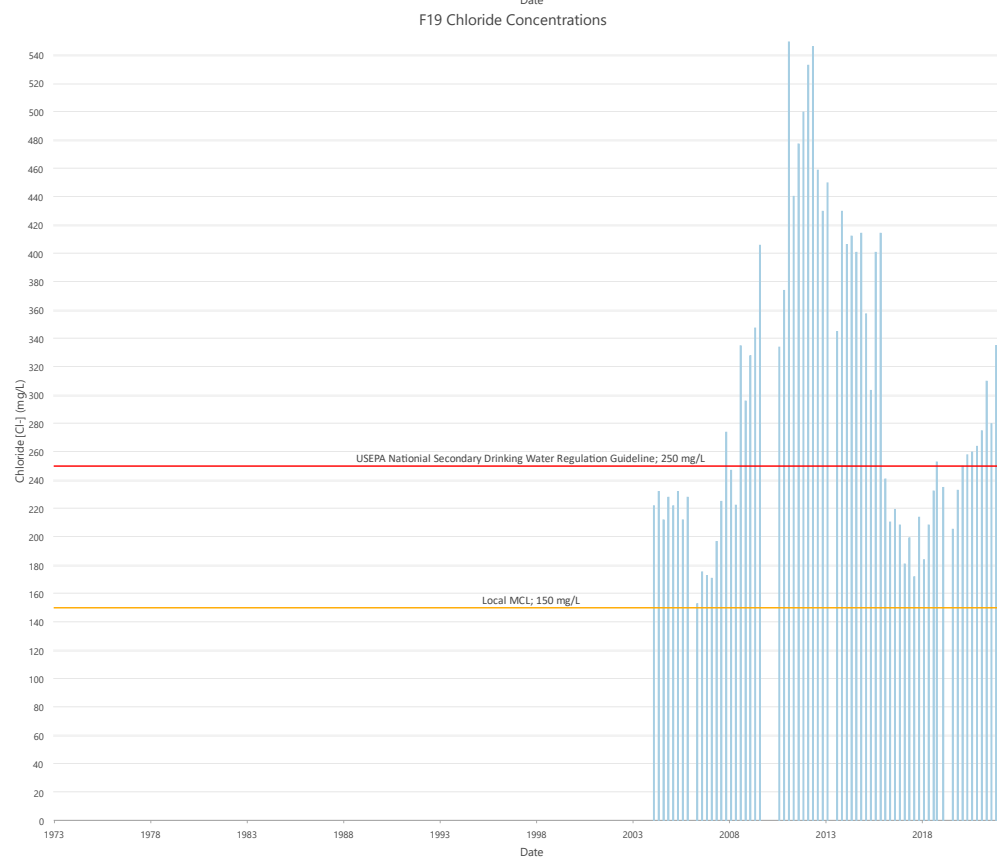
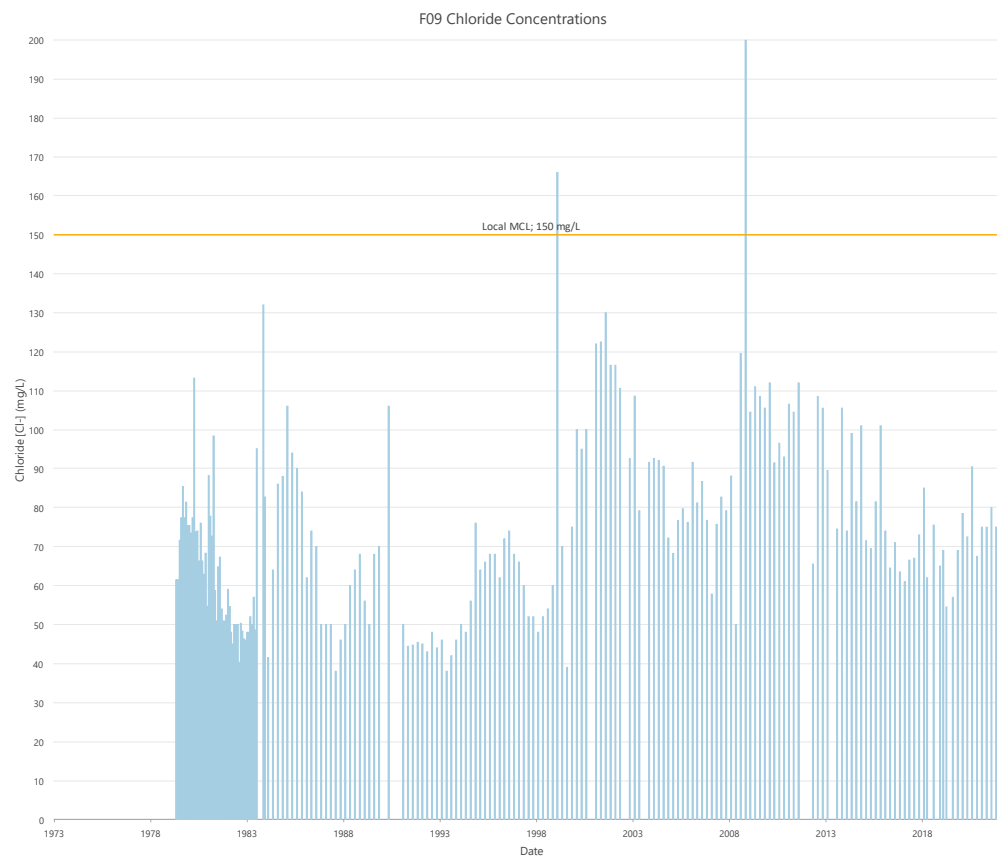


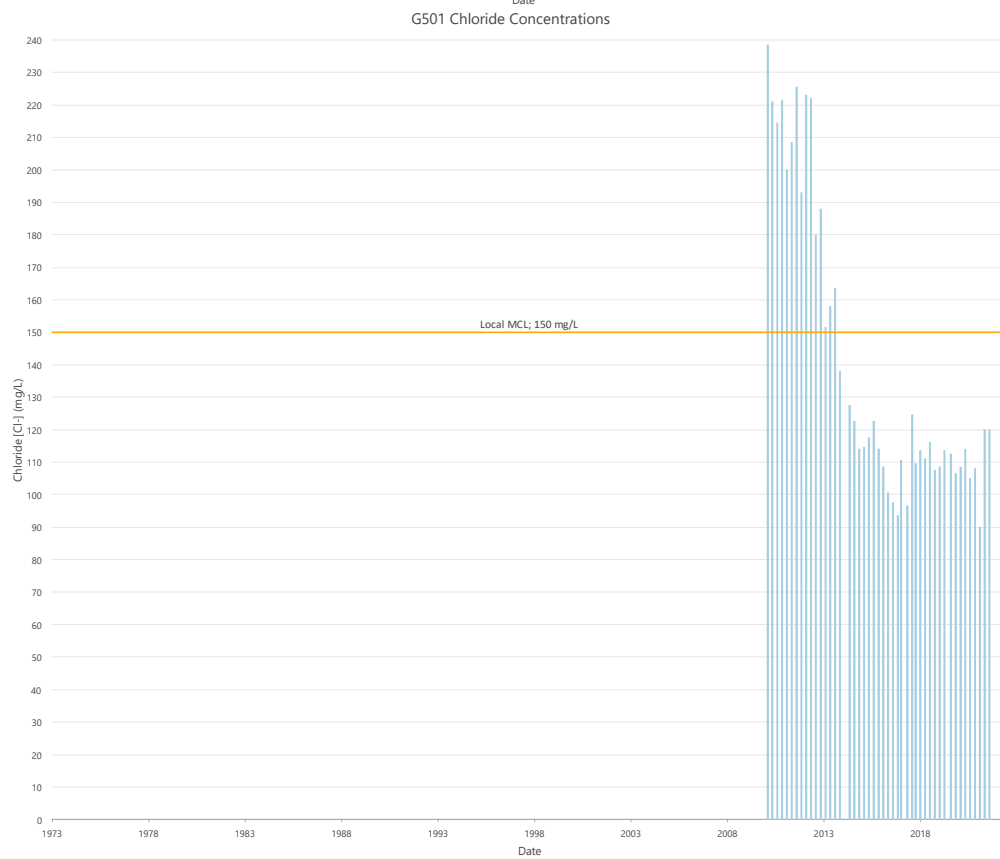
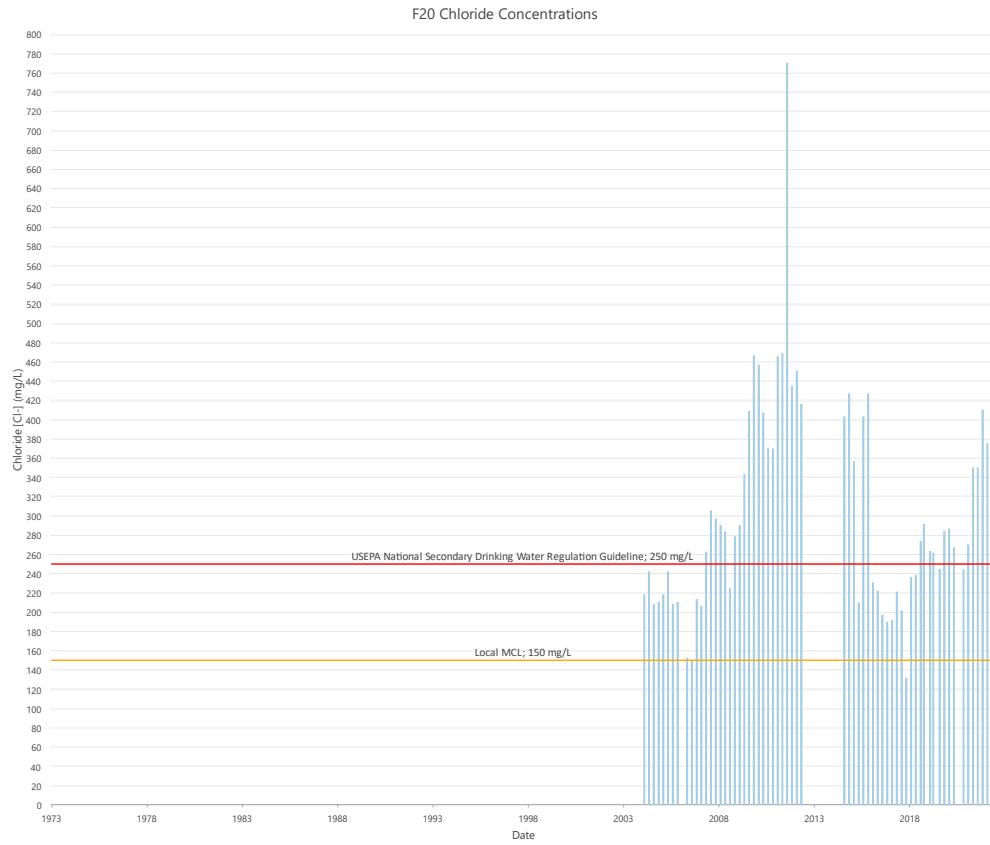


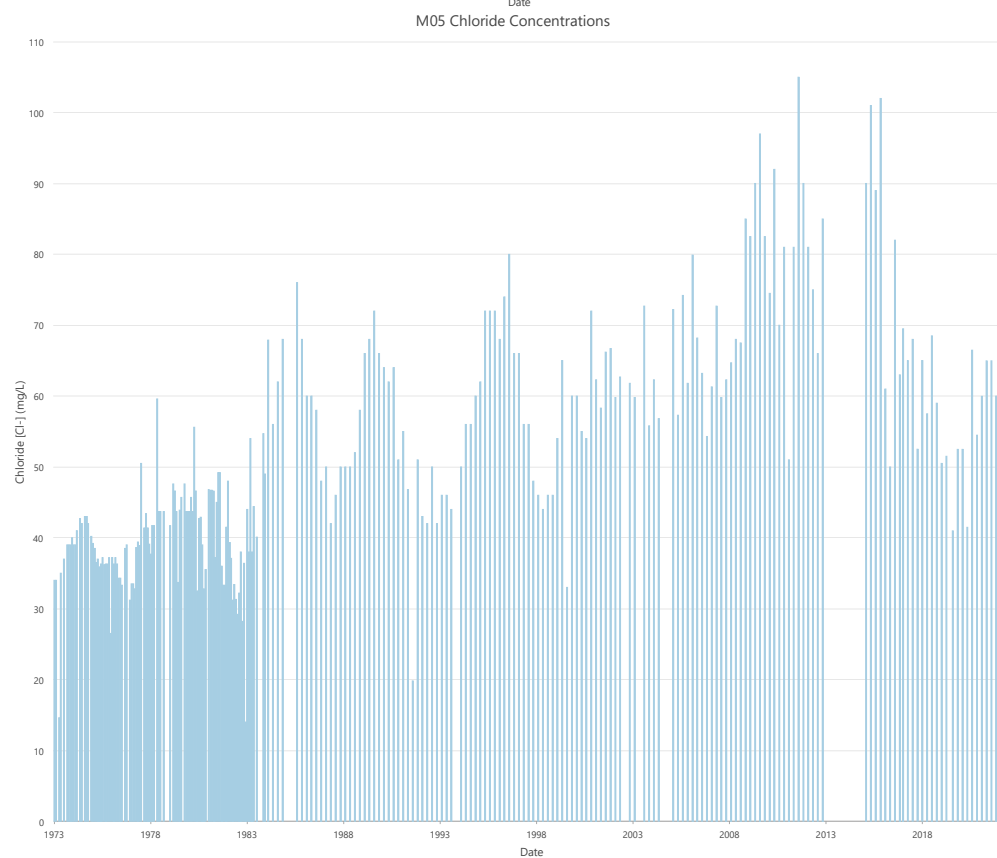
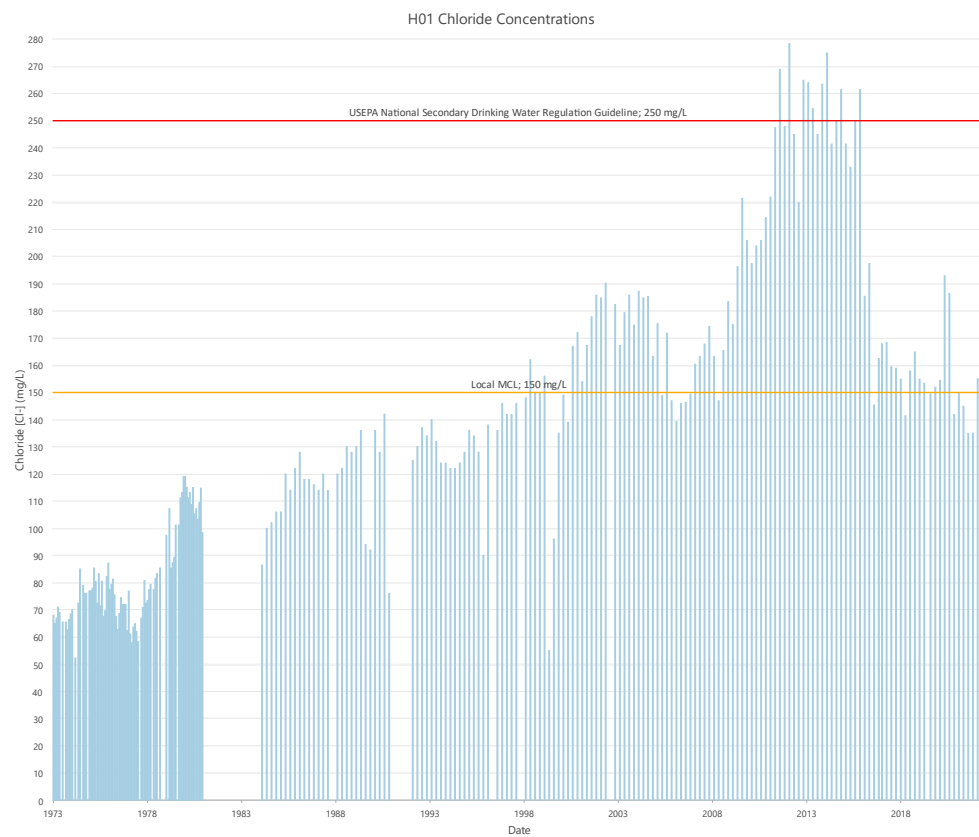


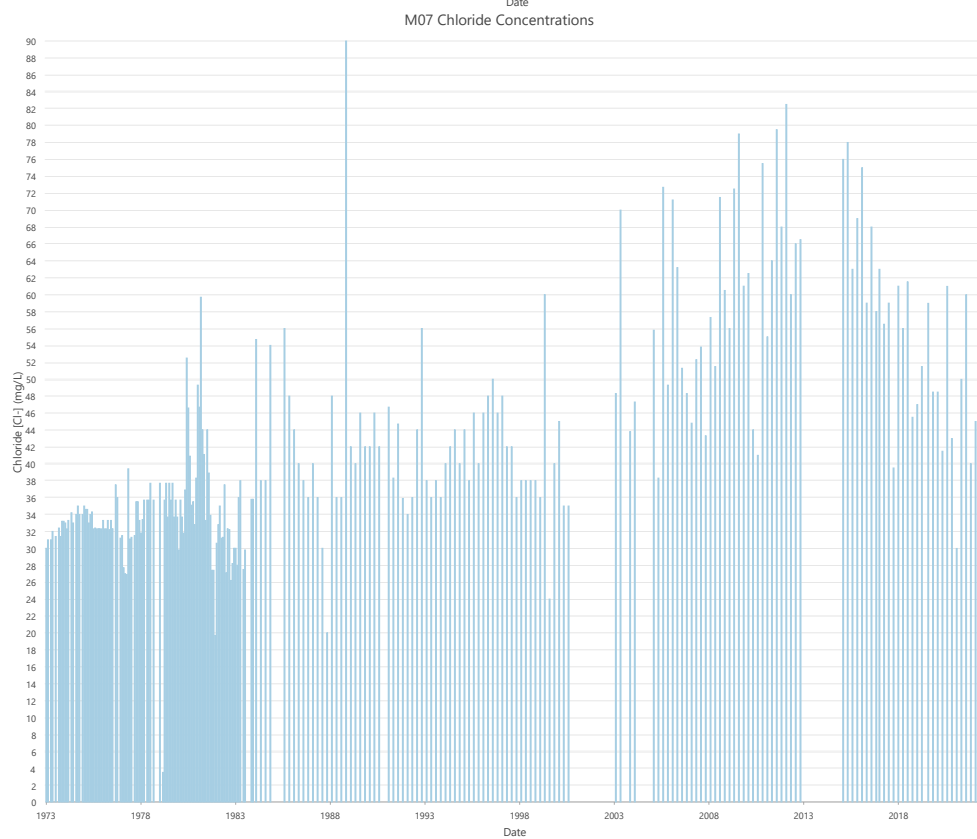
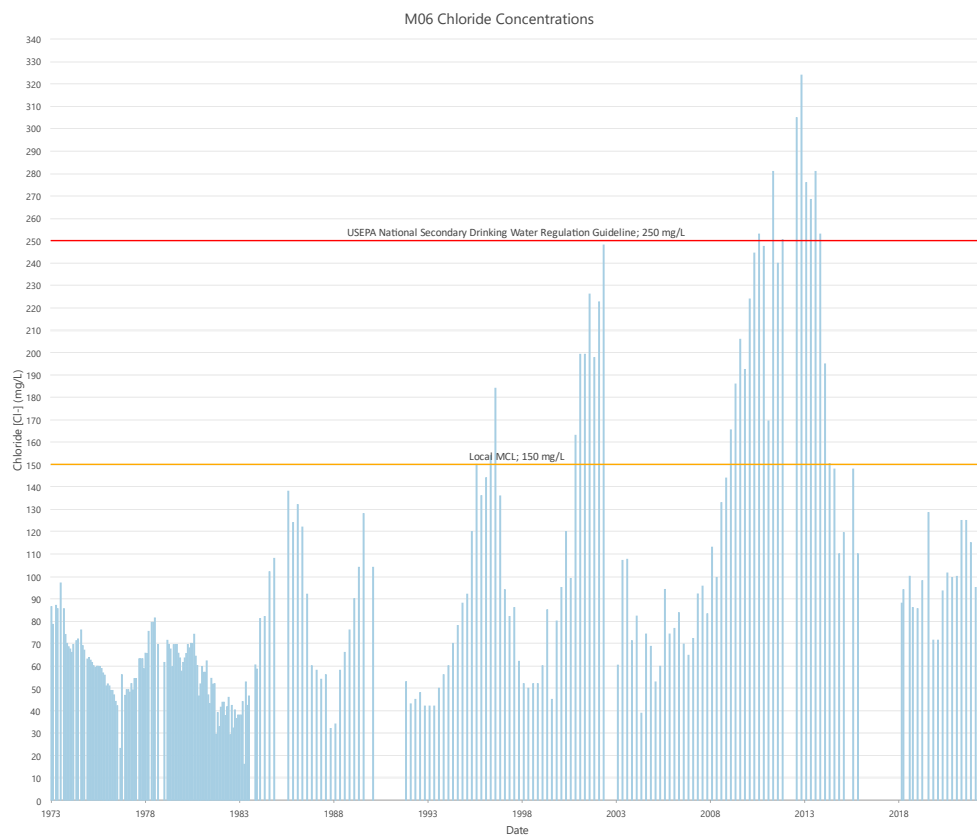


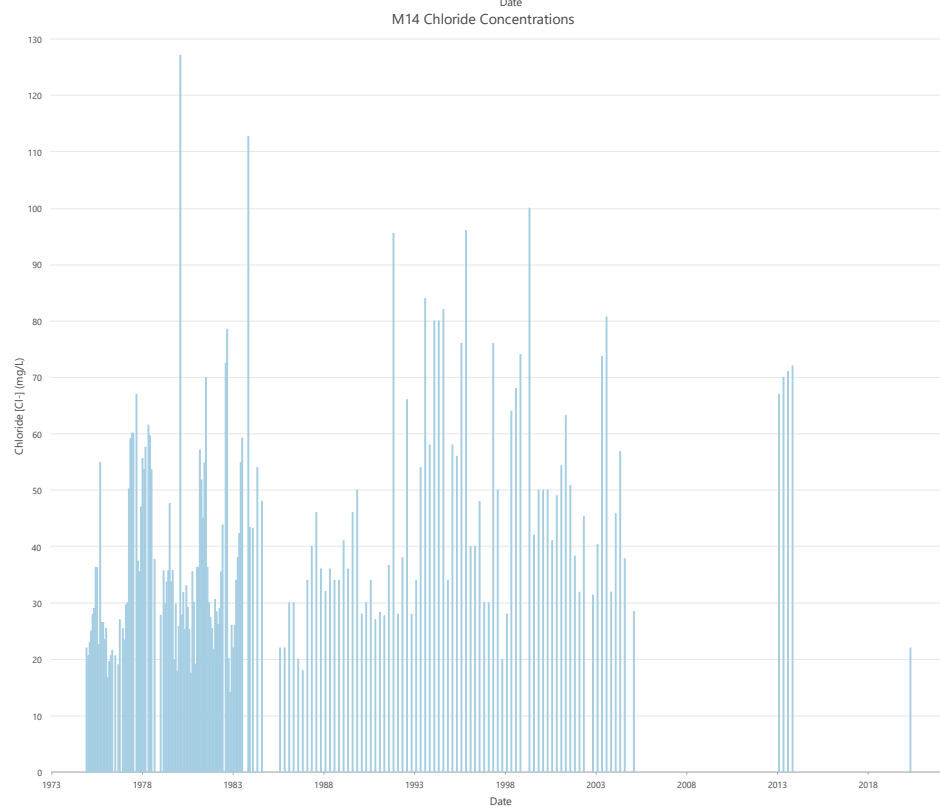
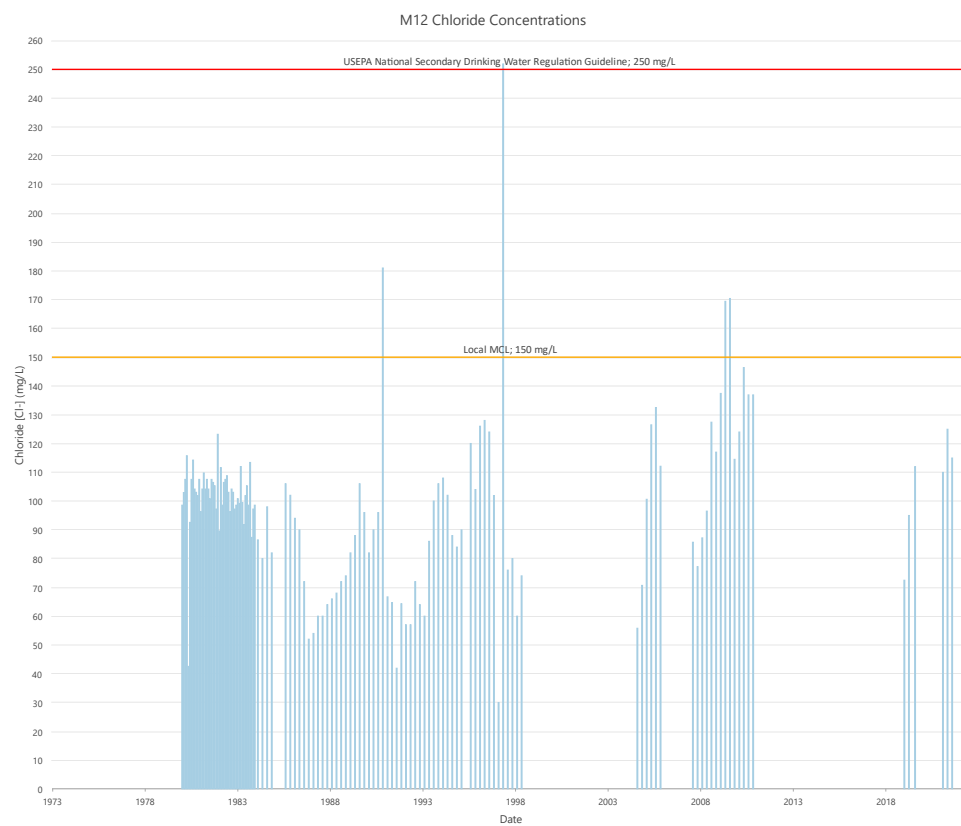


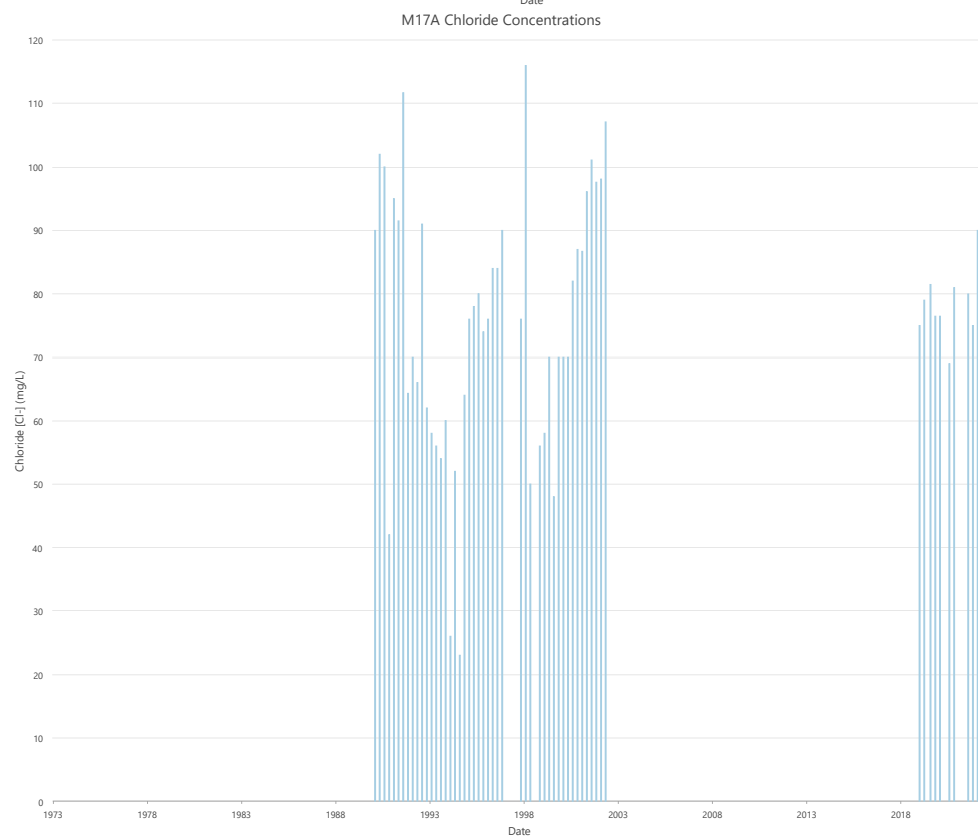
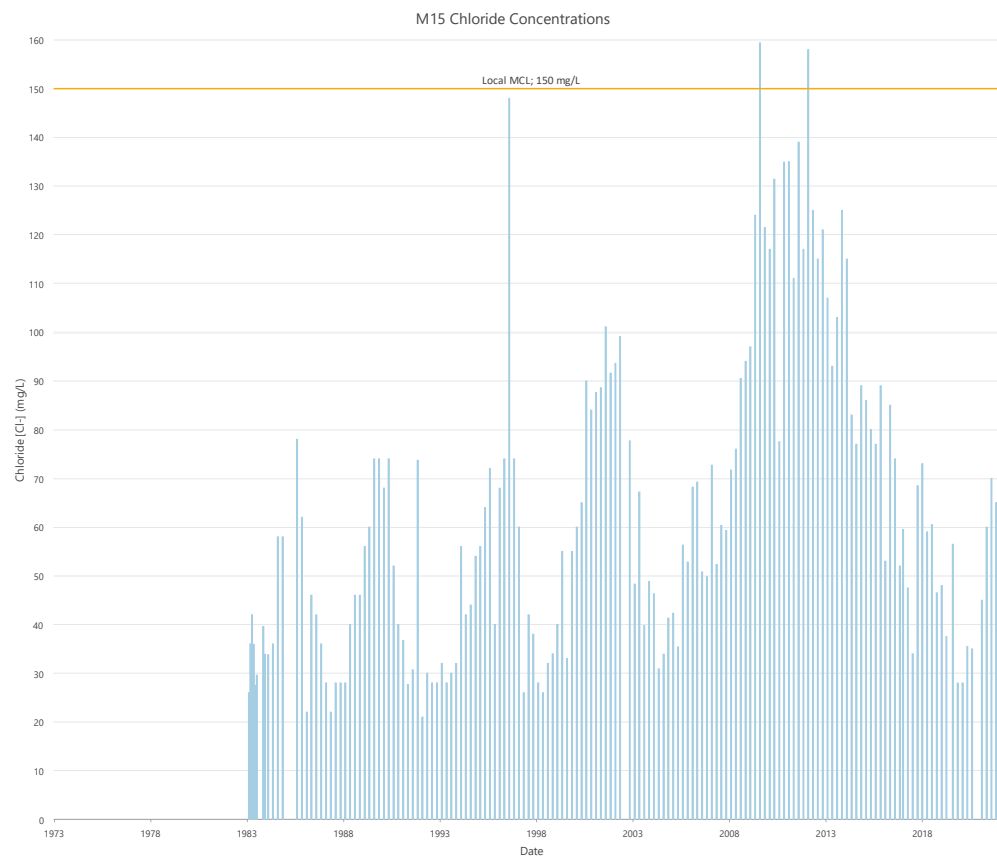


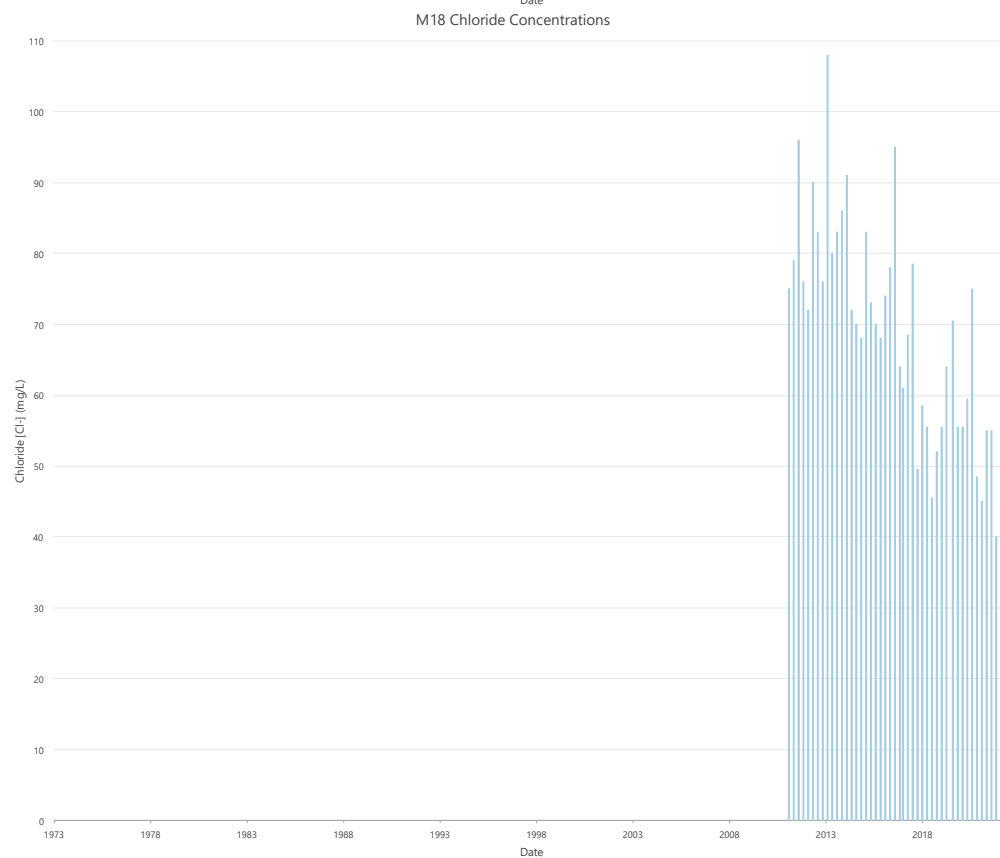
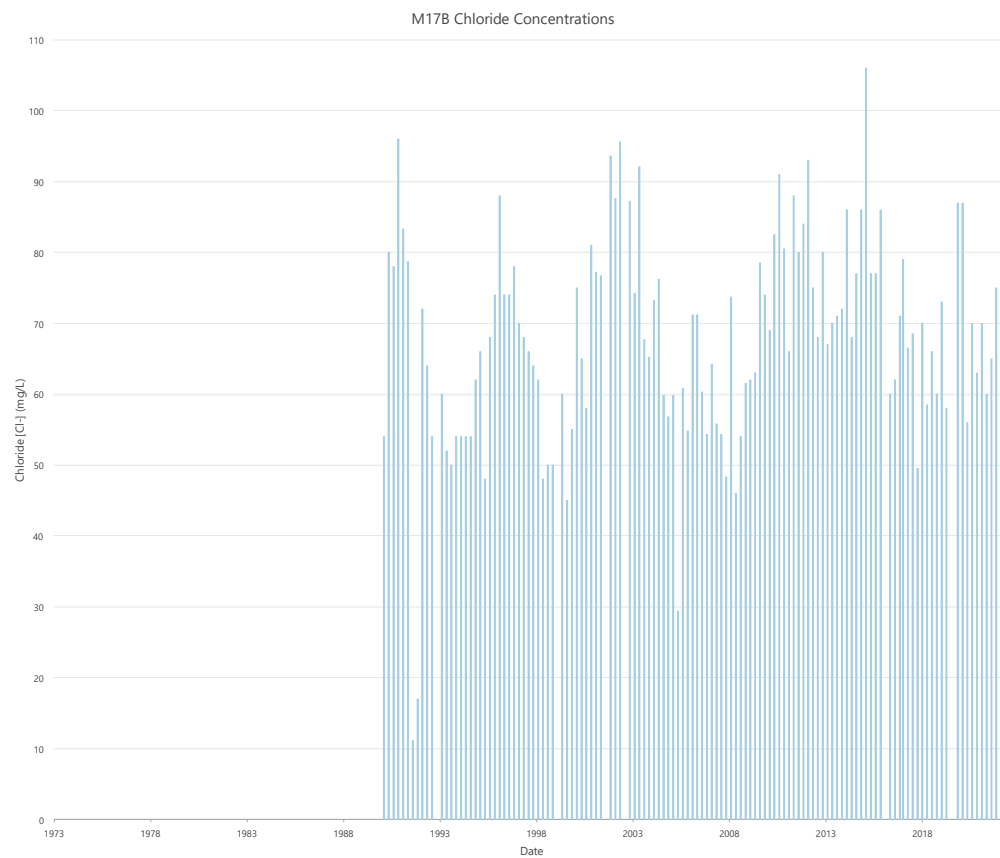


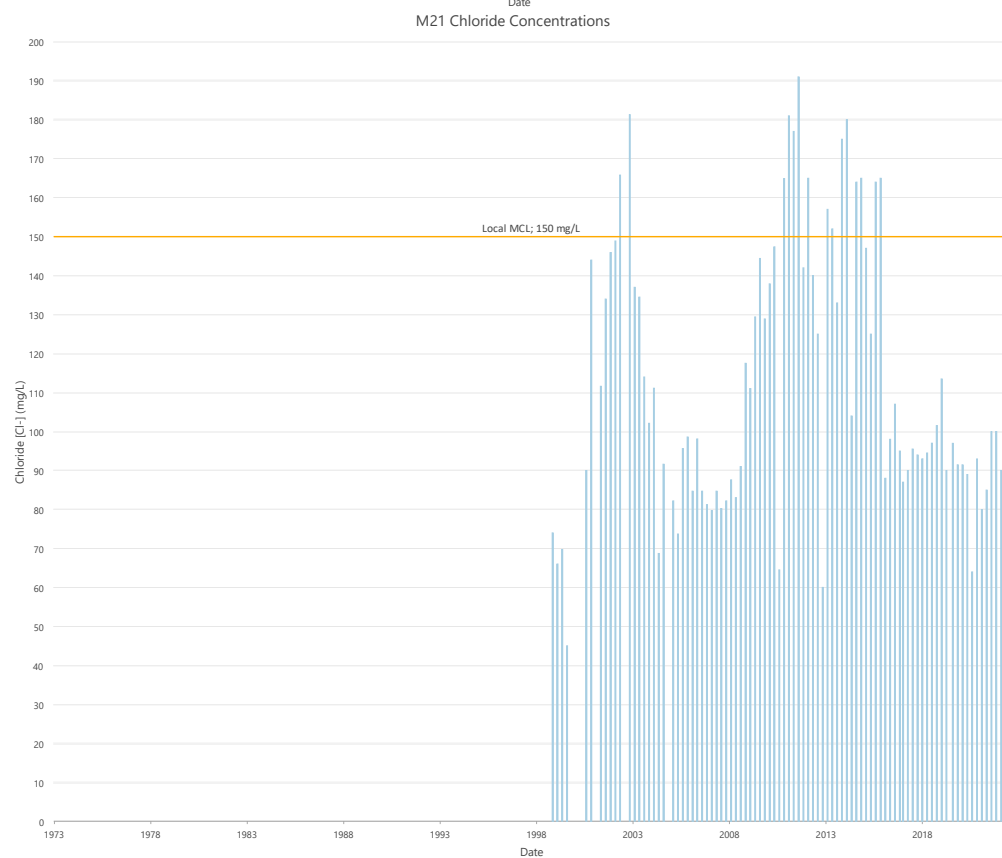
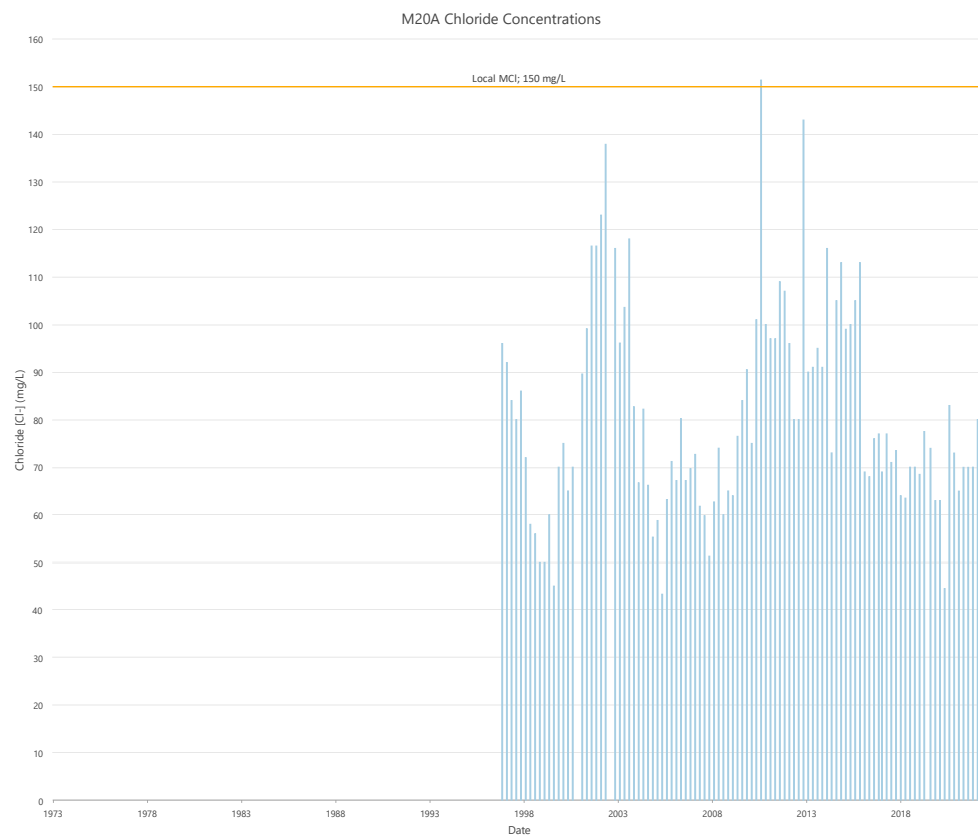




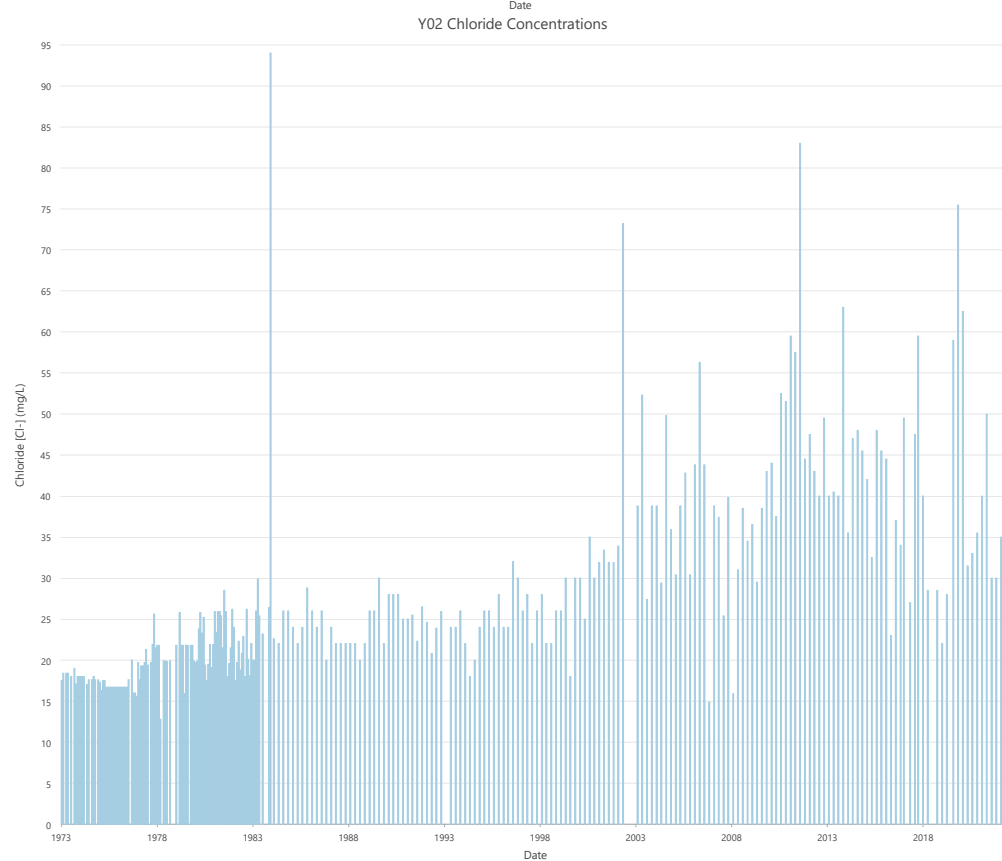
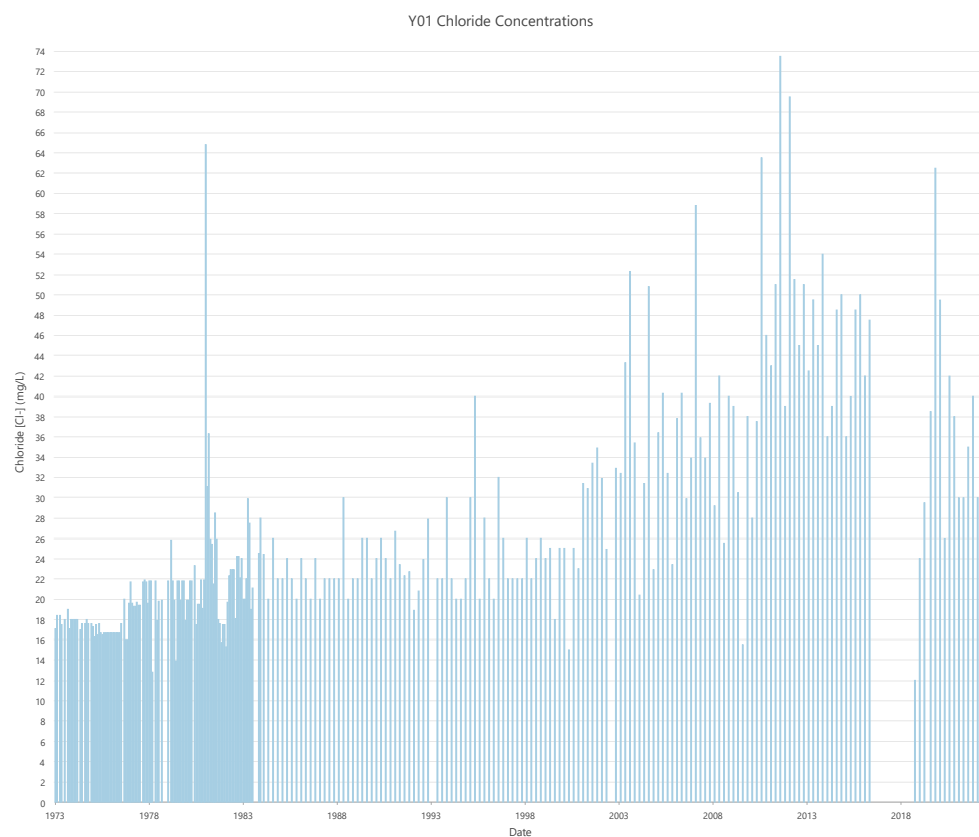


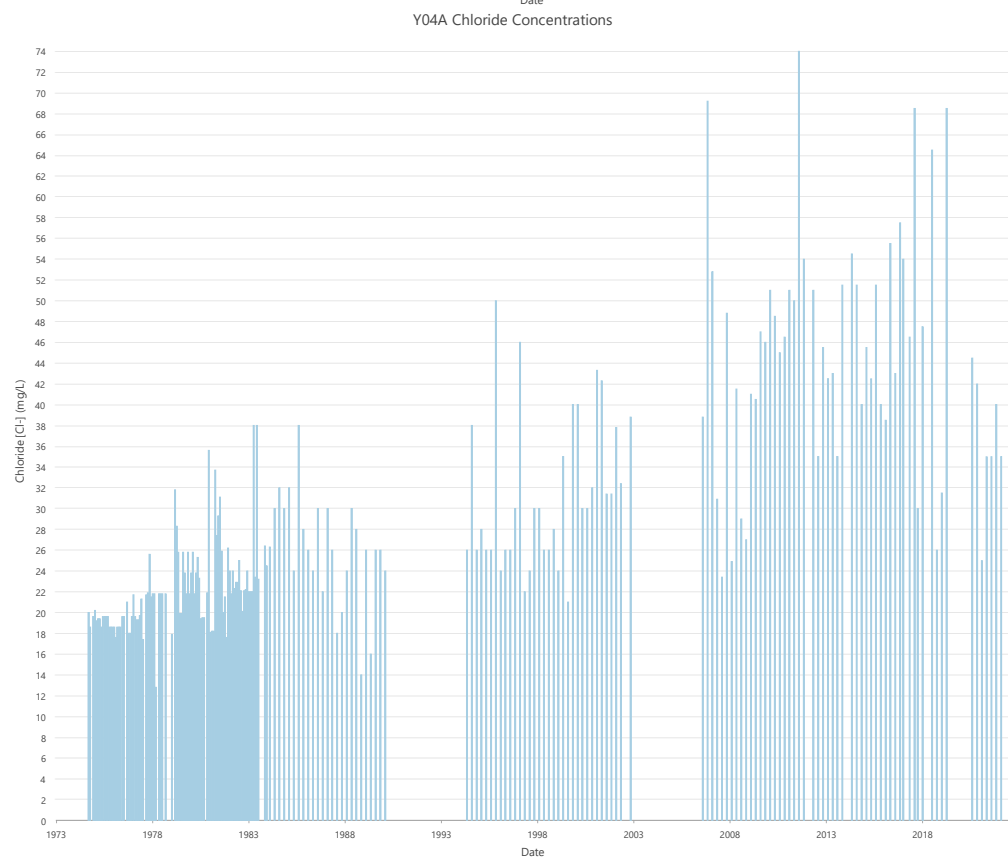
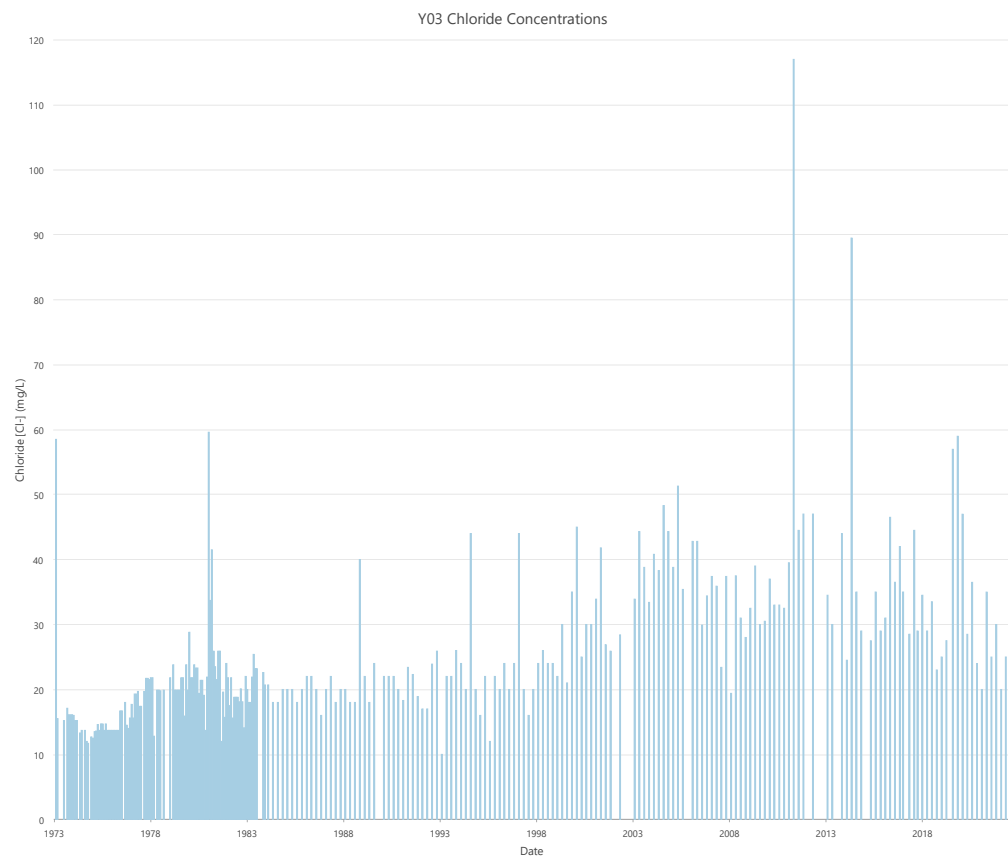


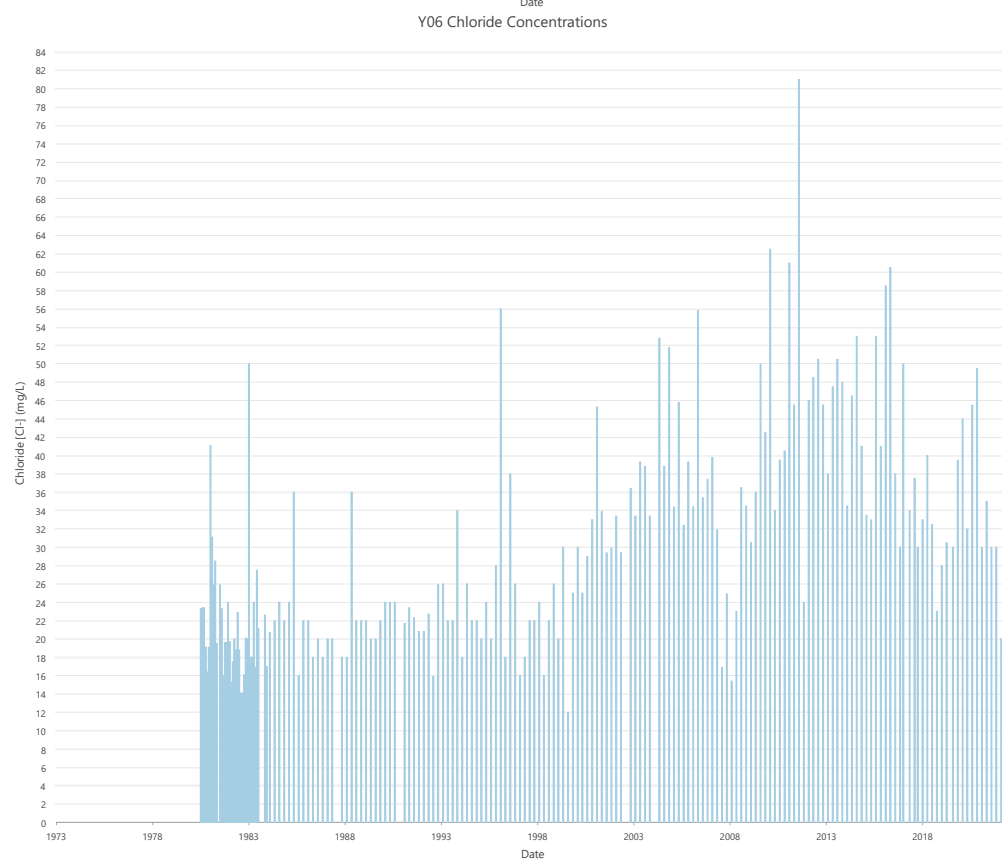
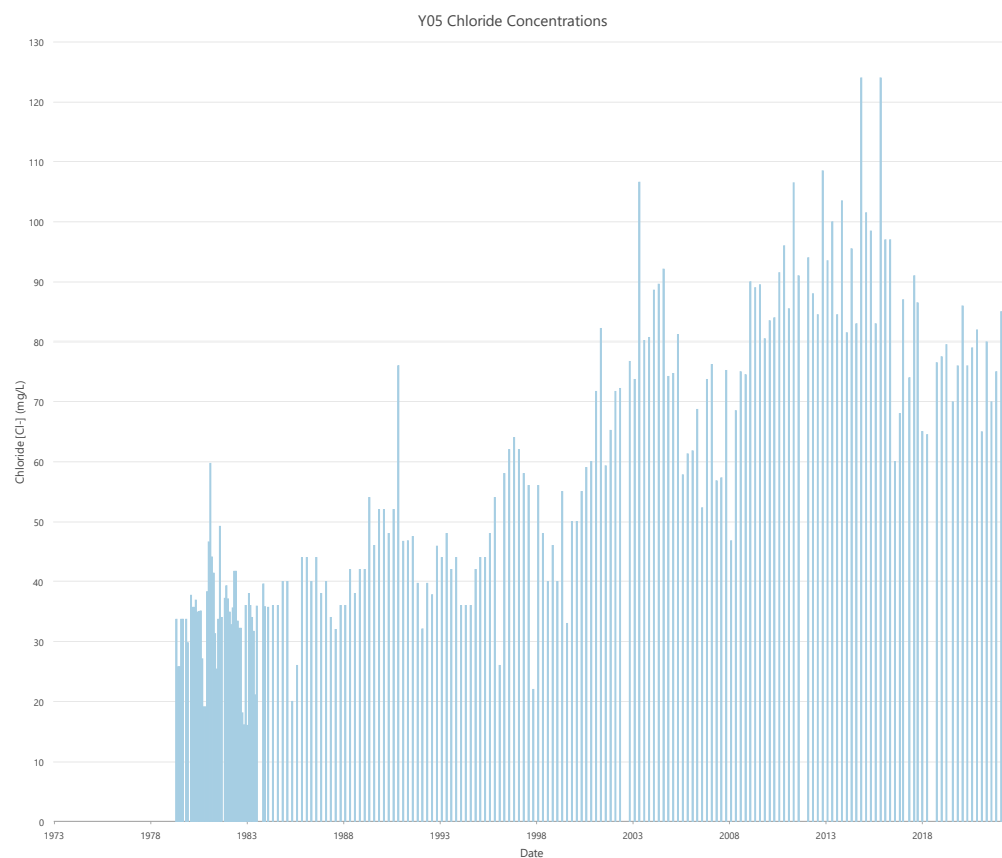


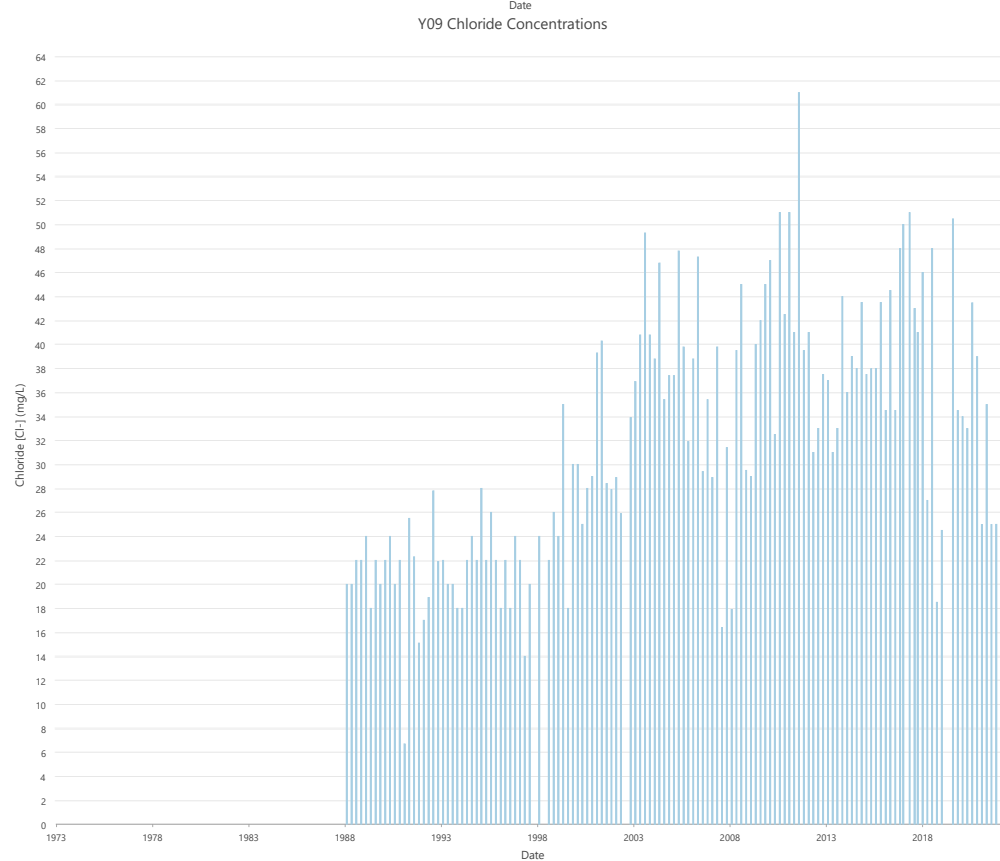
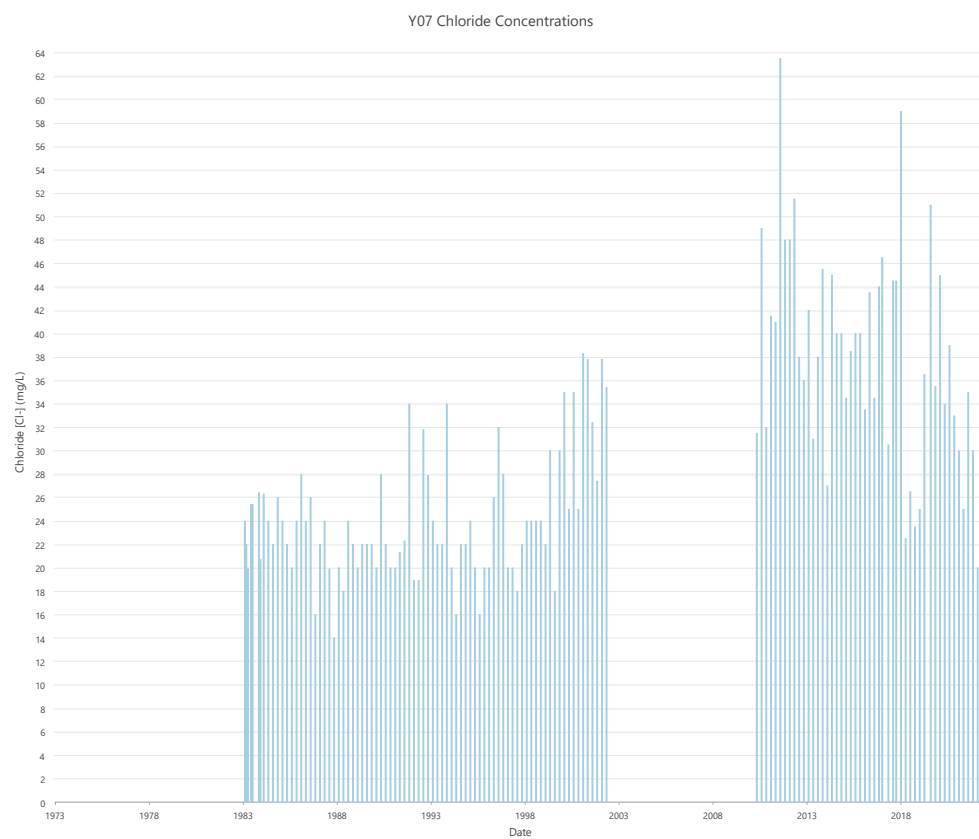


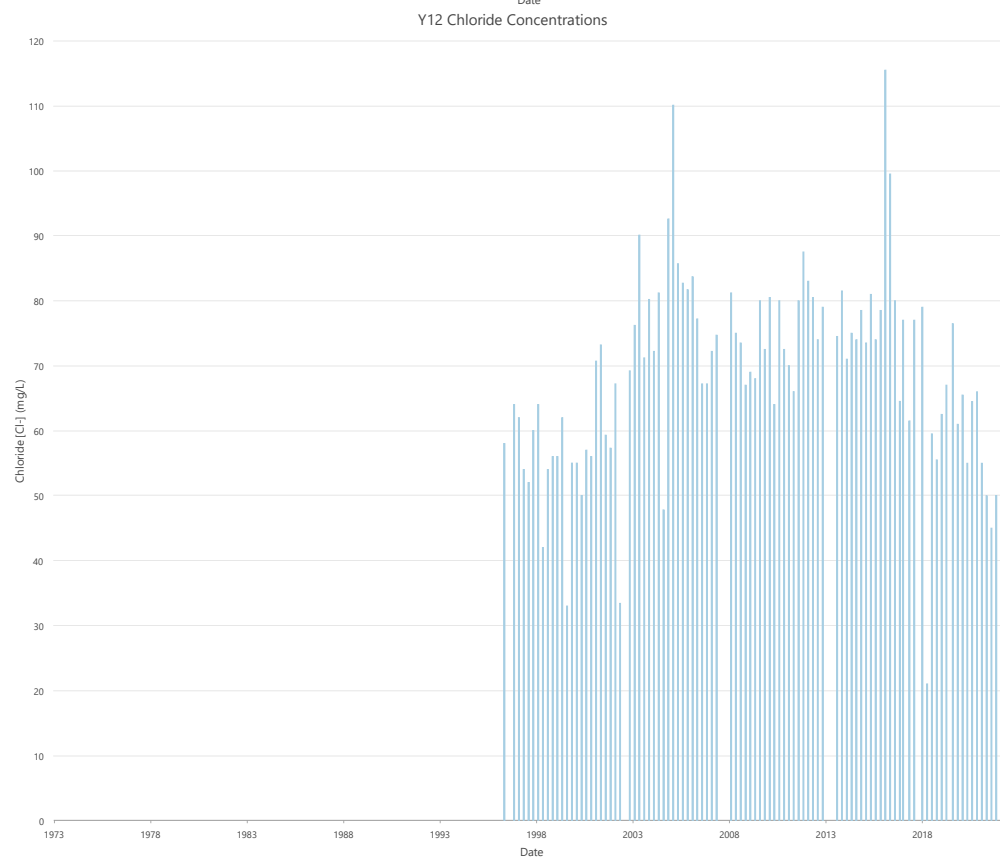
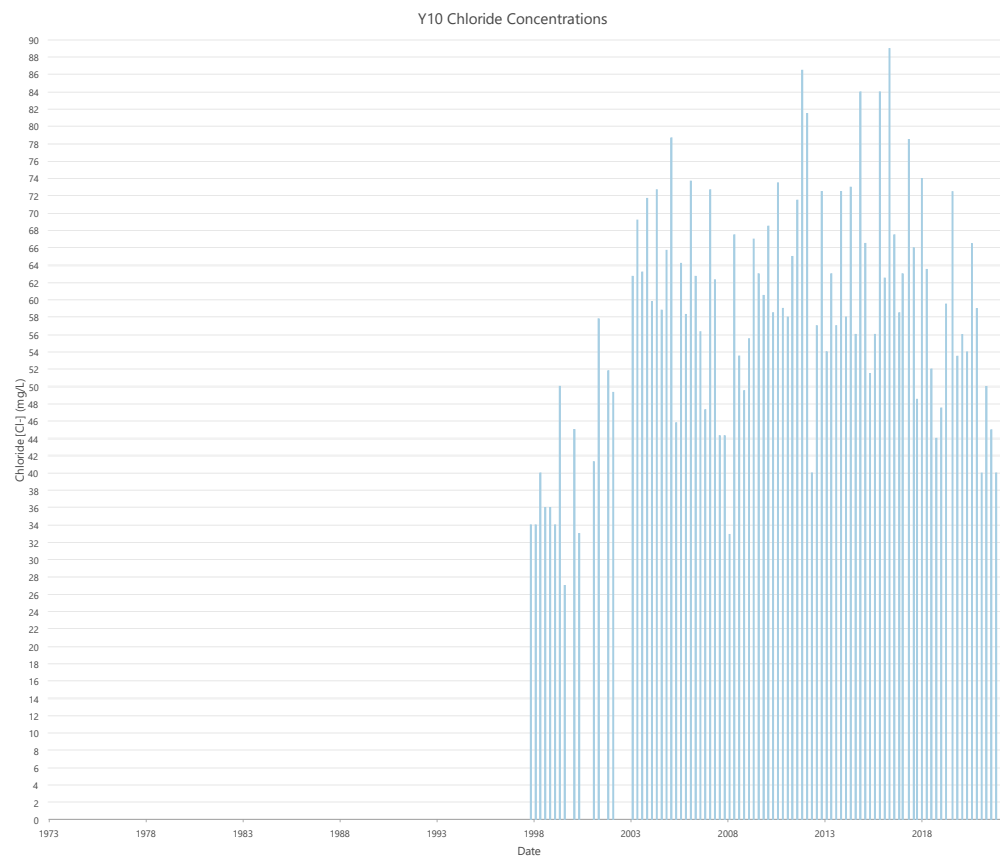


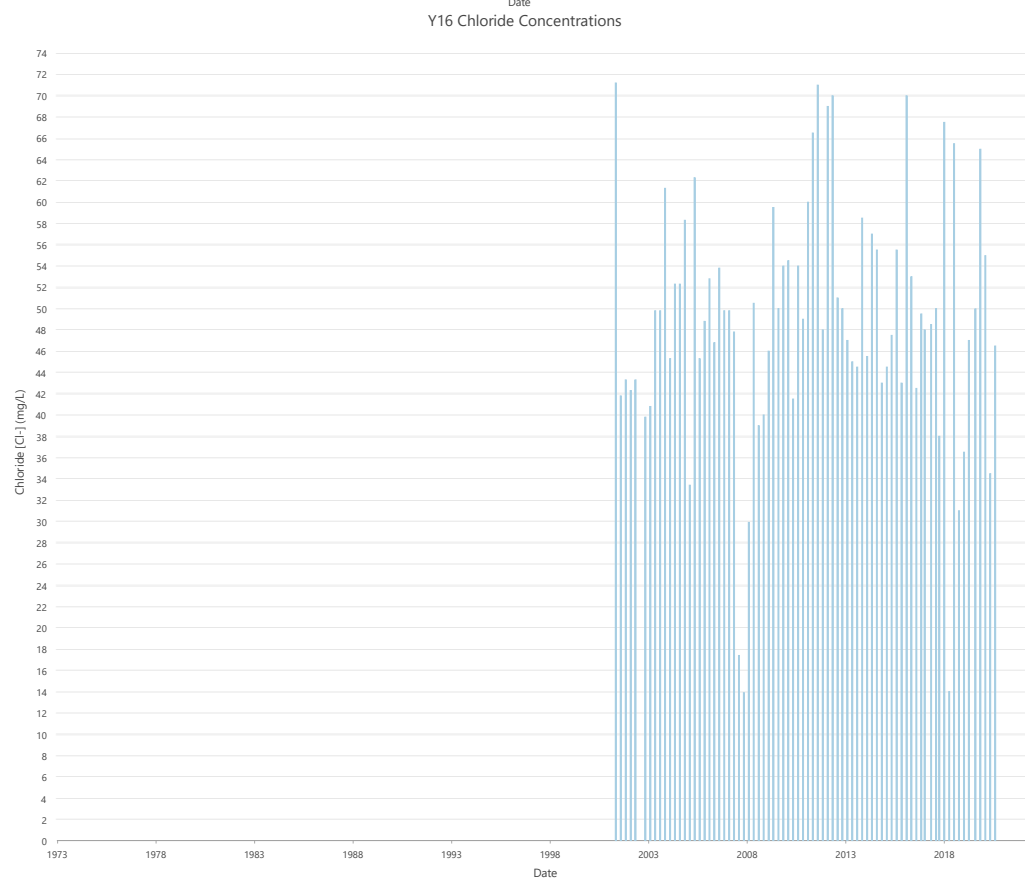
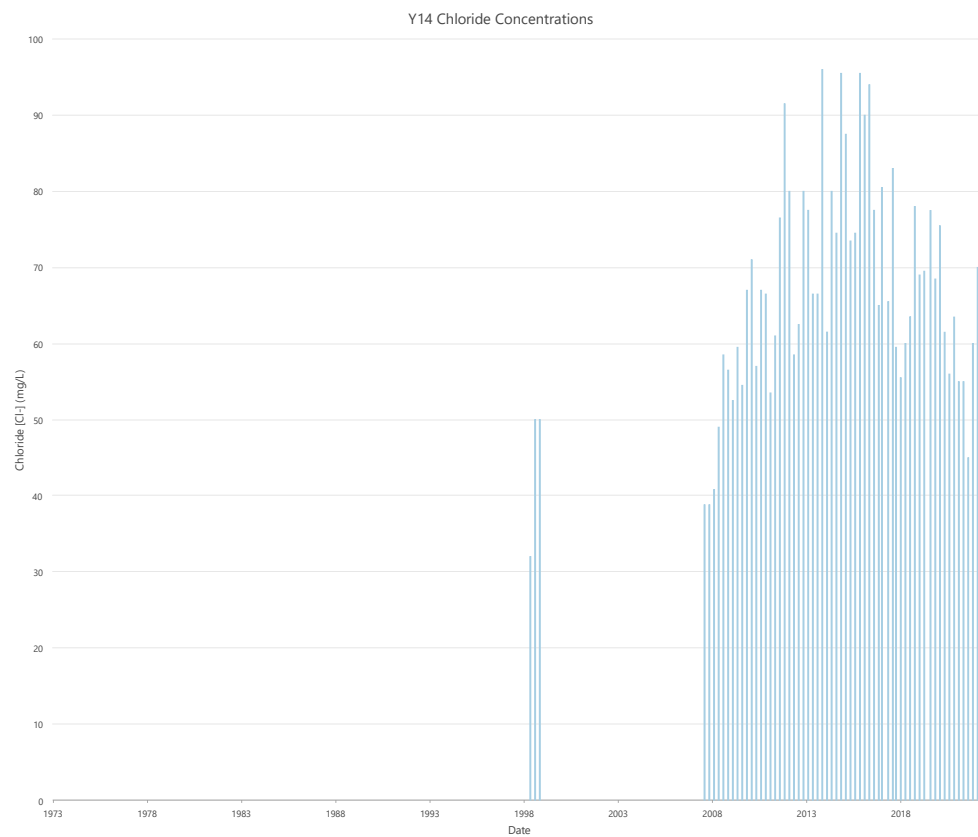


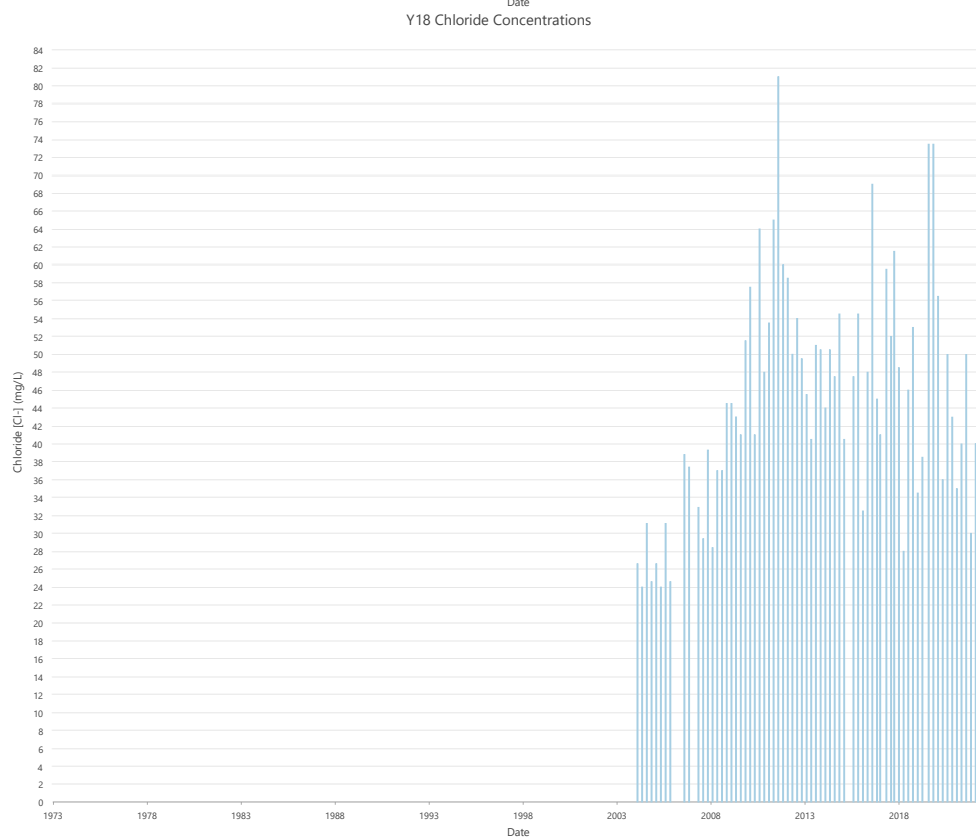
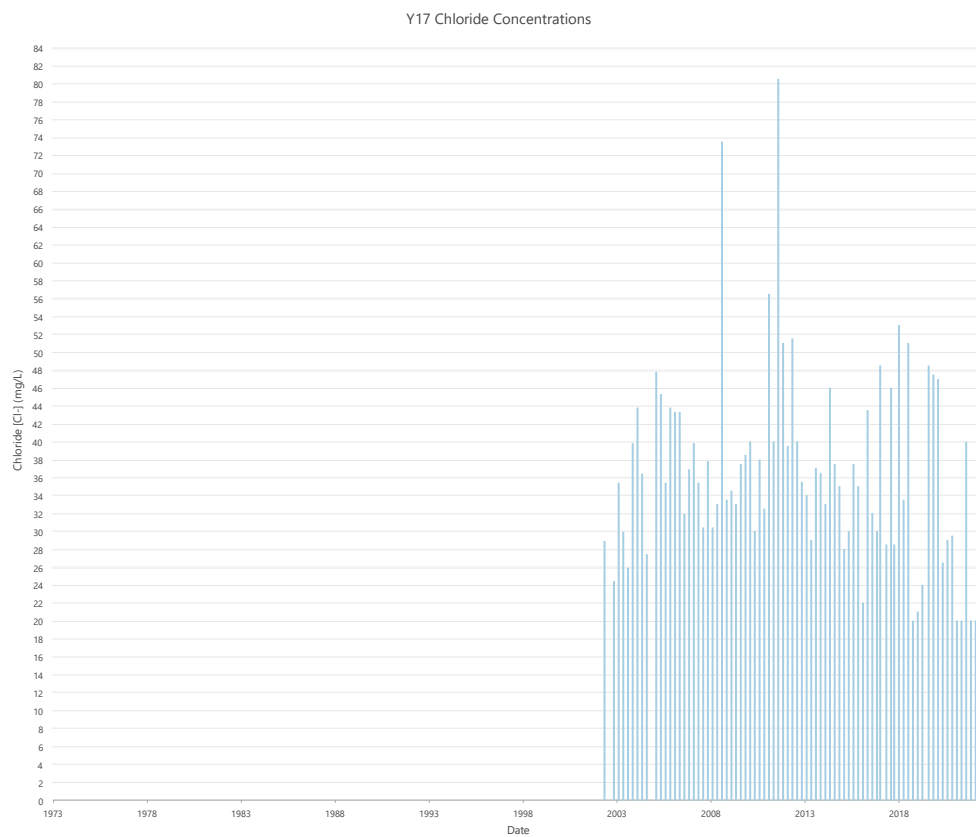


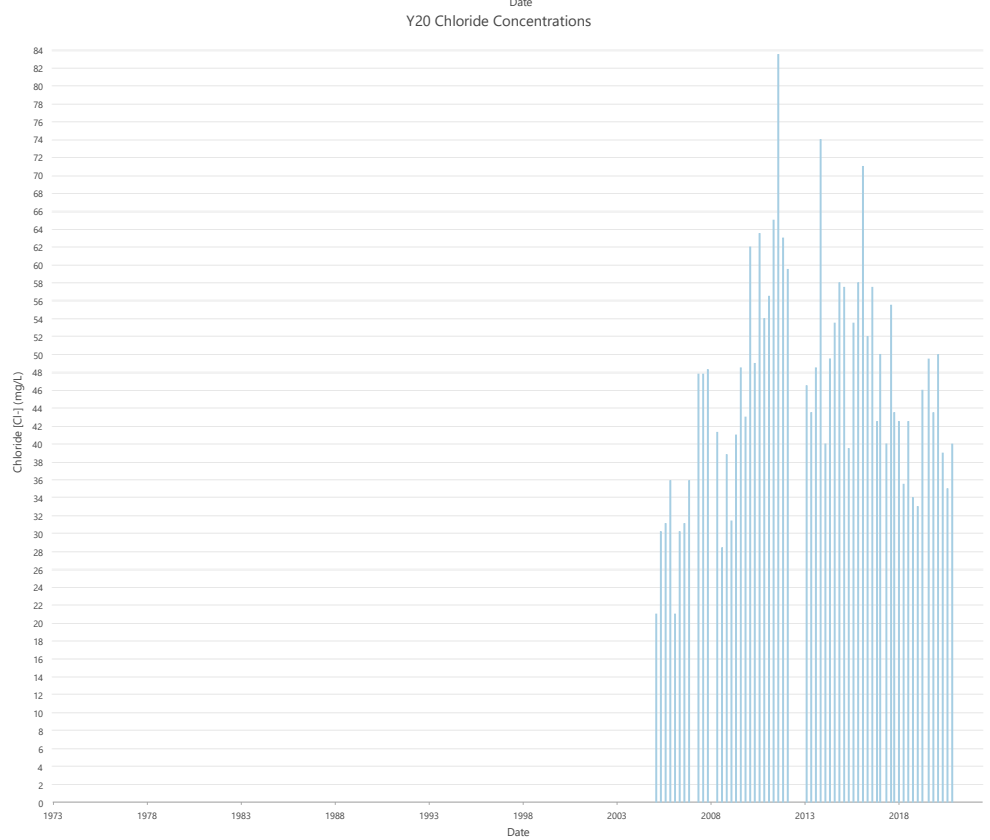
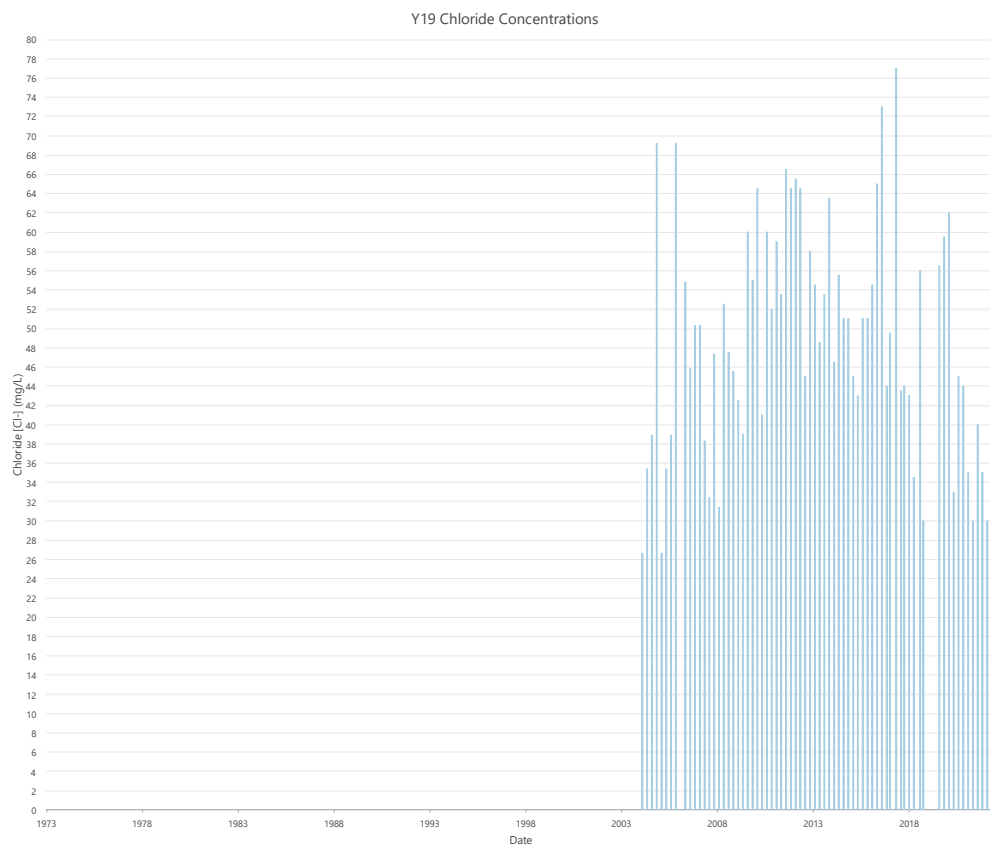




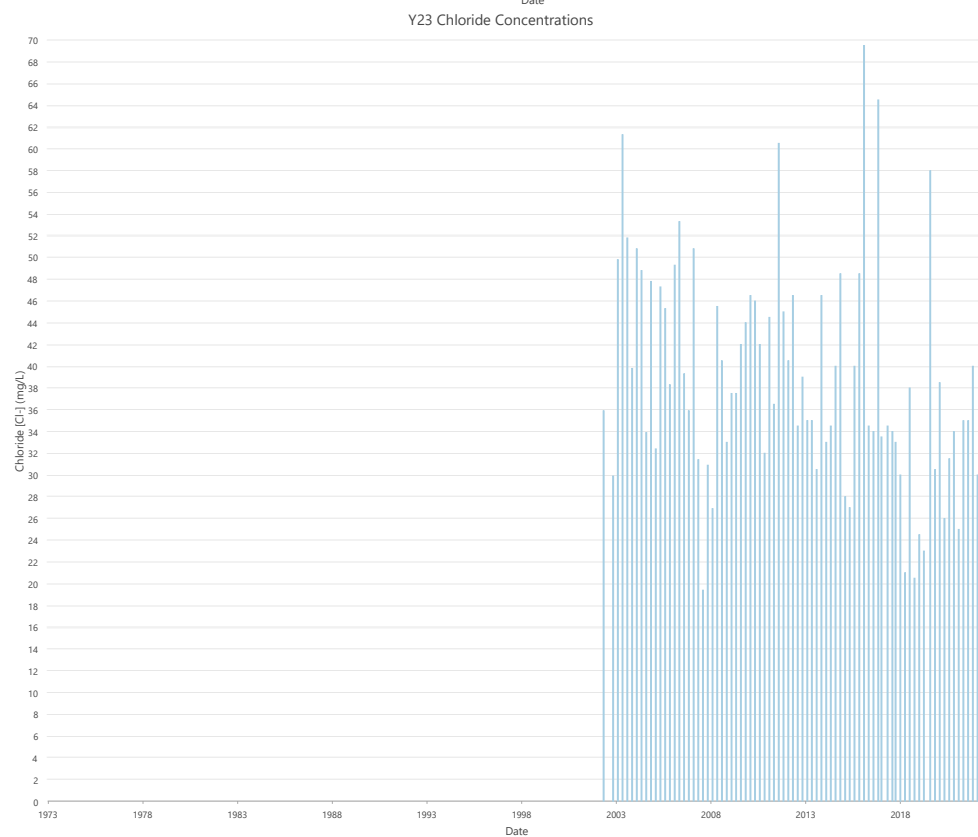
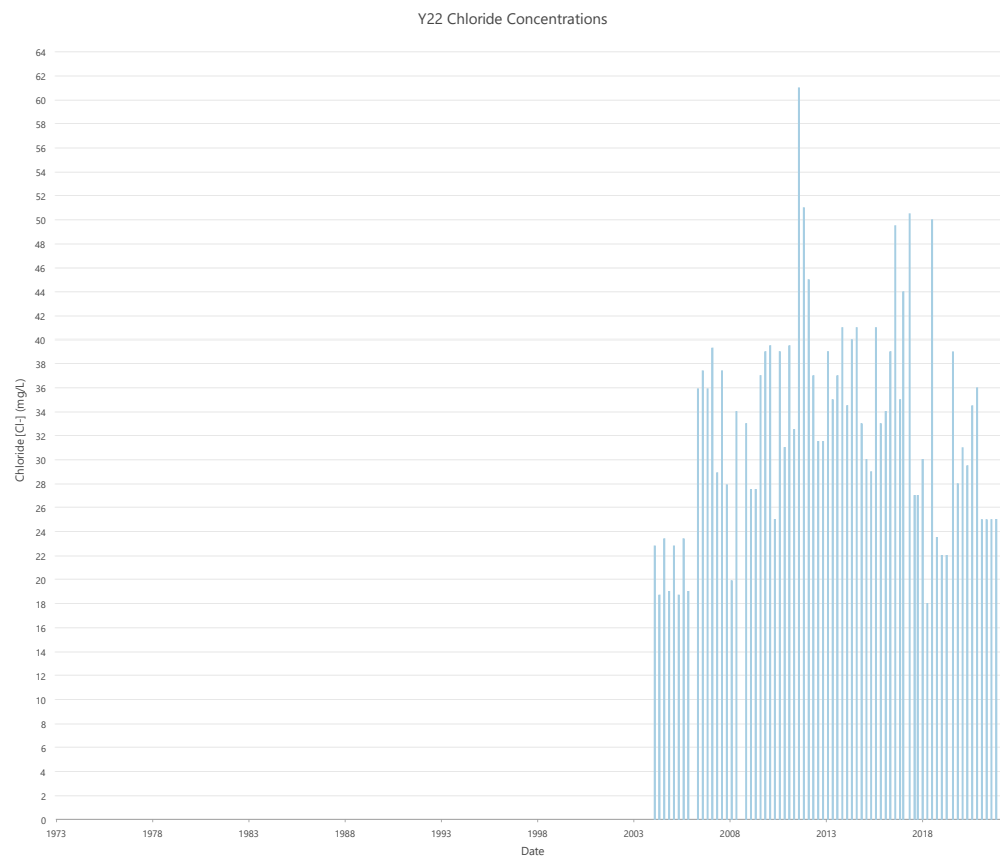


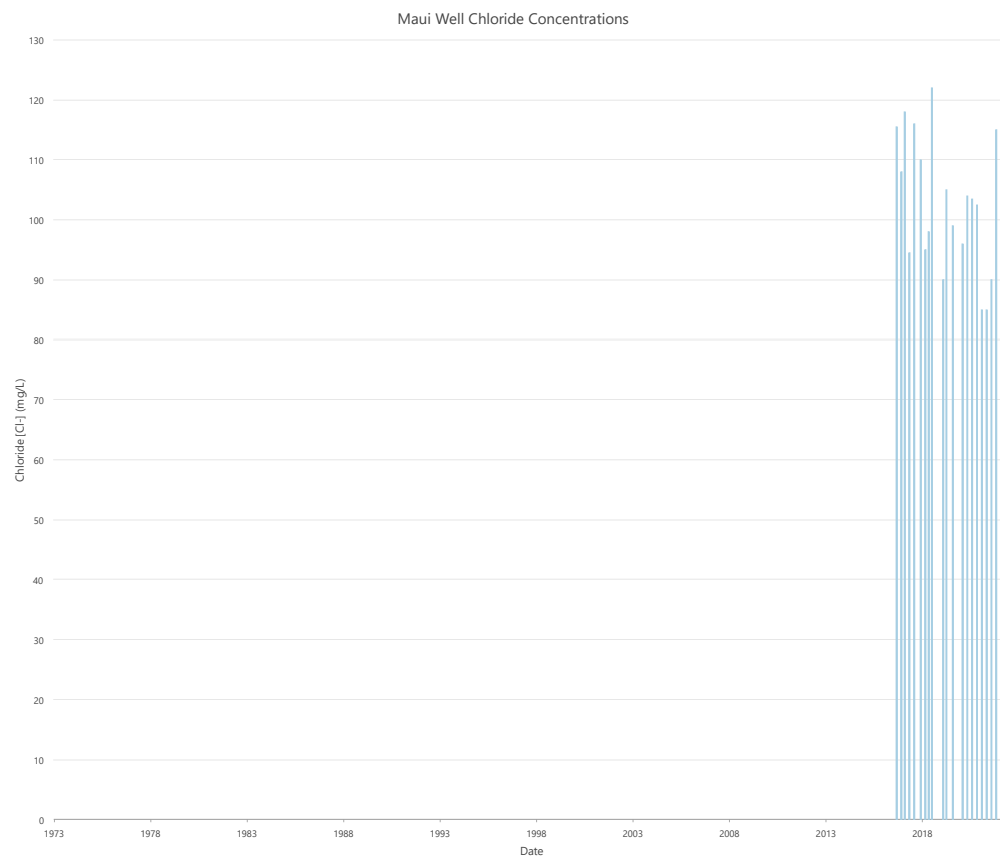






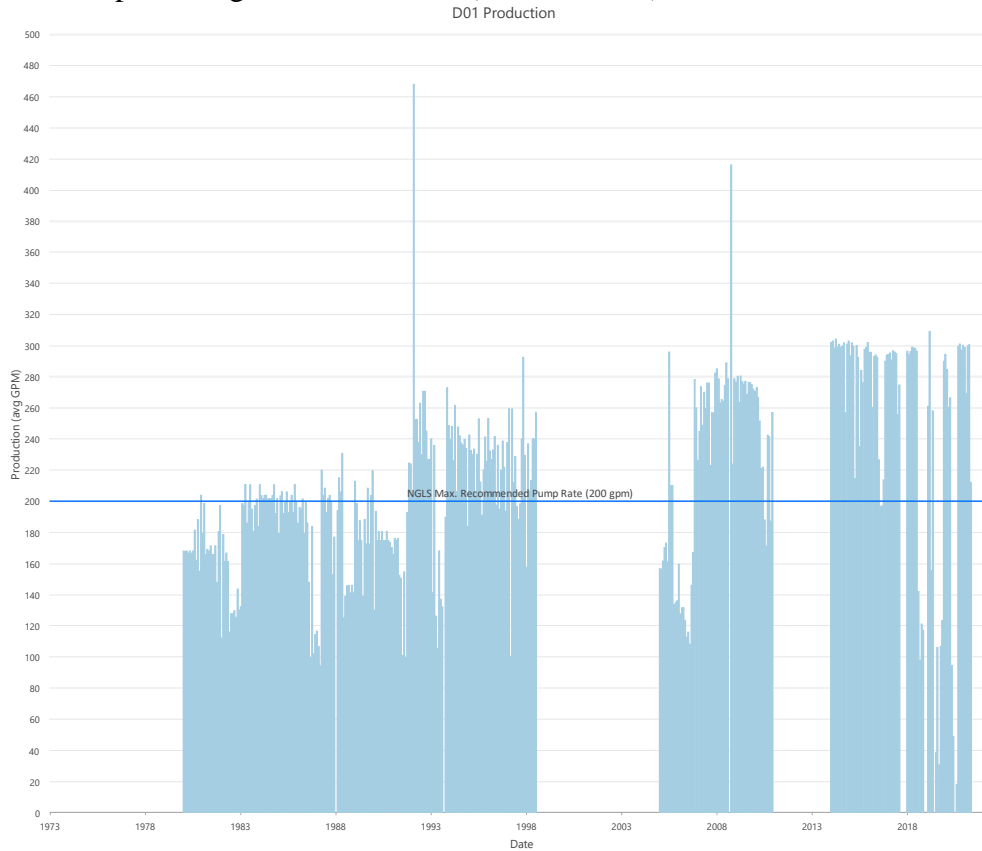


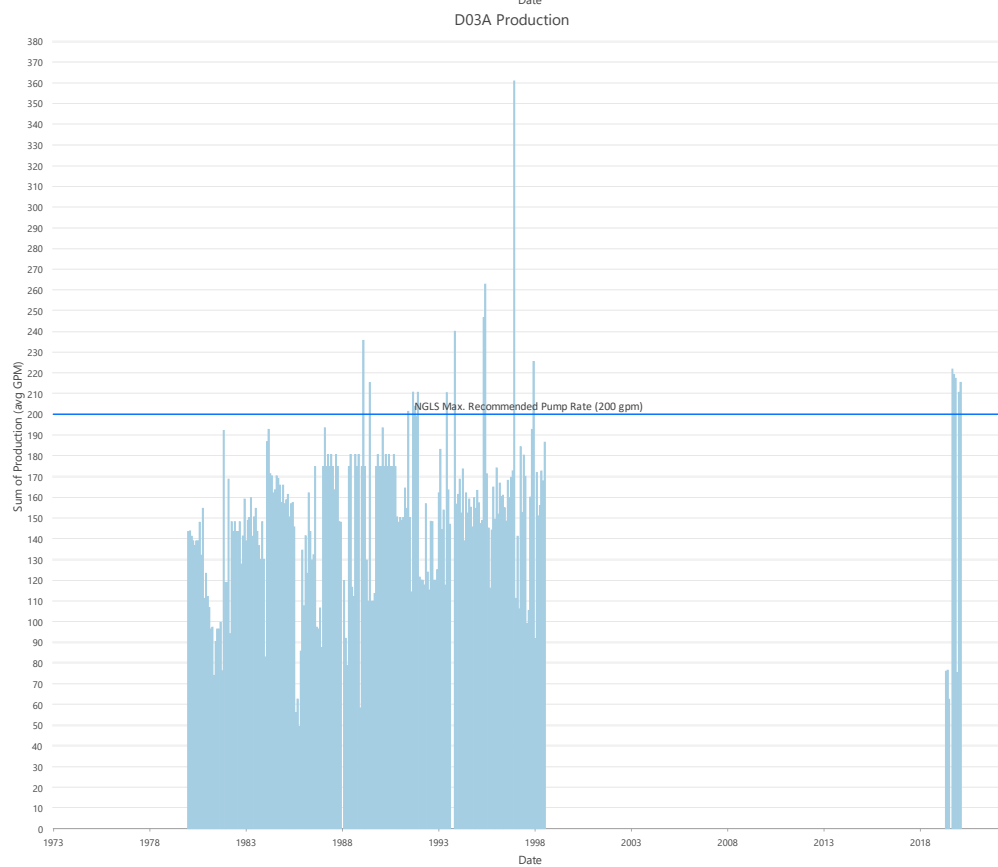
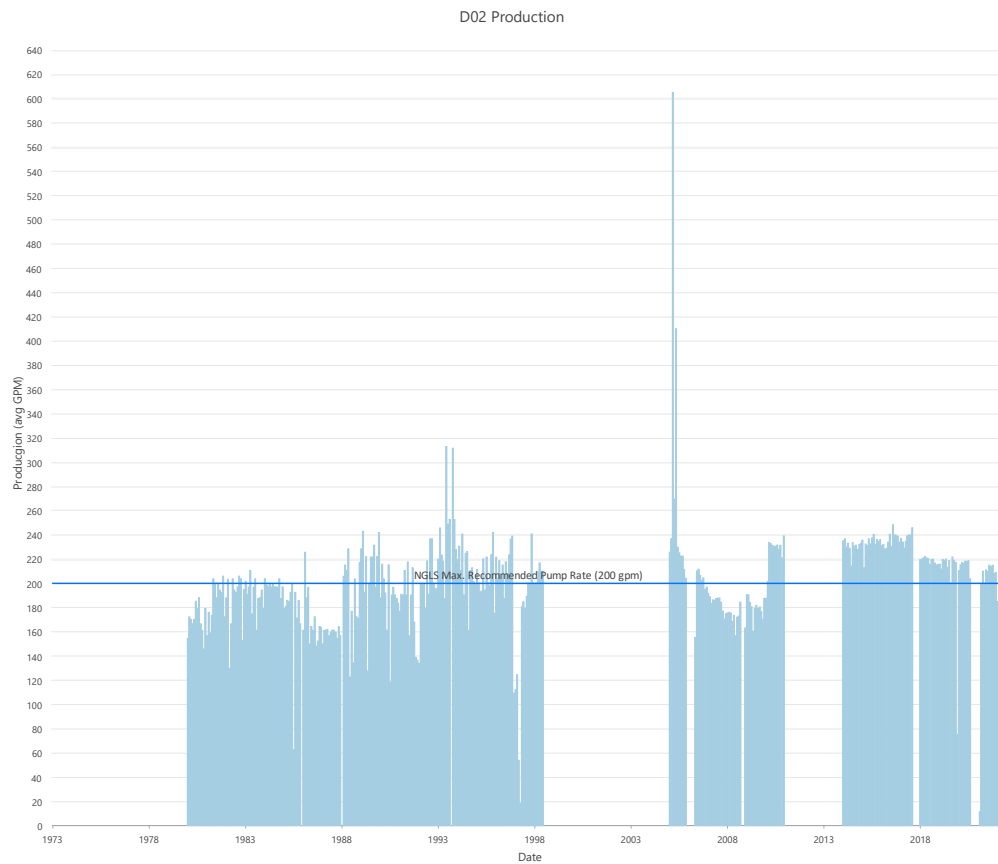


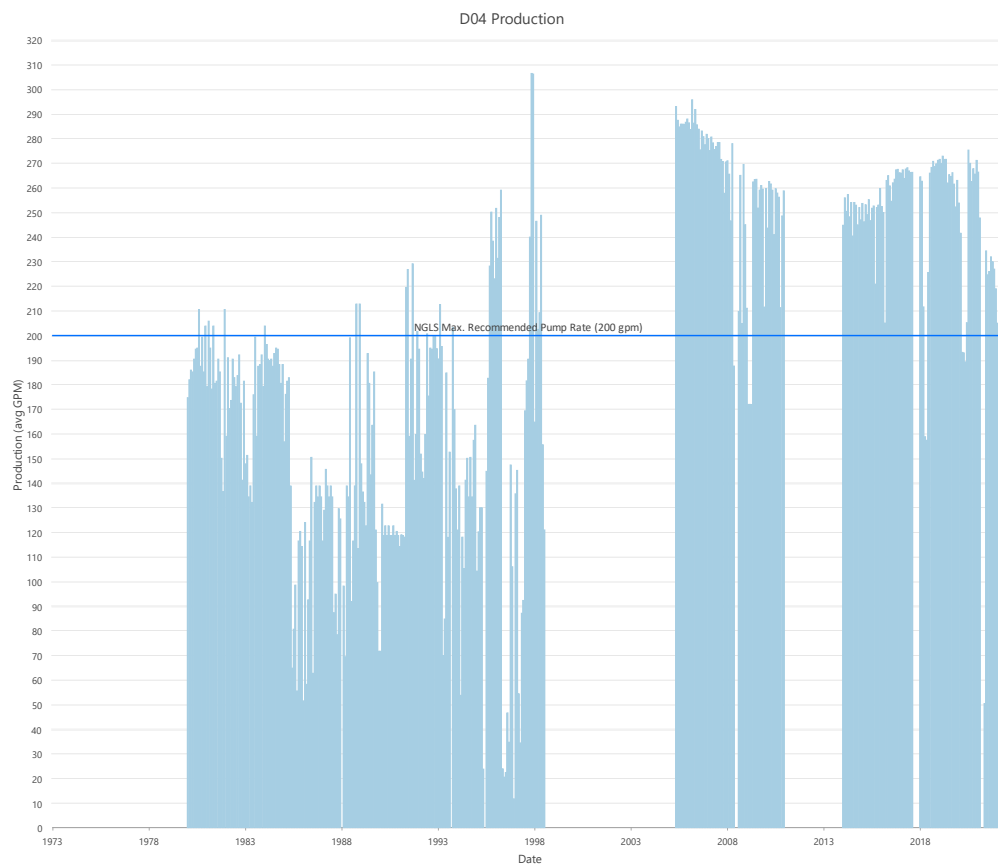


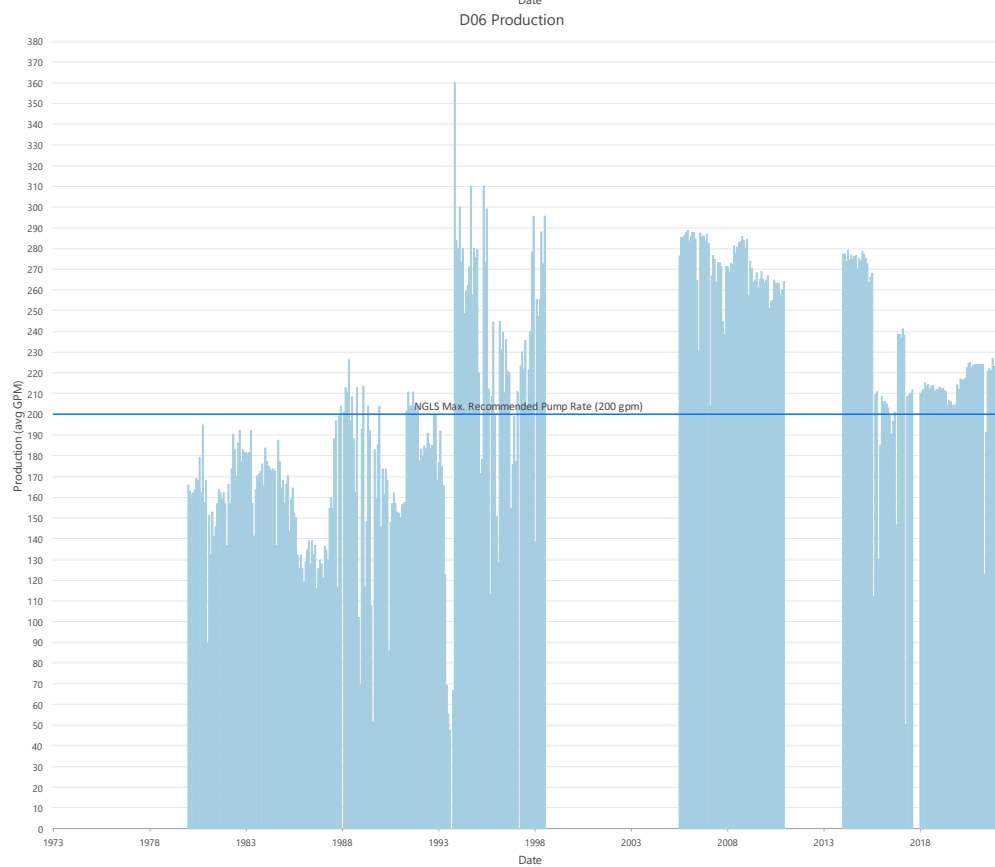
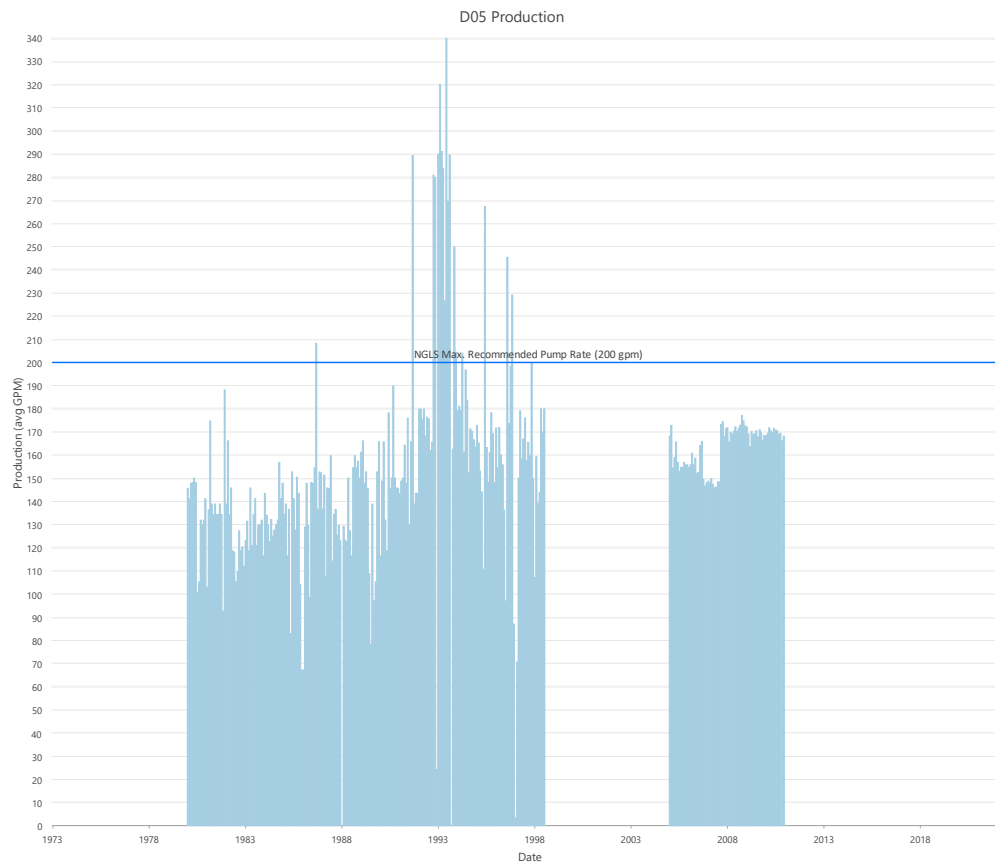
## Appendix D: Bar Graphs of the Average Production of Individual Wells Over Time

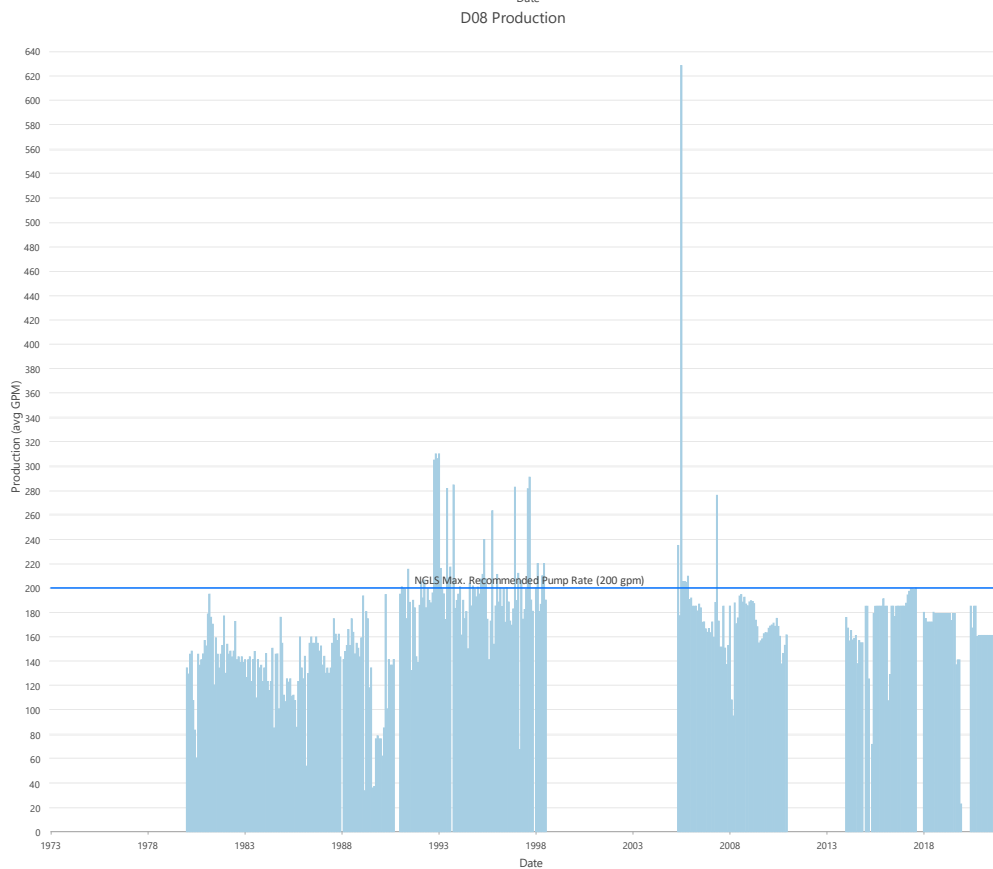
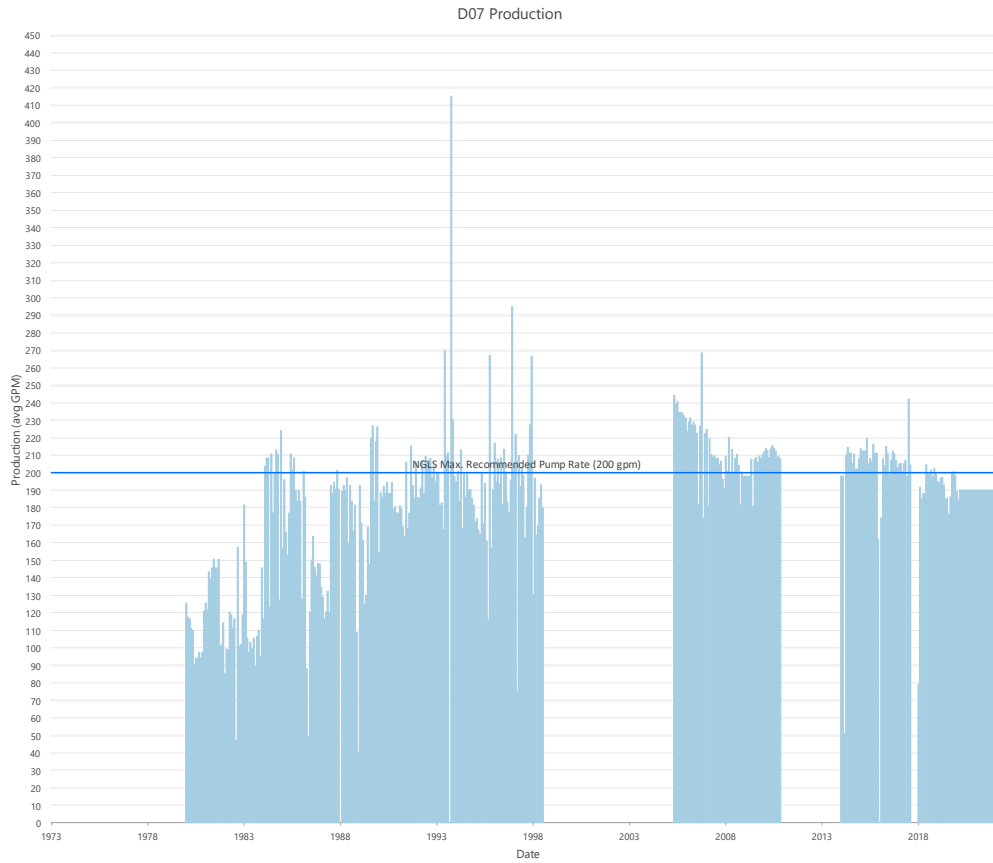
The guidelines depicted are the NGLS Recommended Pump Rate for each groundwater zone. There are no recommended pump rates for horizontal wells like Maui Well or for wells located in the suprabasal groundwater zone (Y17 and Y23).

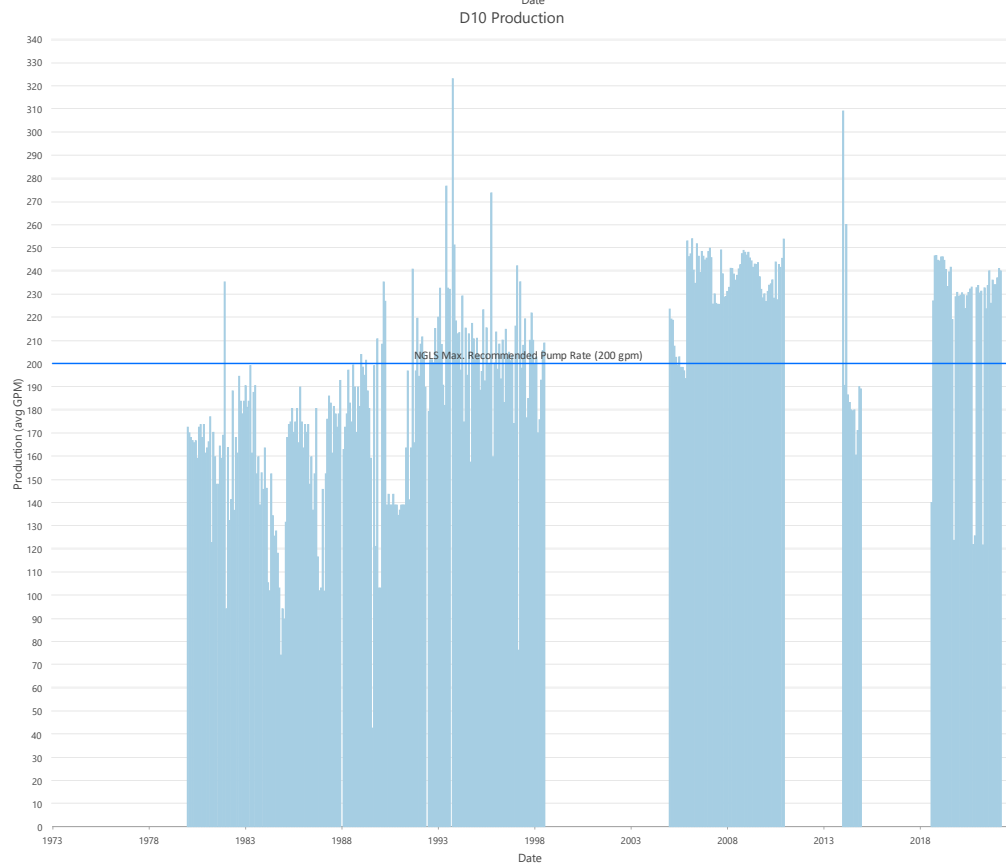
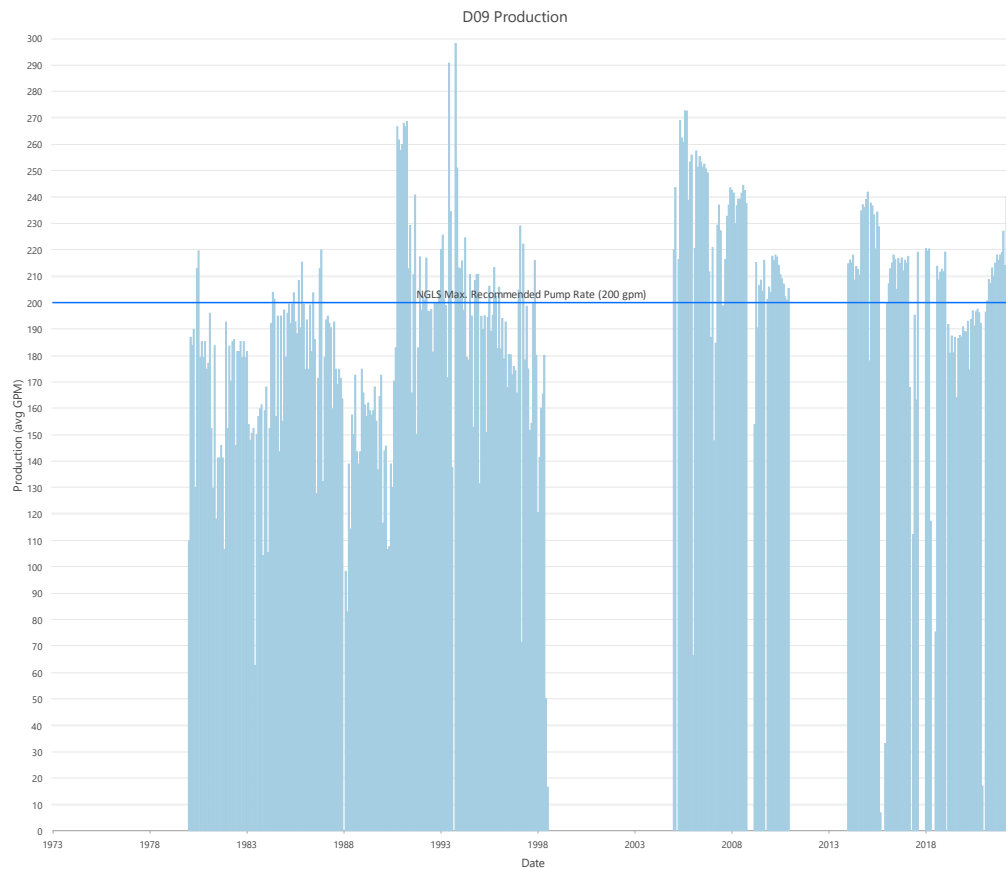




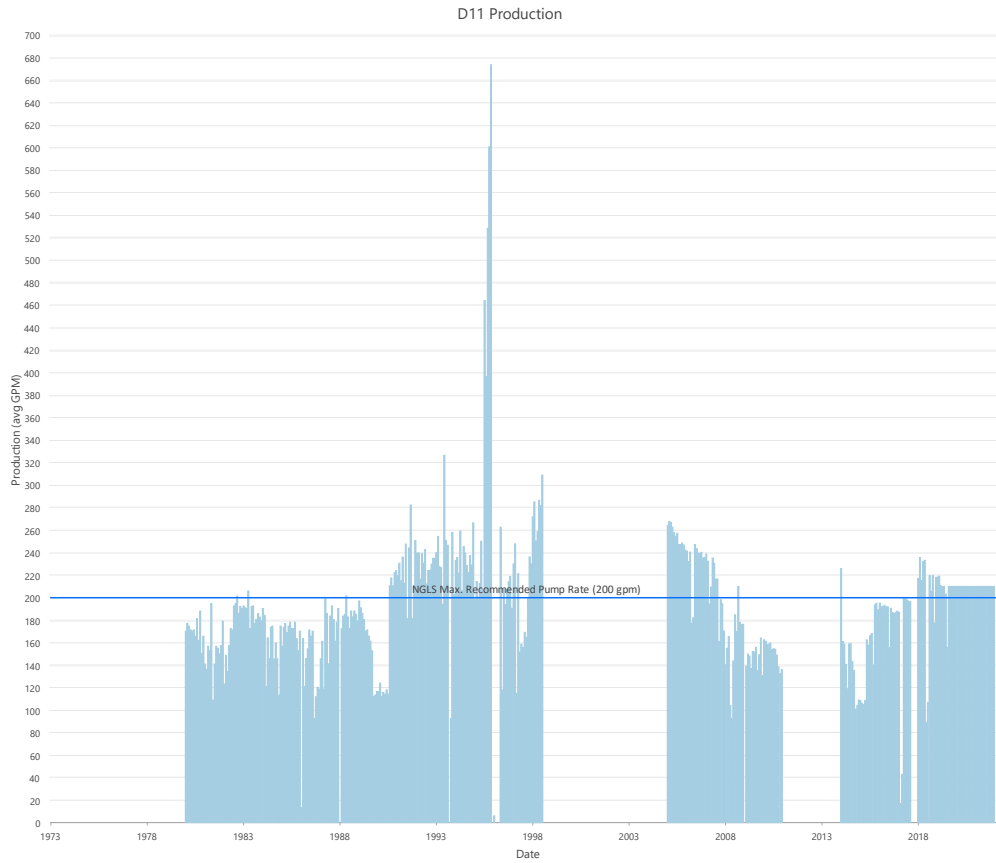


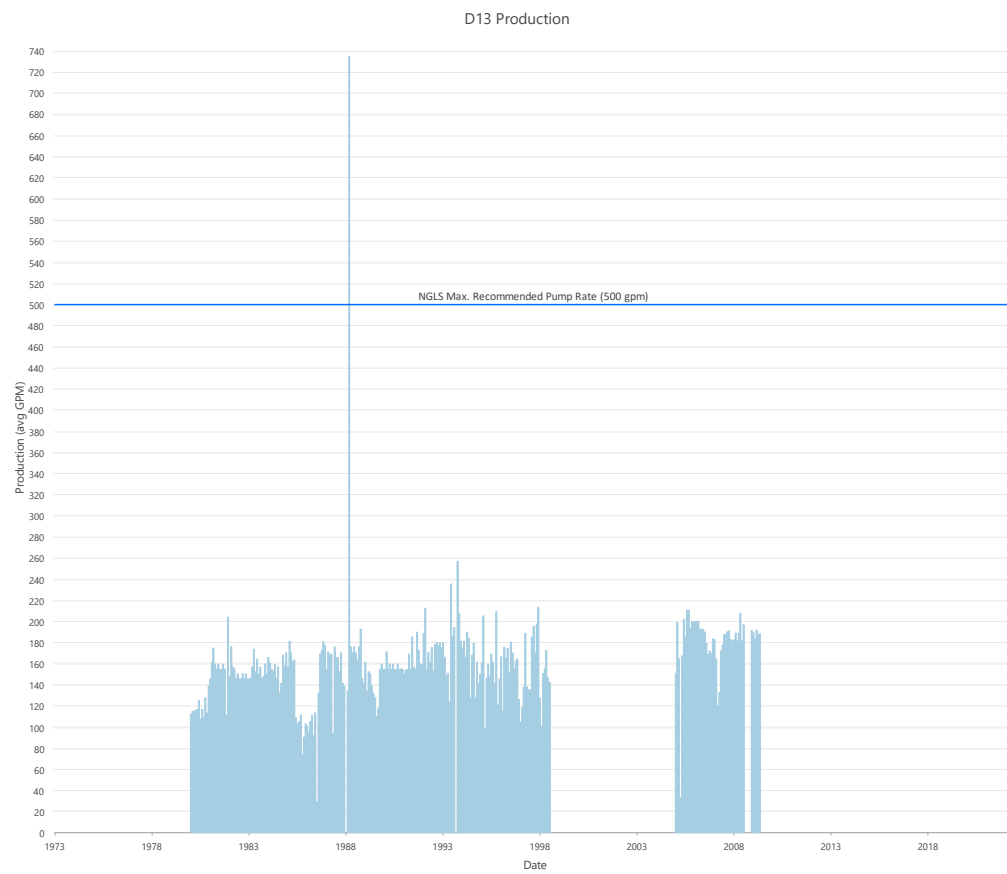


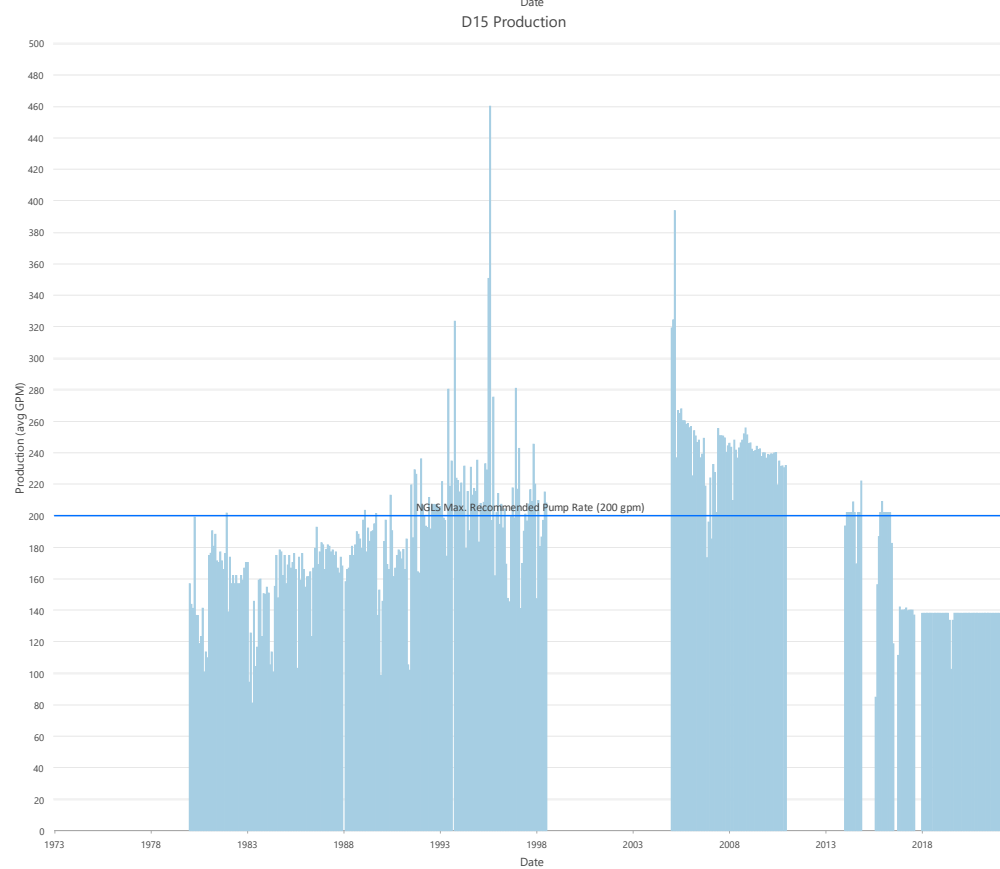
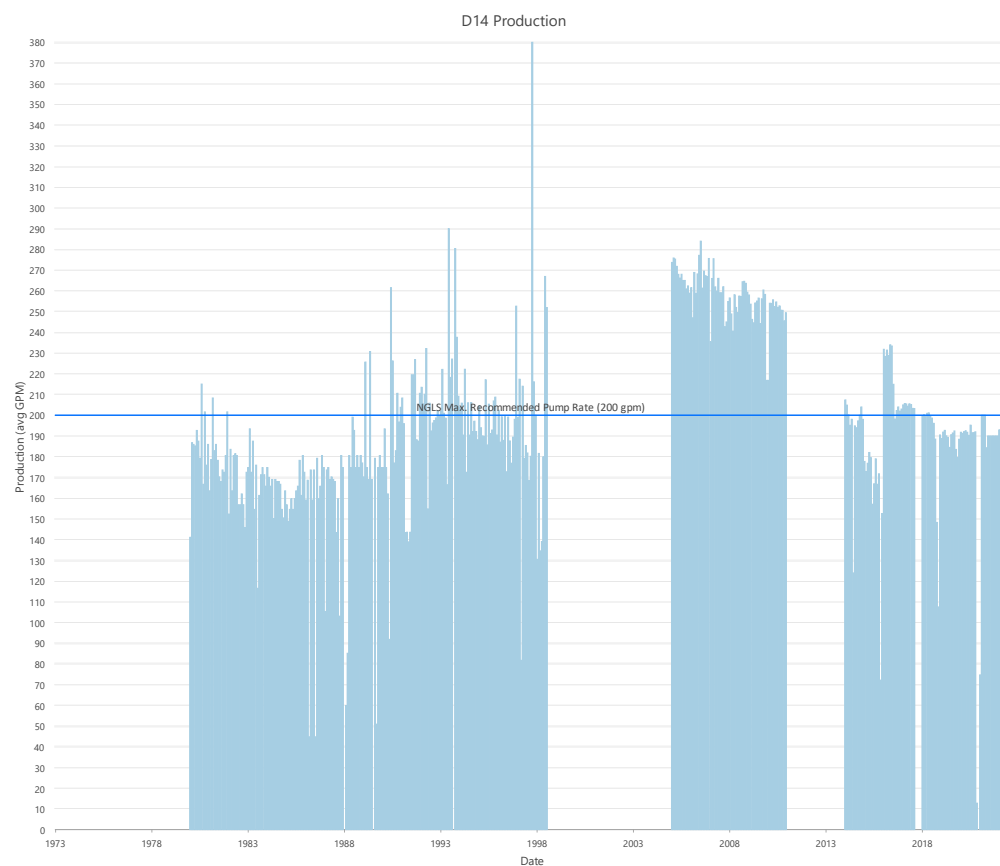


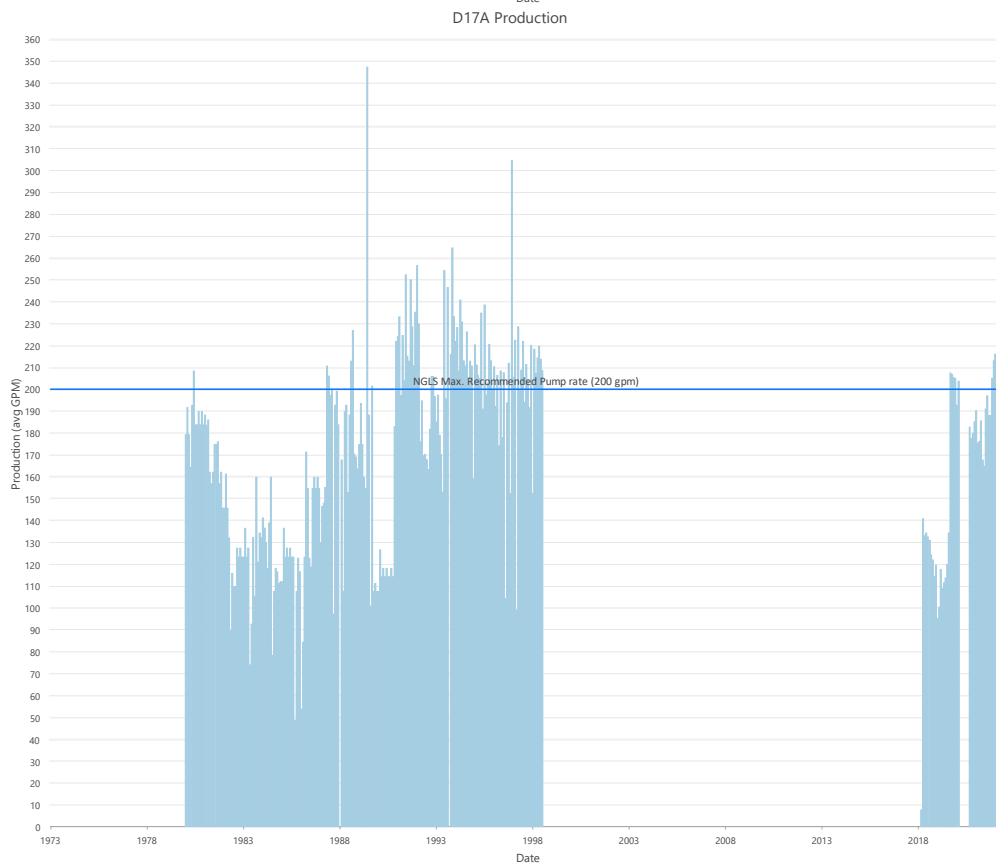
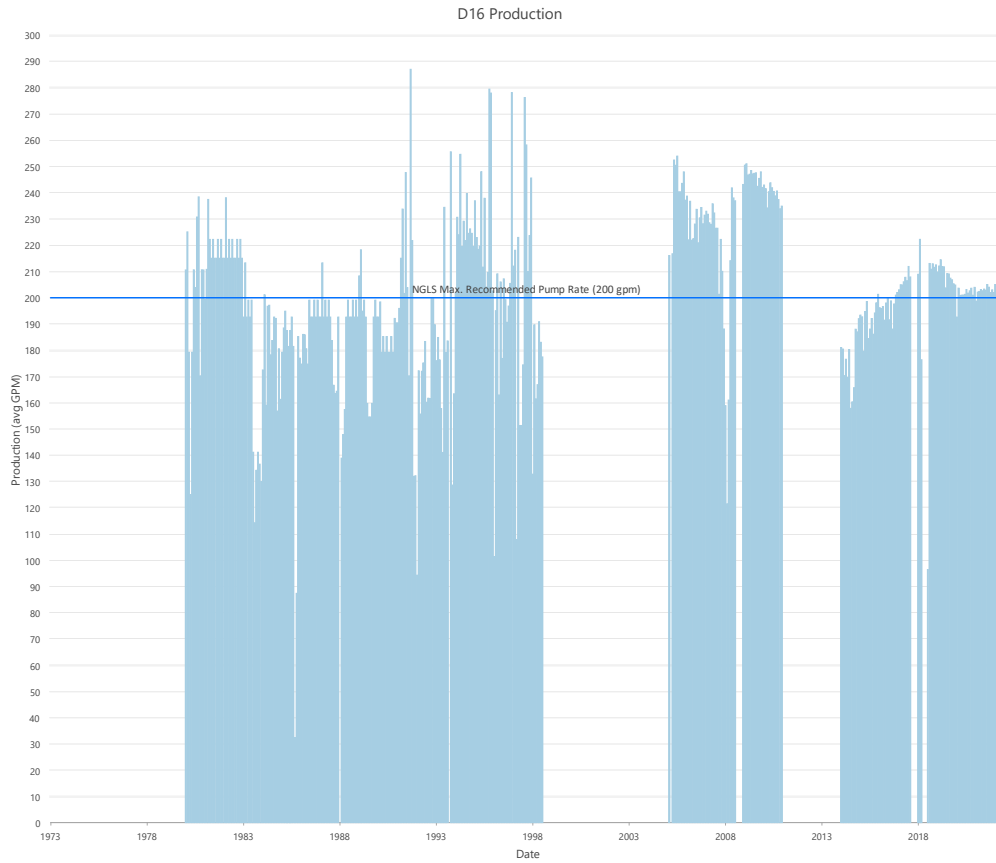


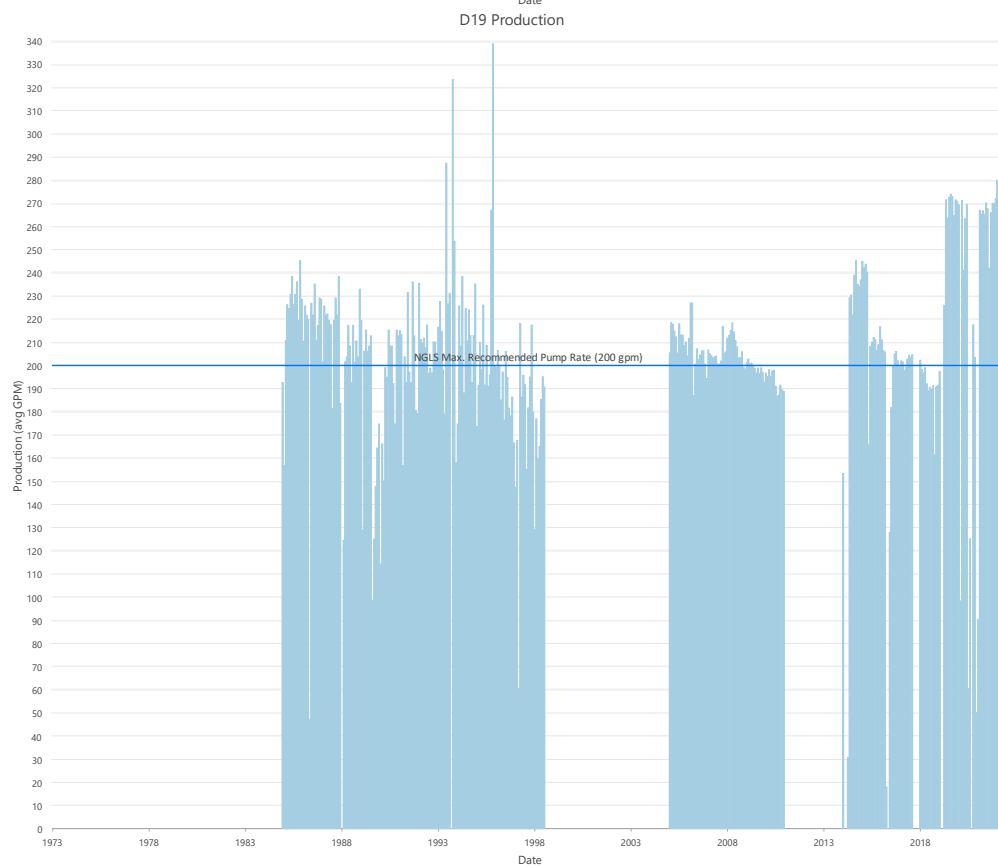
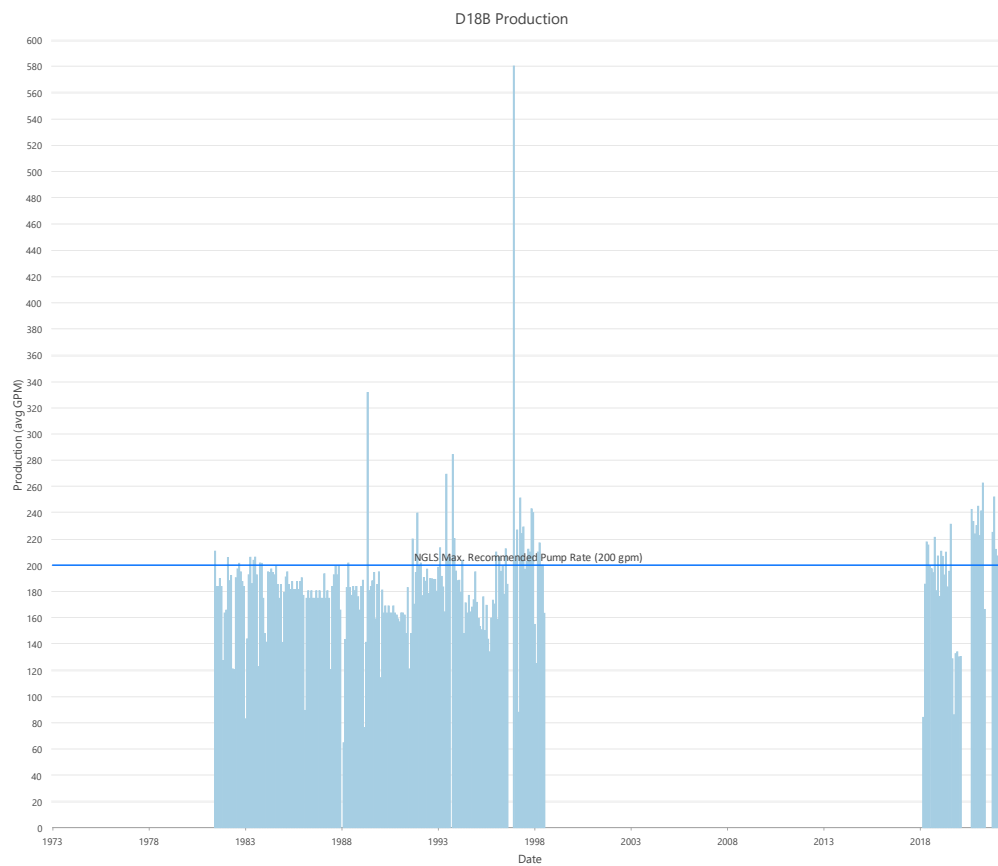


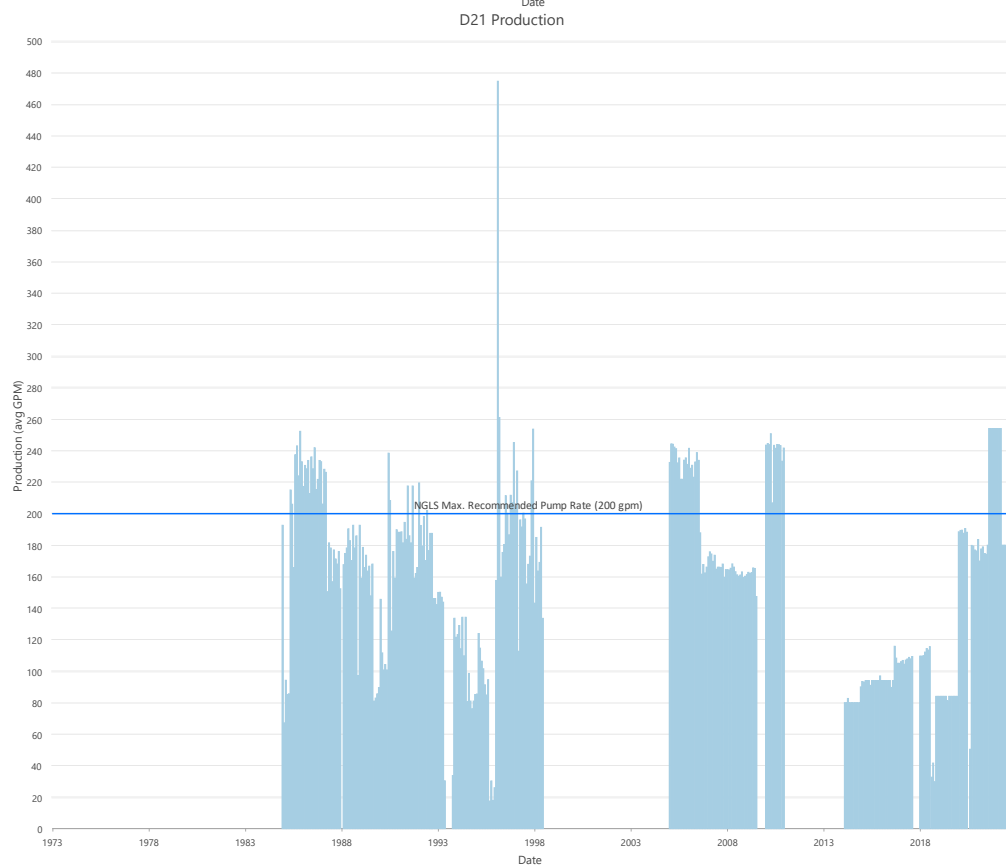
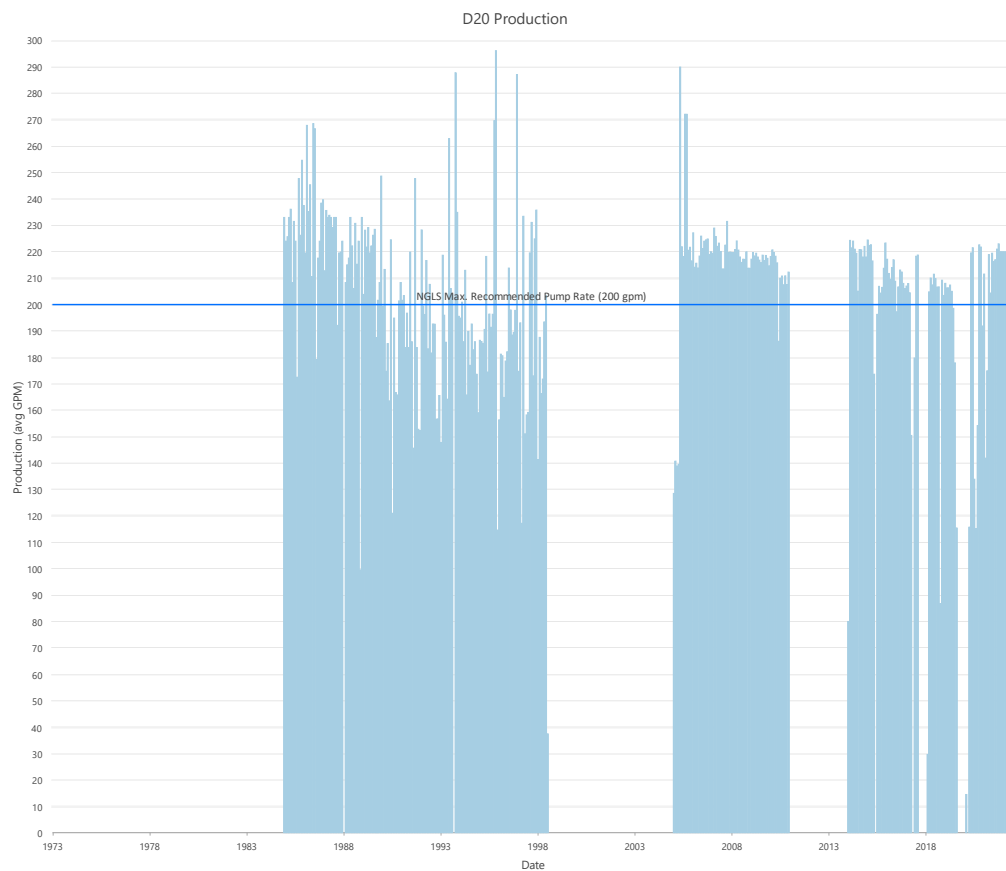


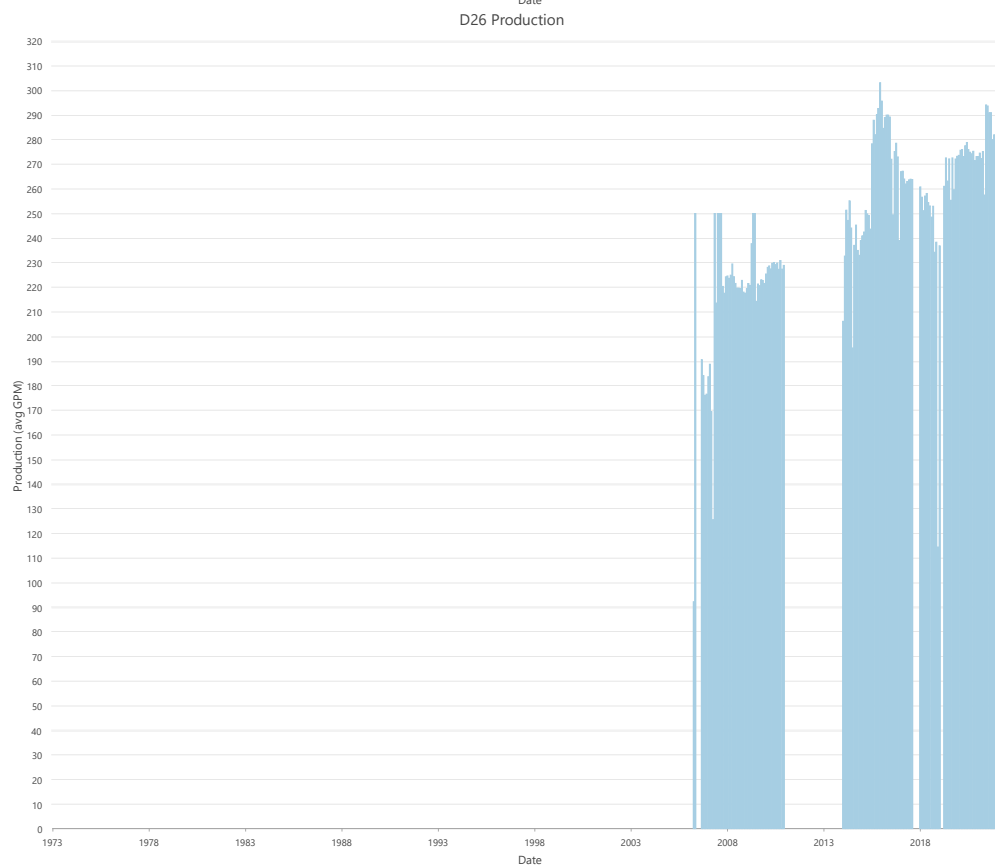
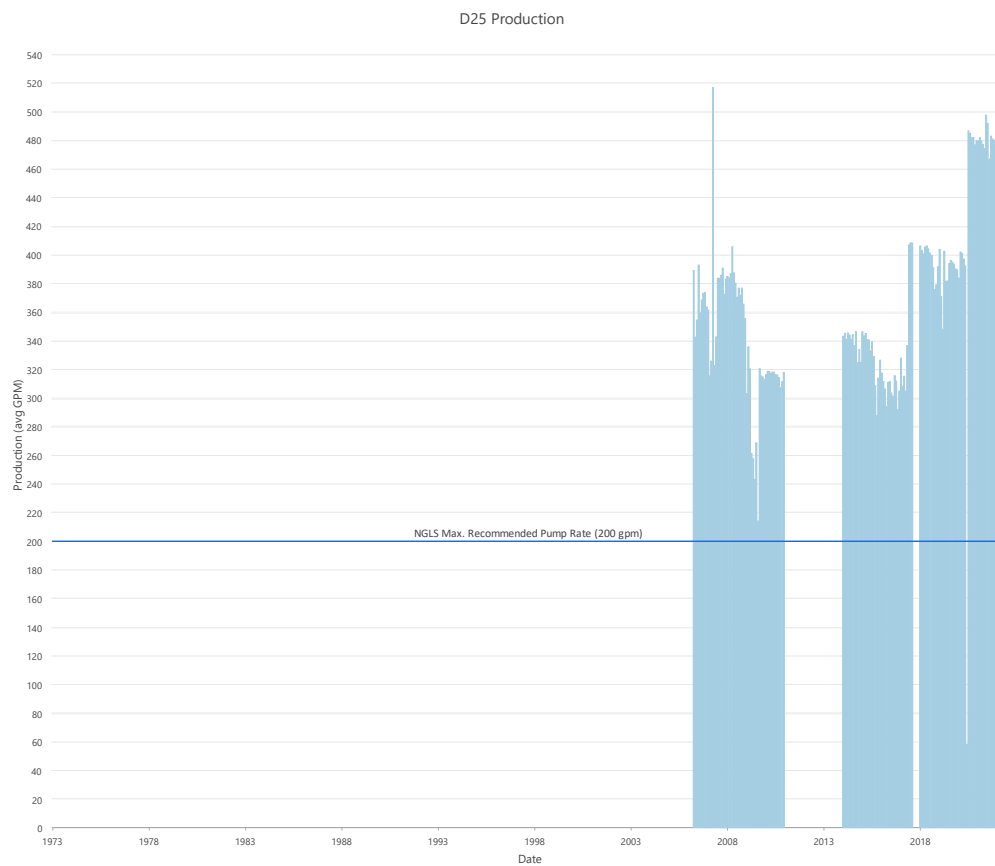


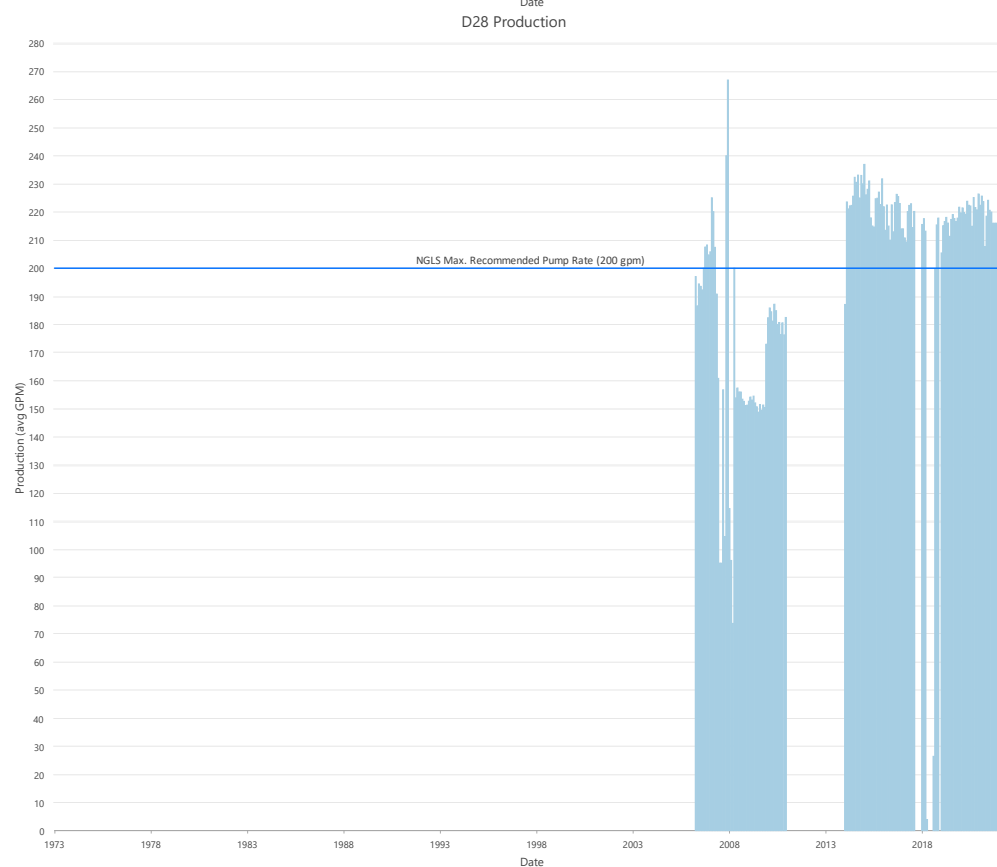
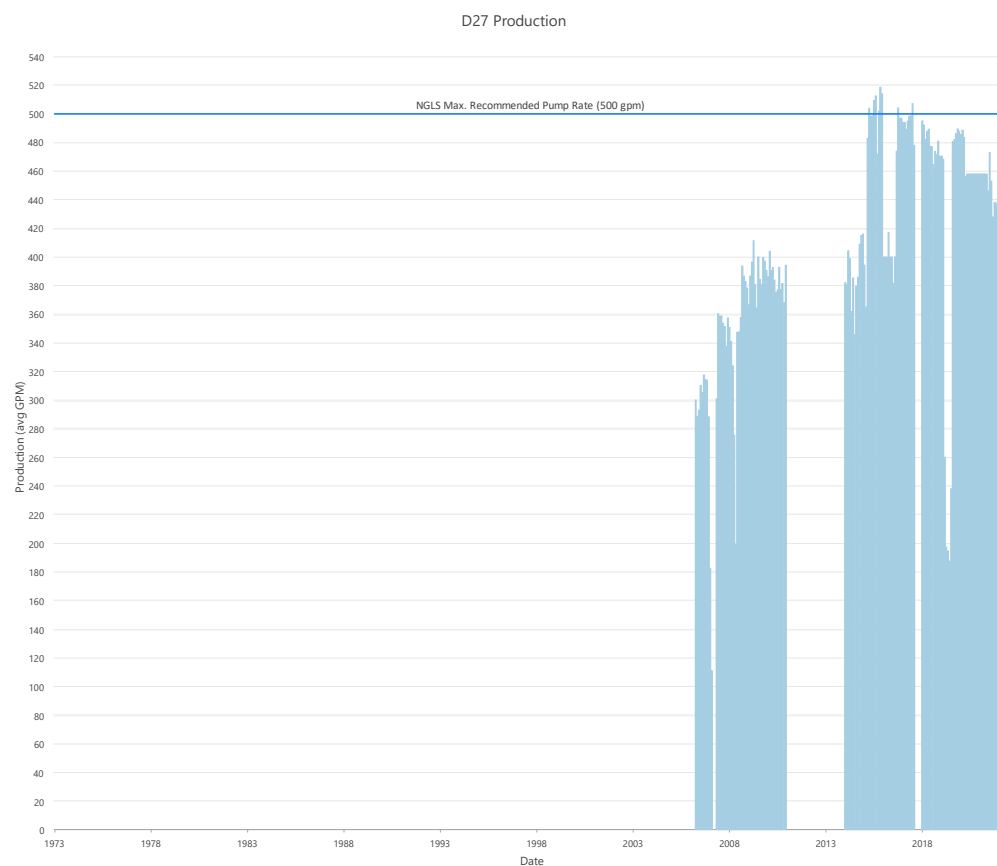




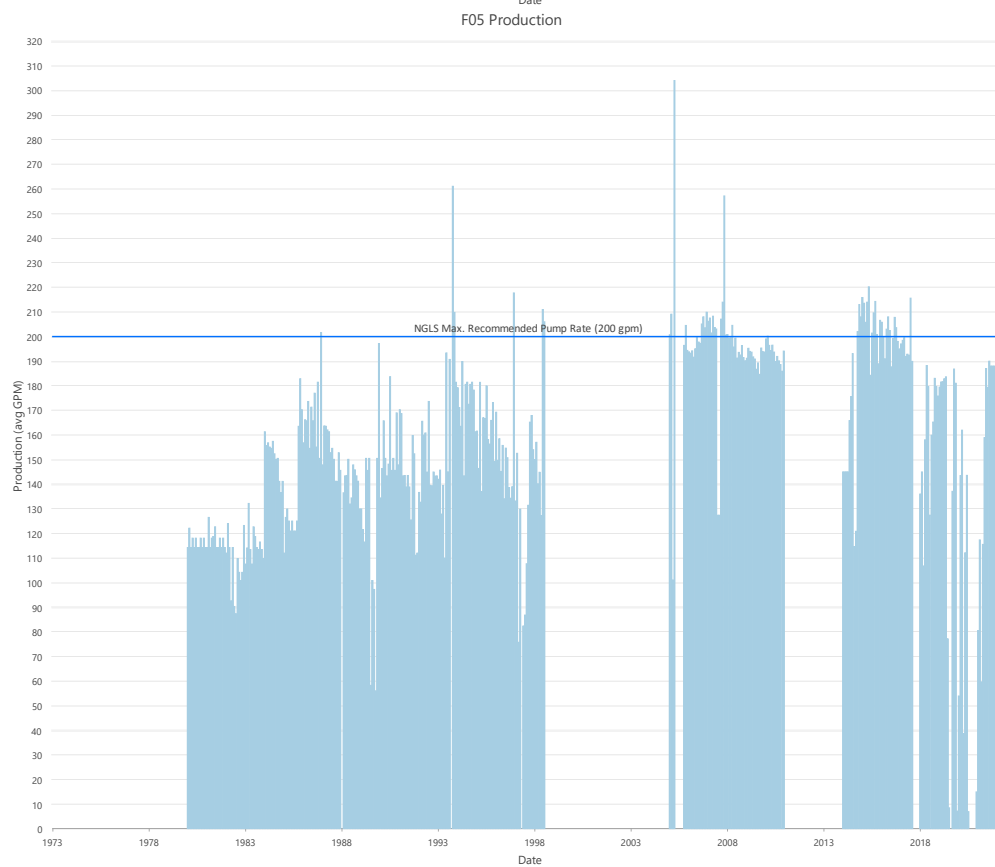
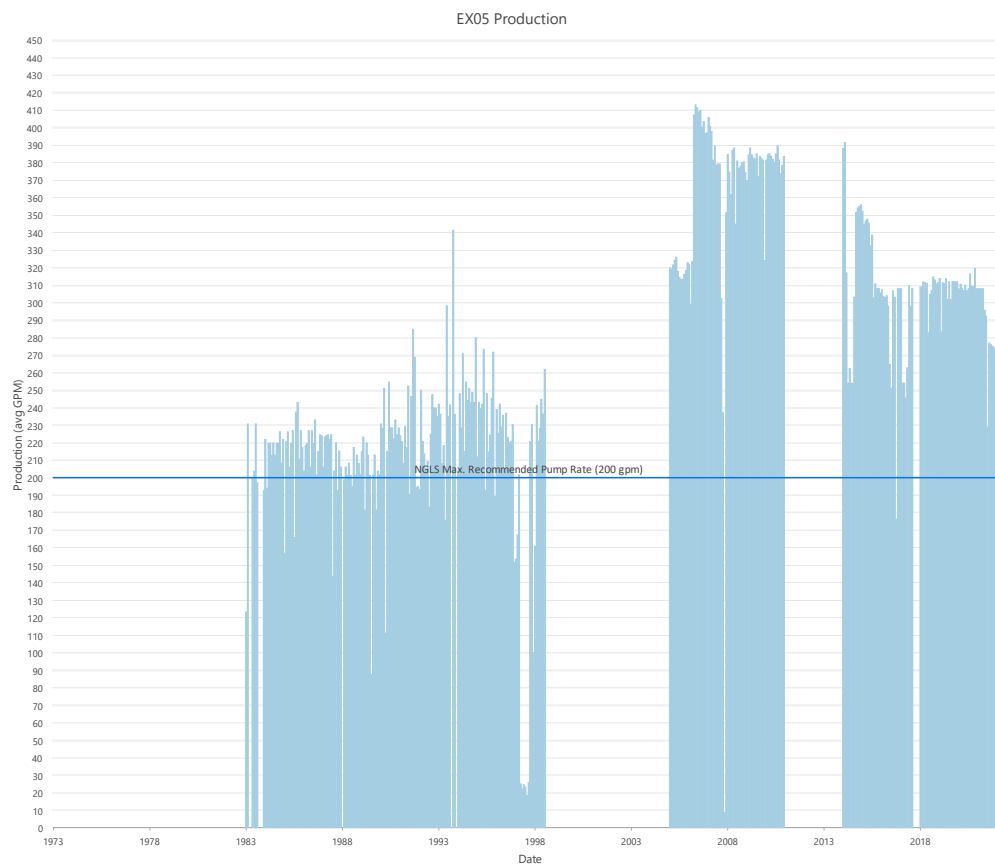


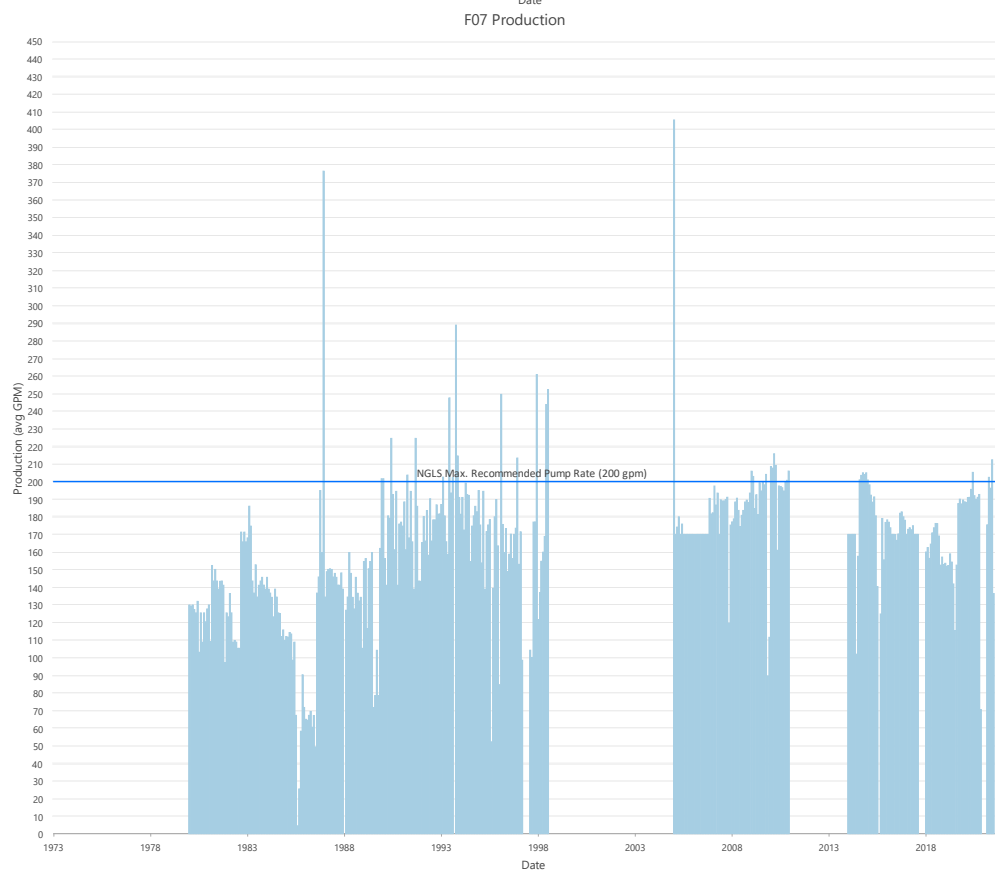
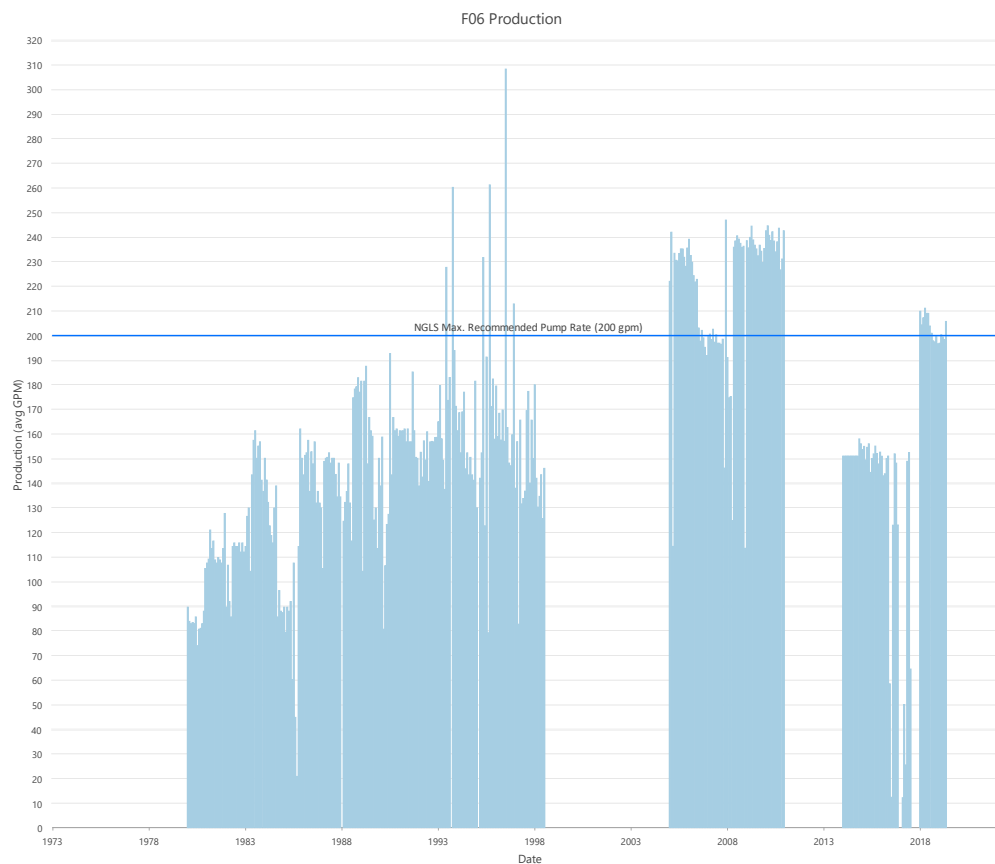


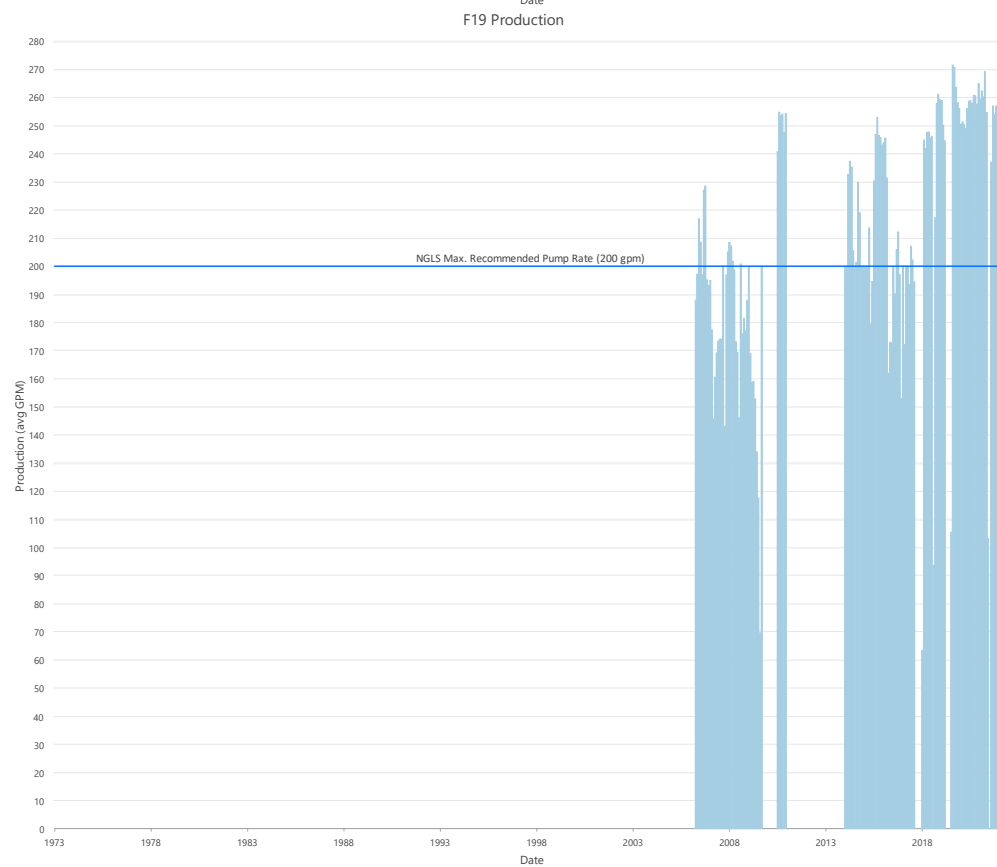
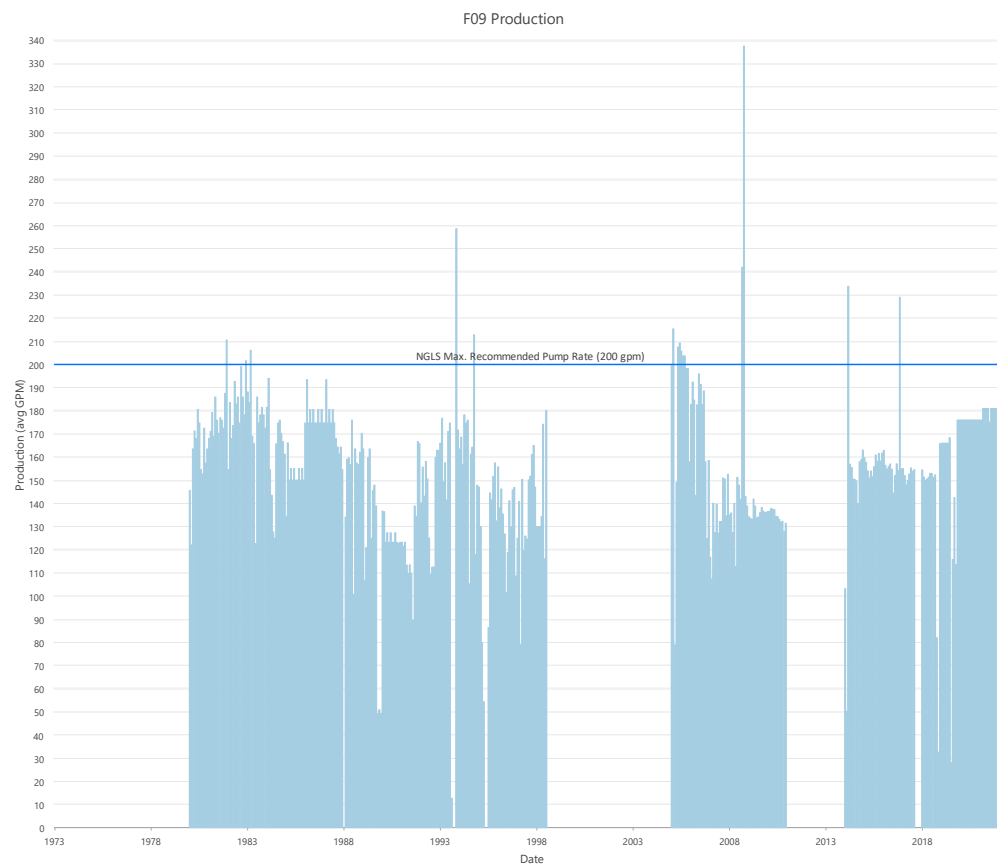


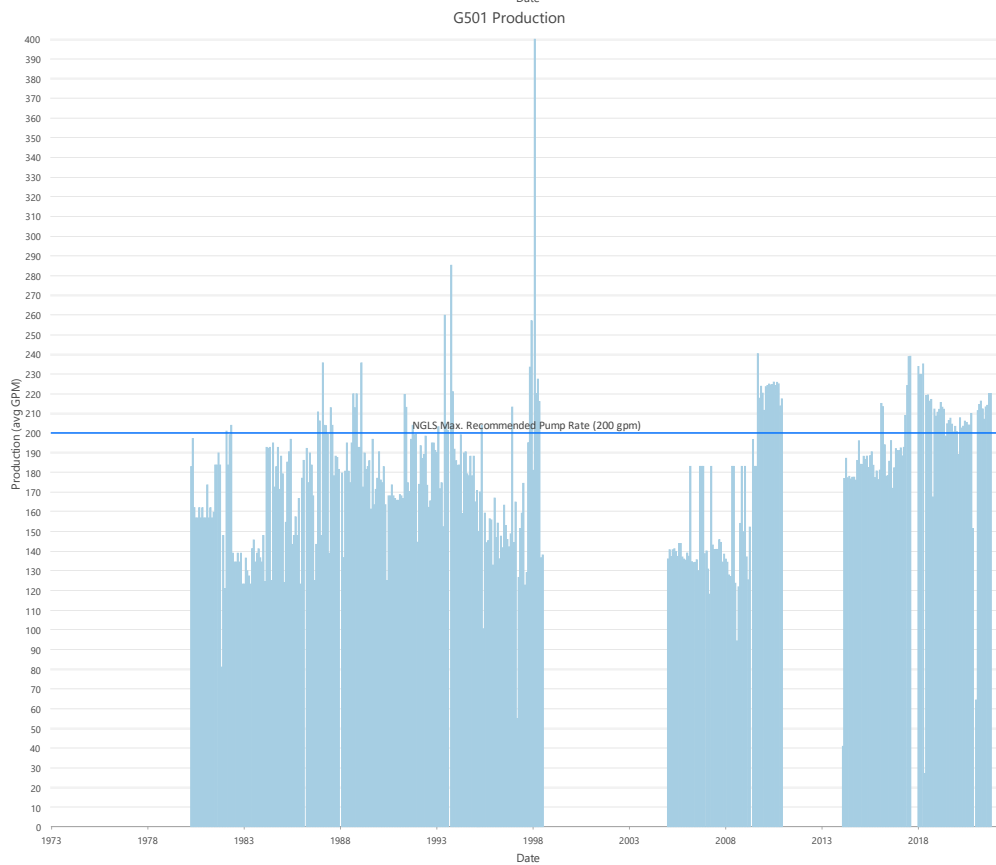
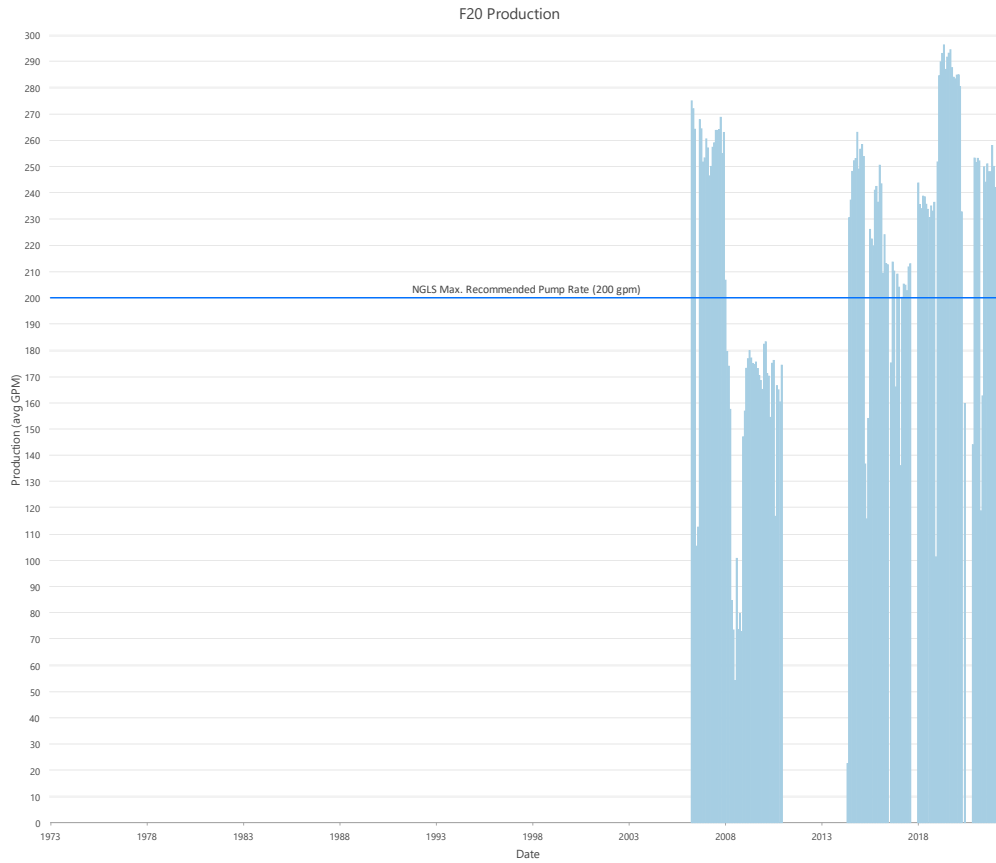


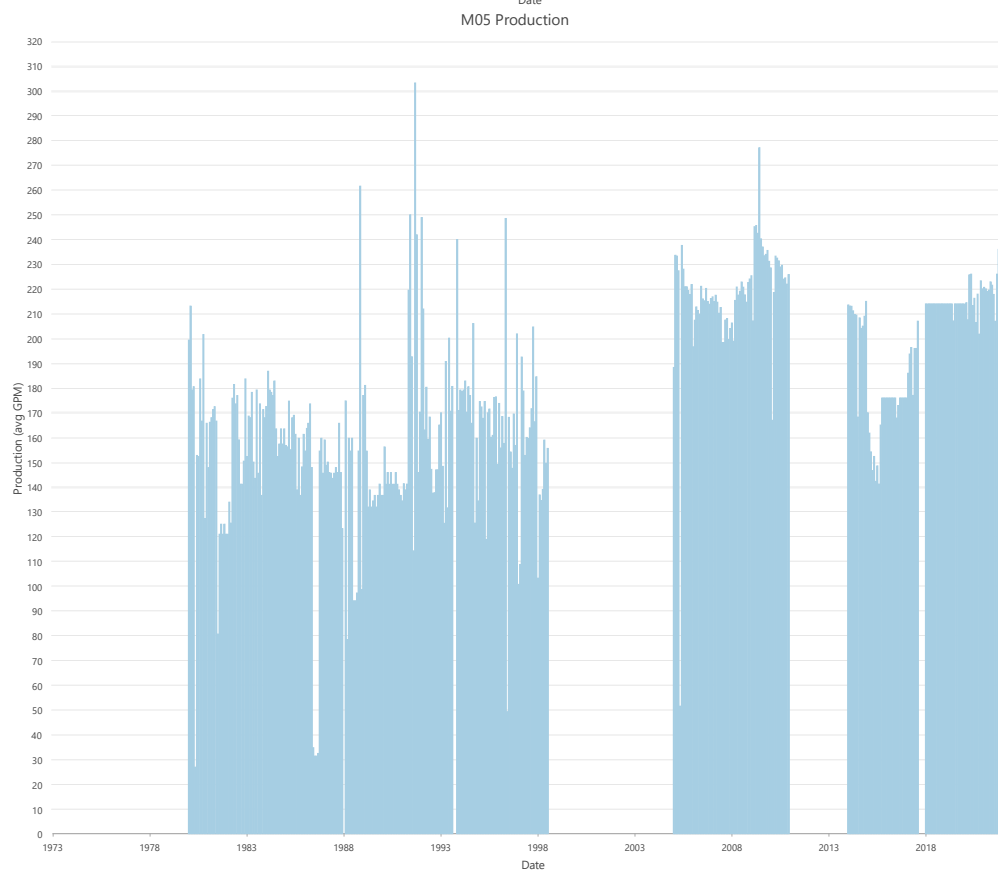
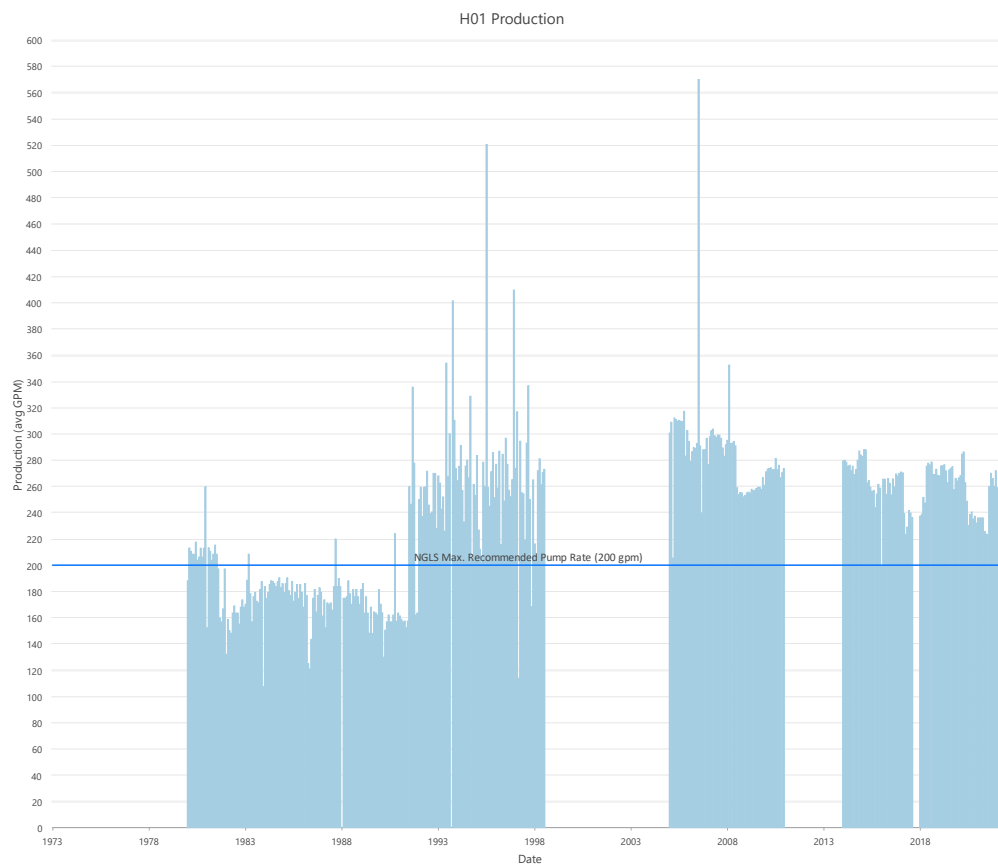


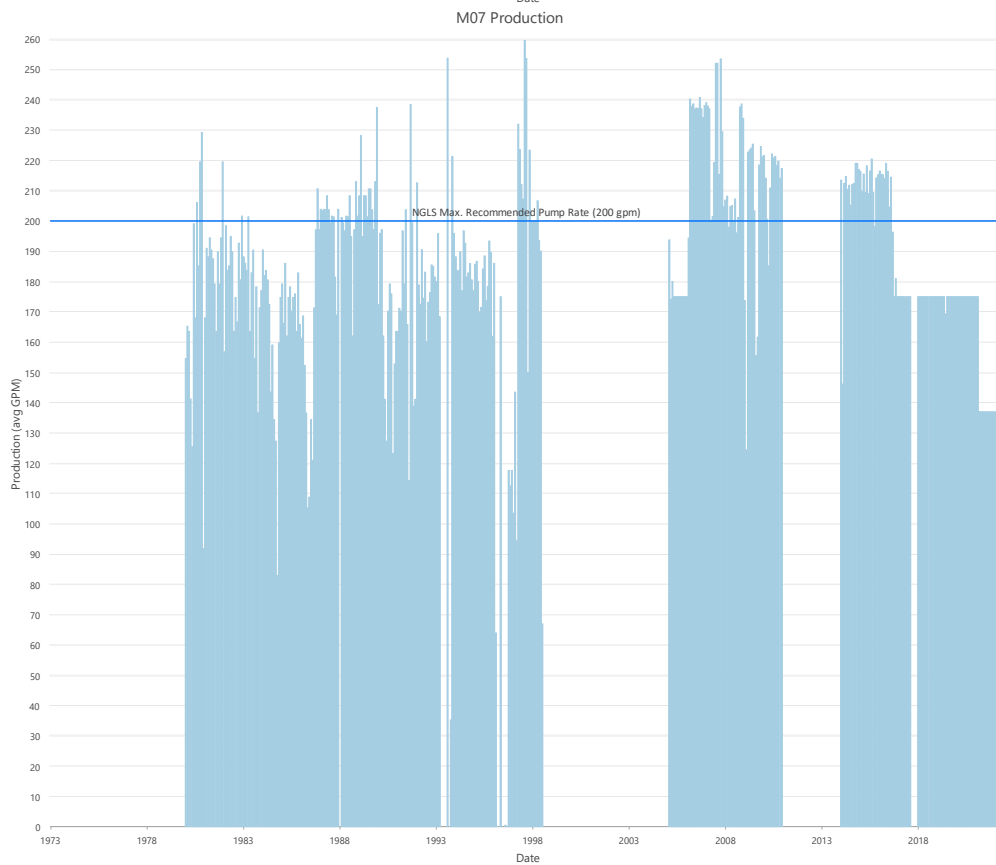
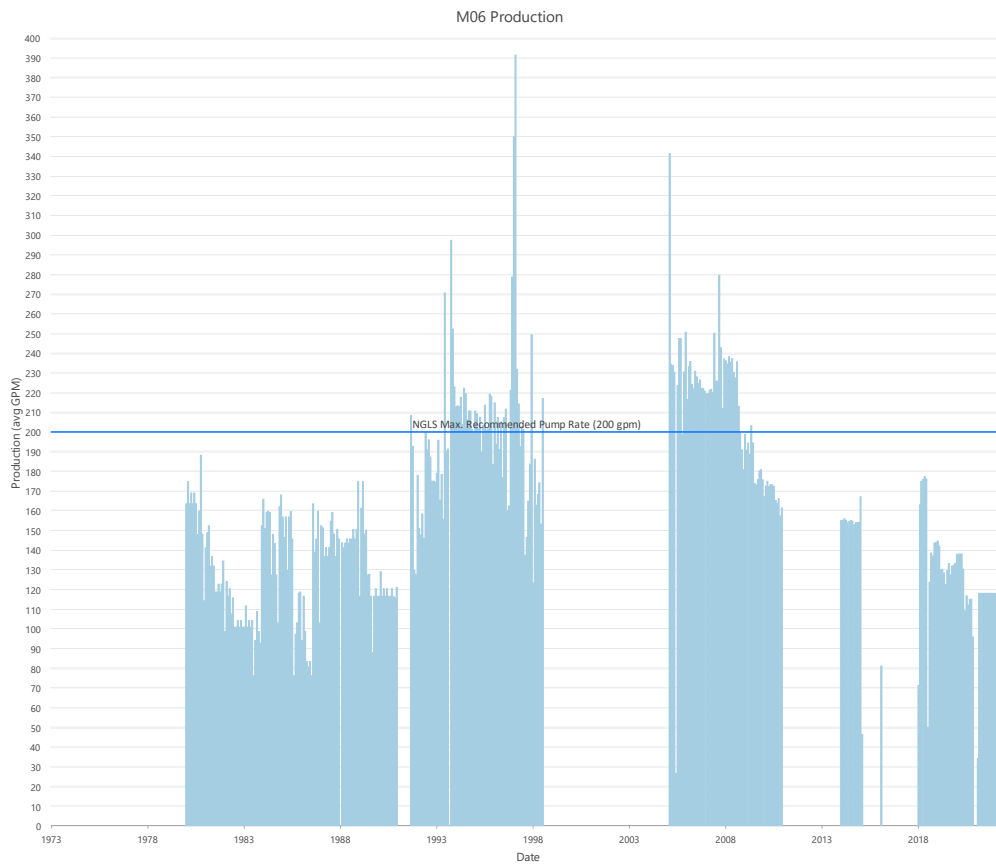


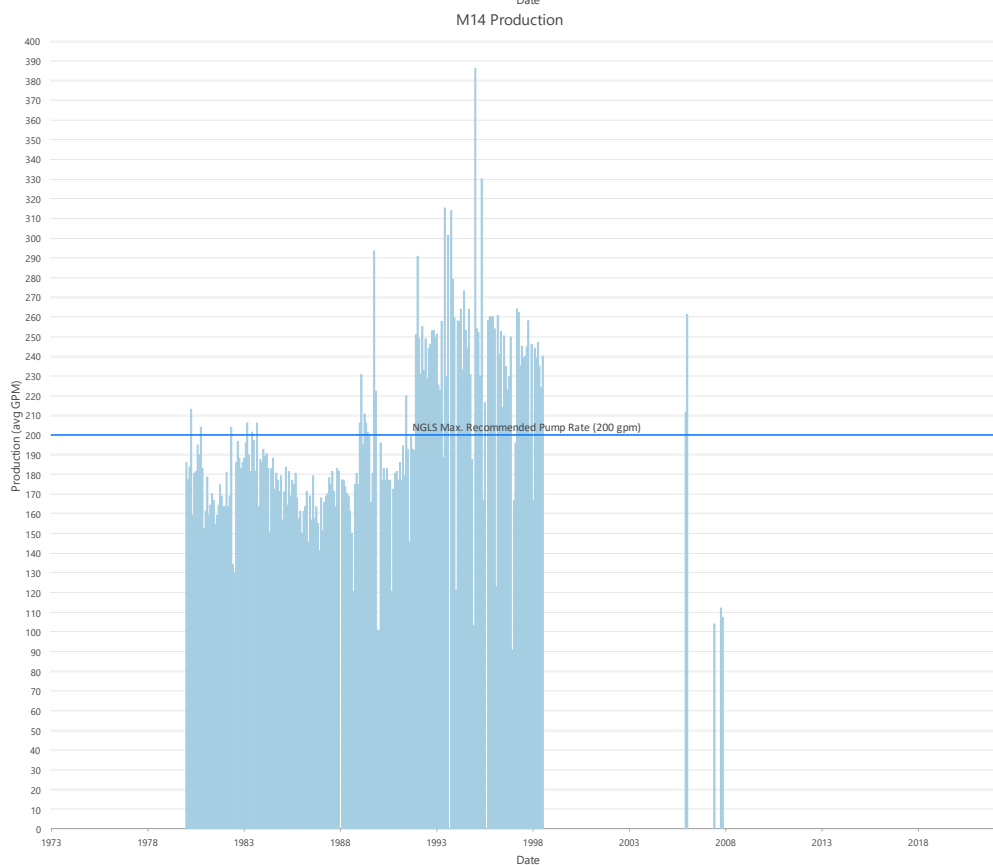
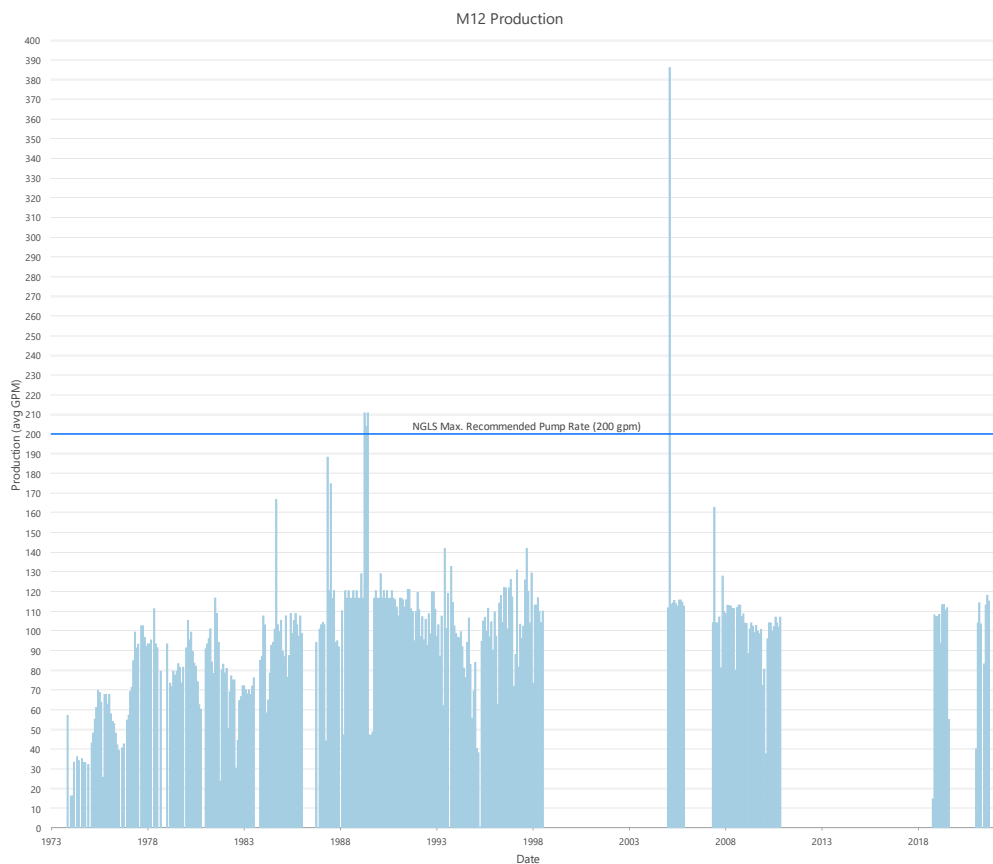


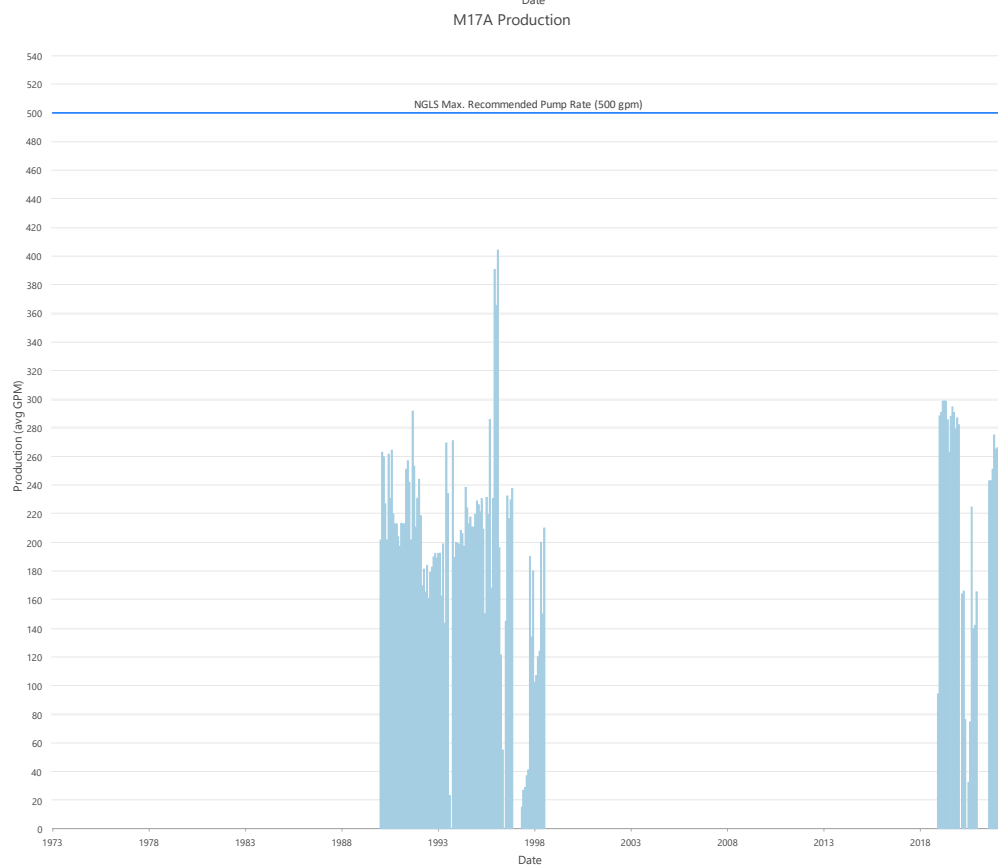
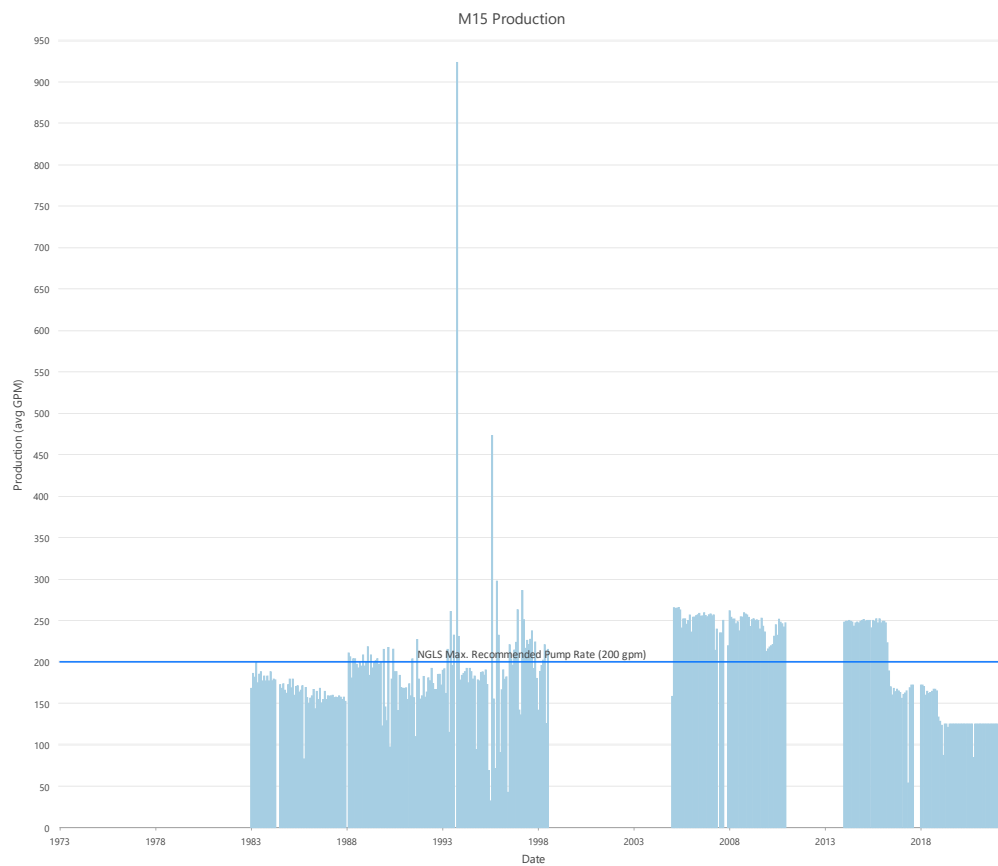




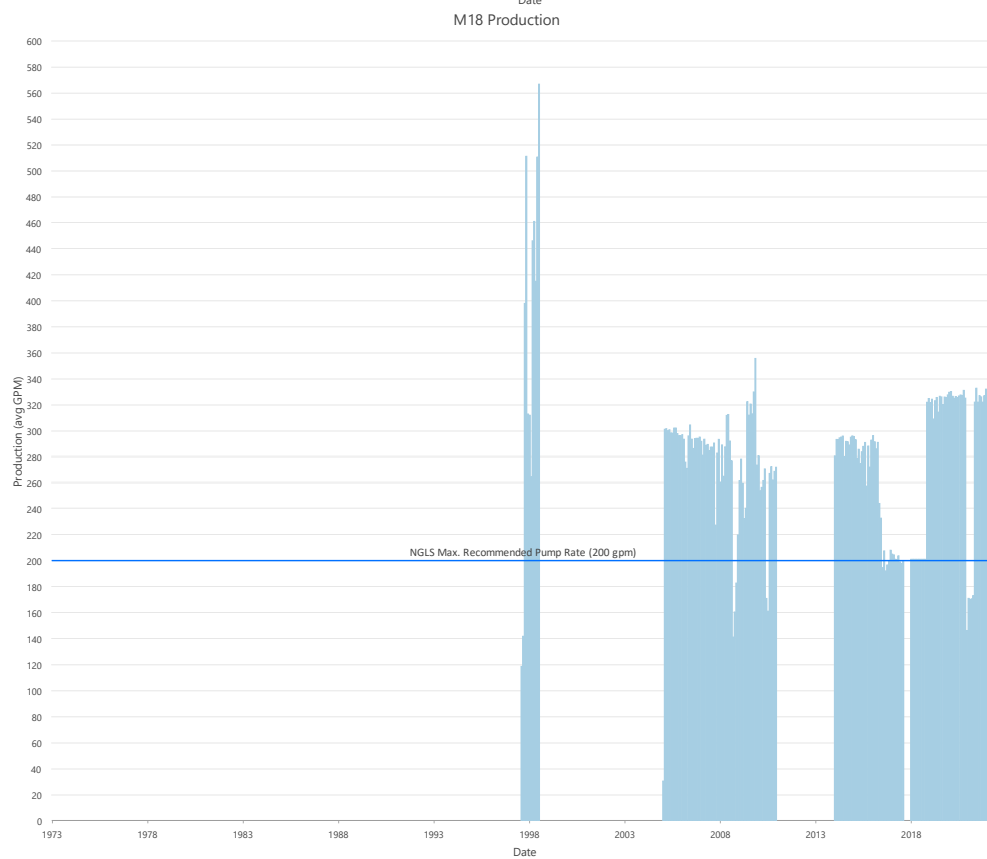
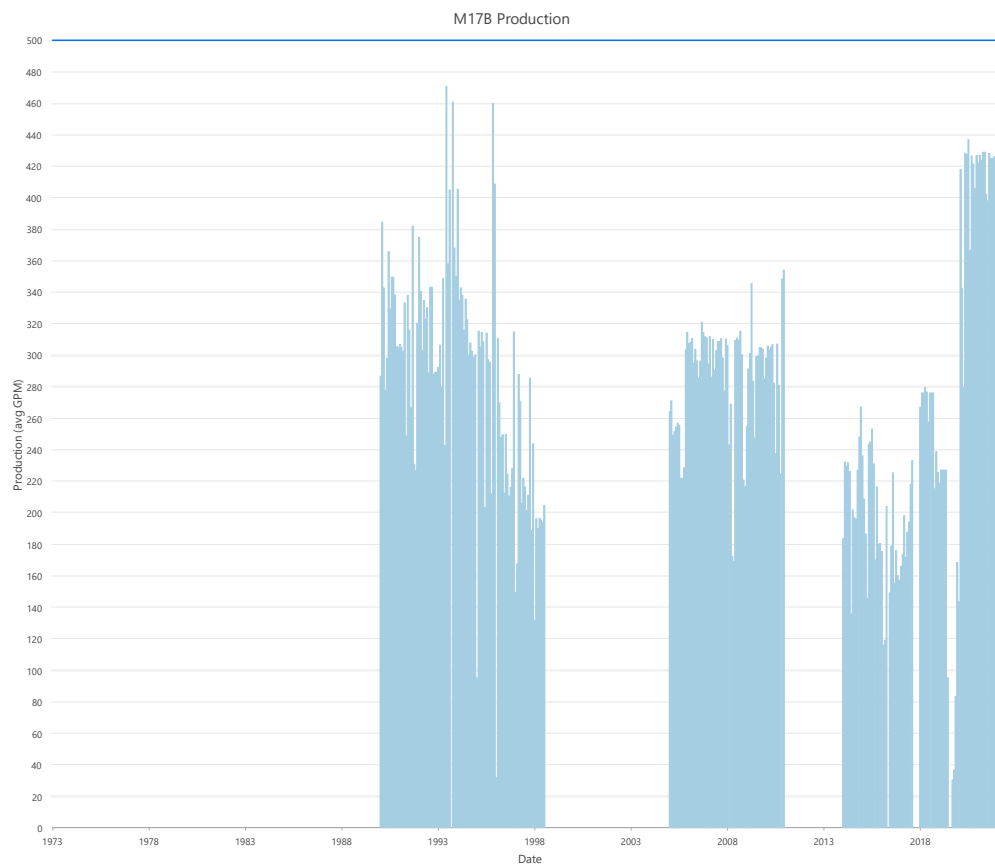


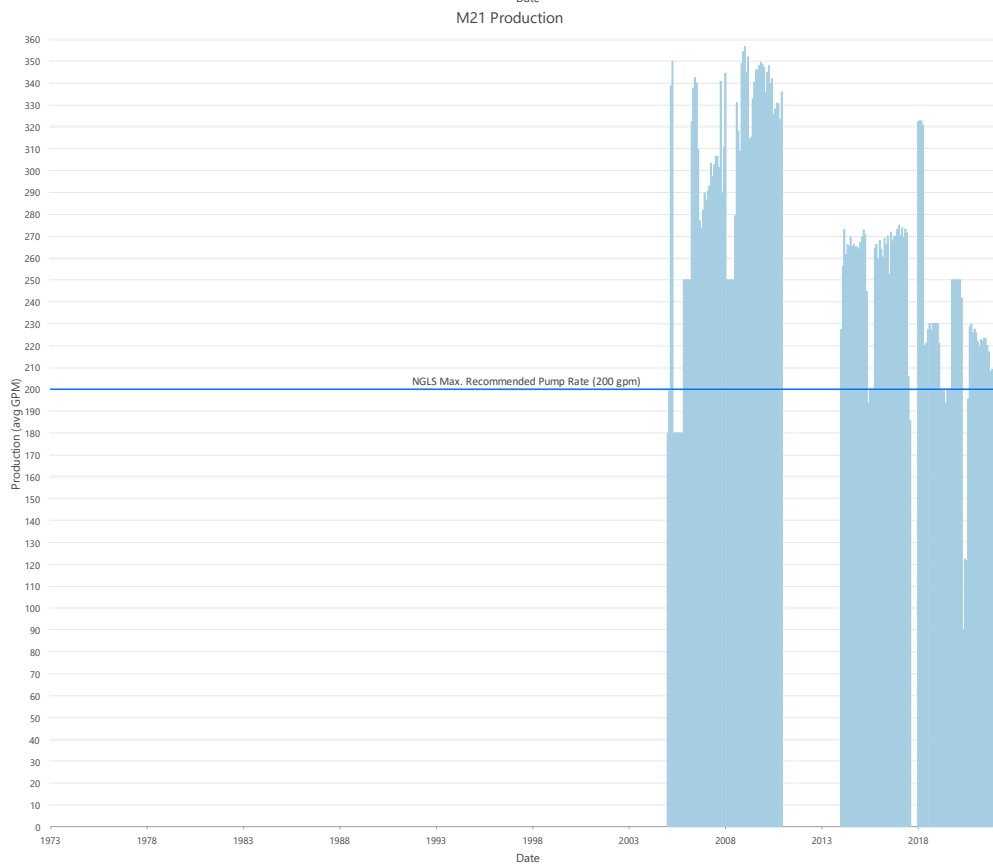
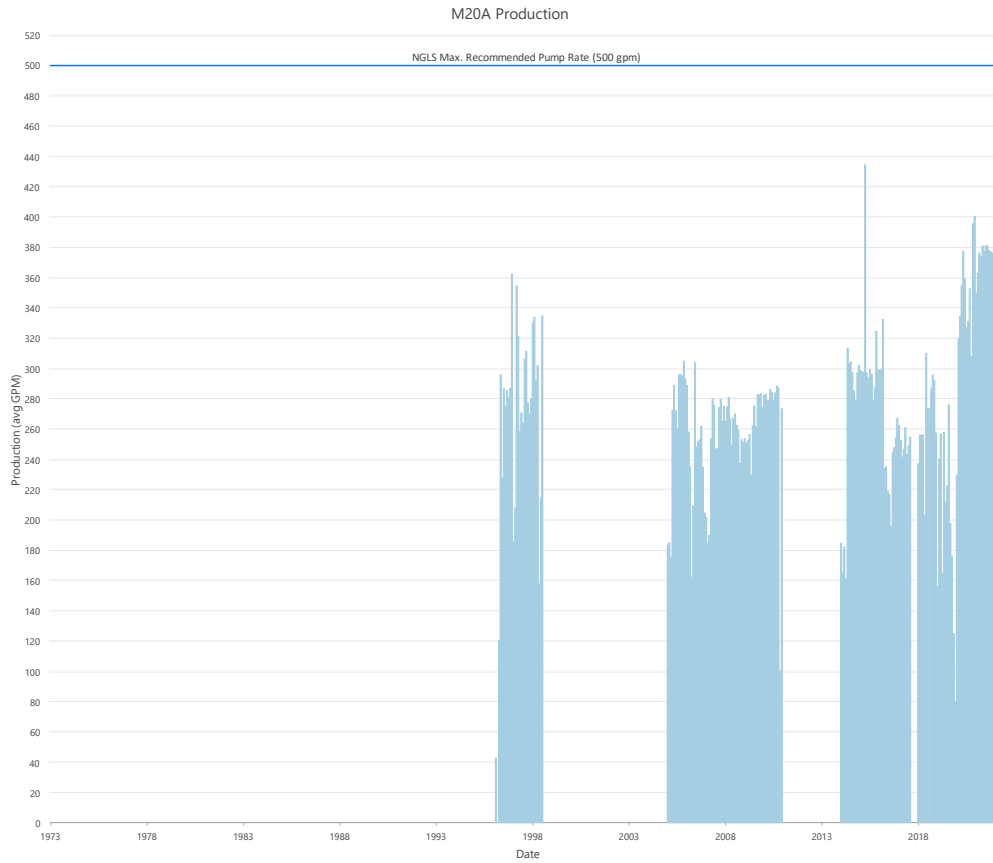


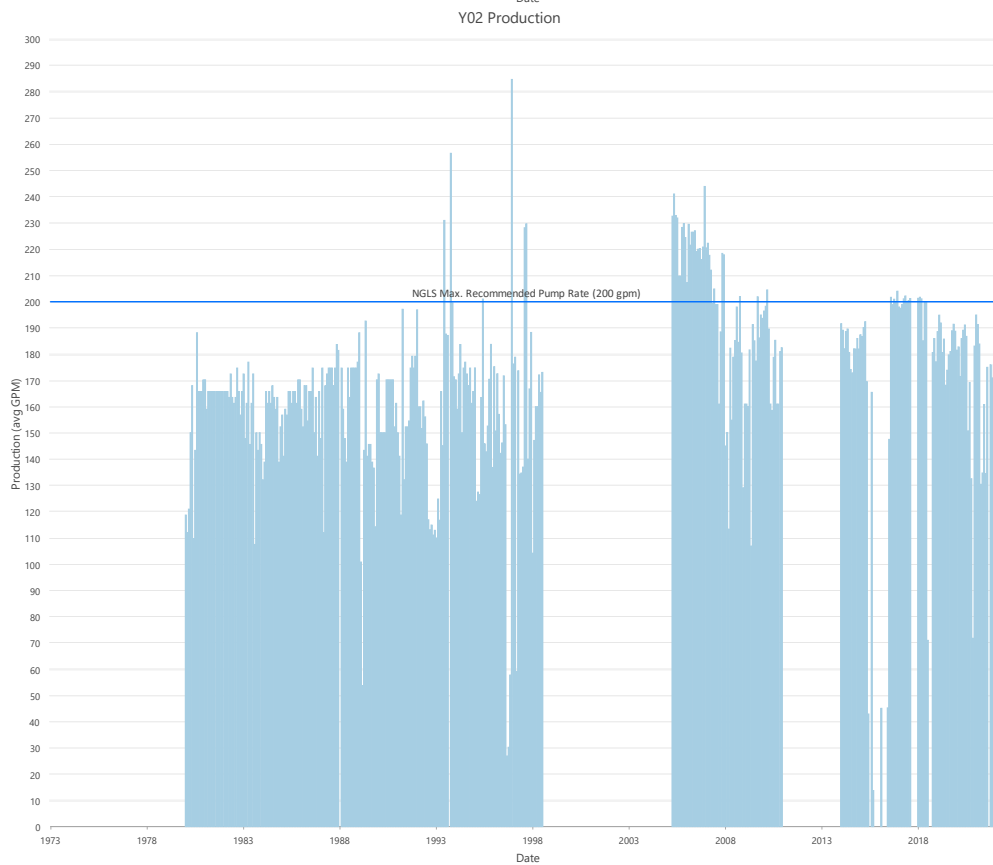
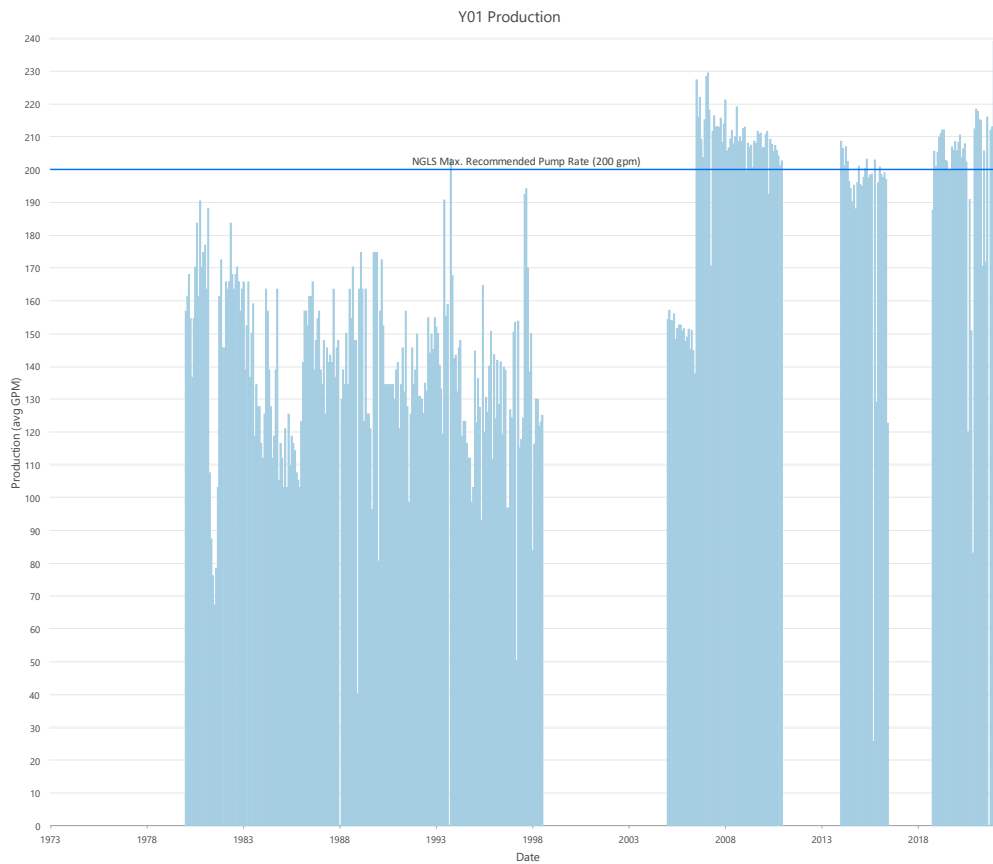


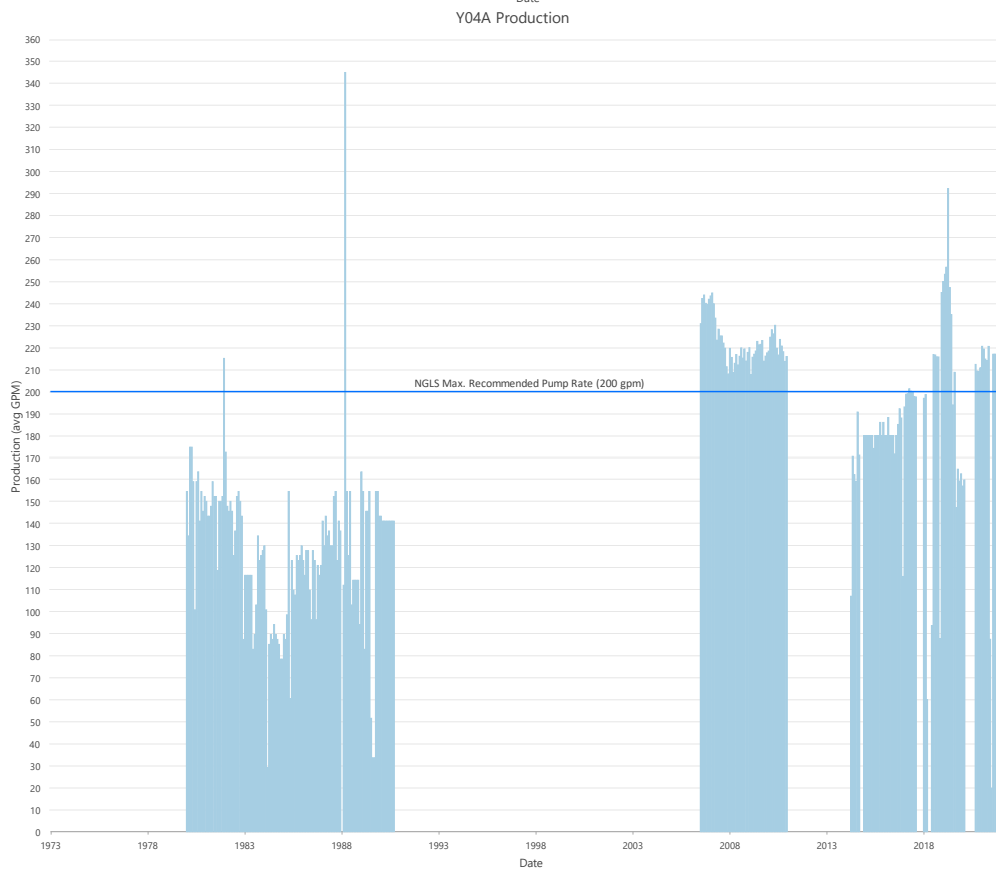
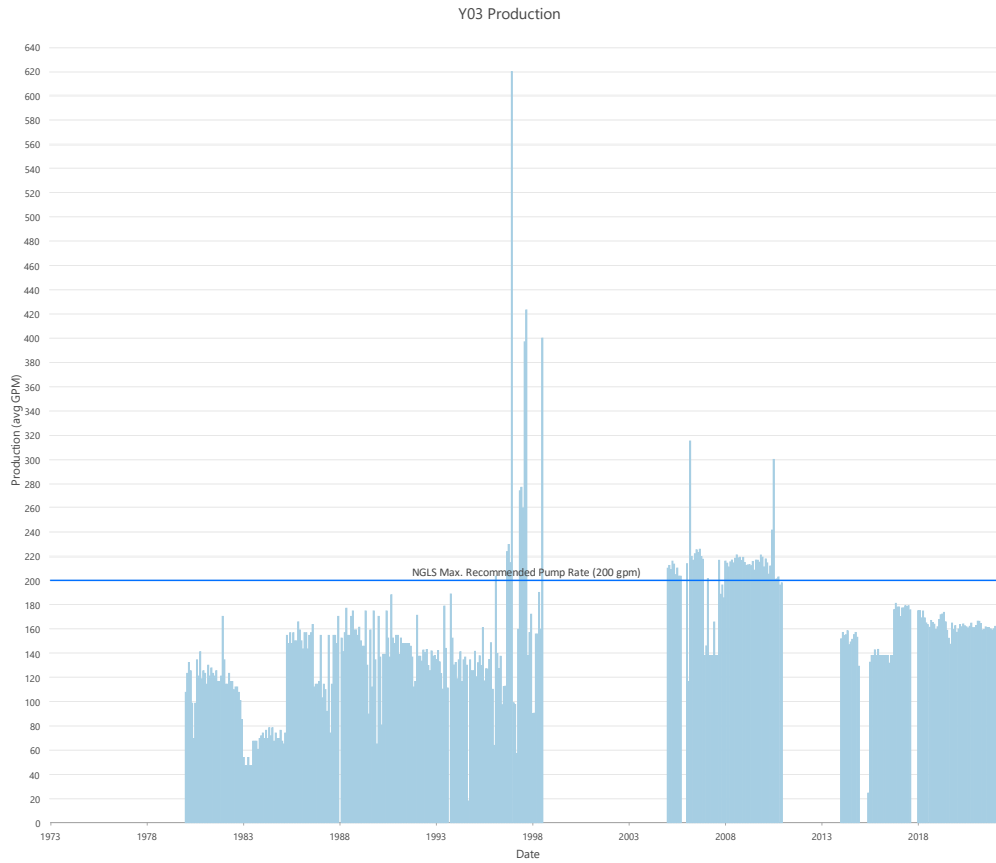


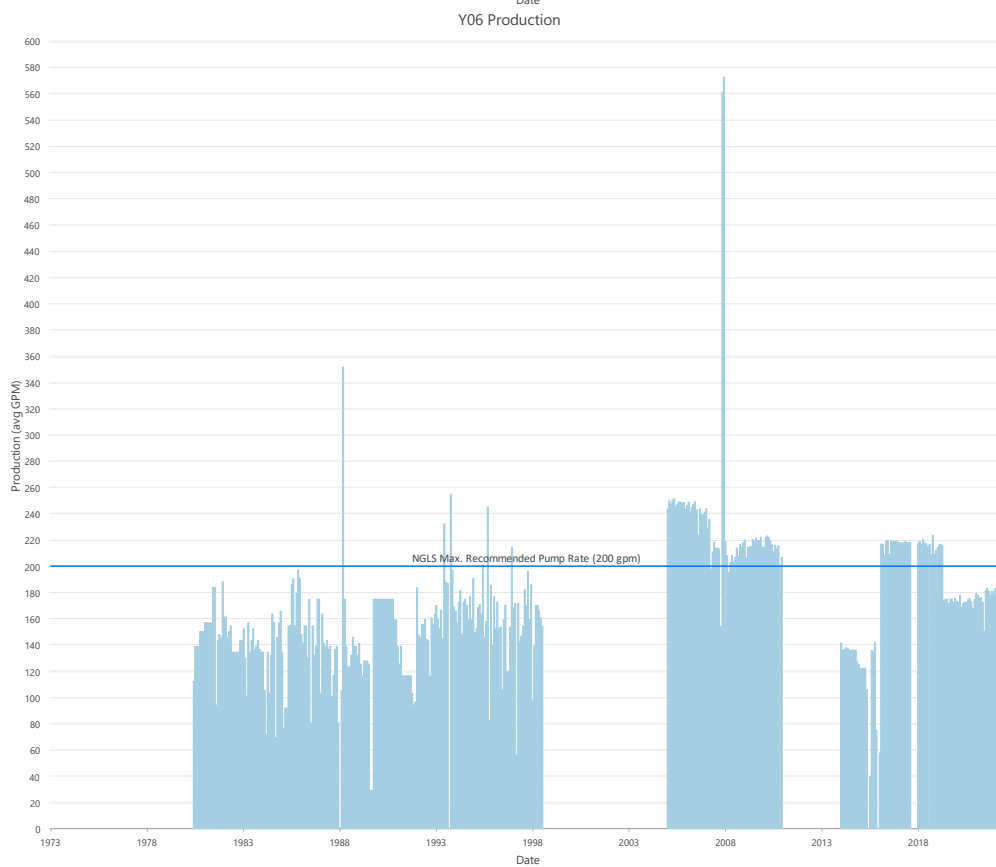
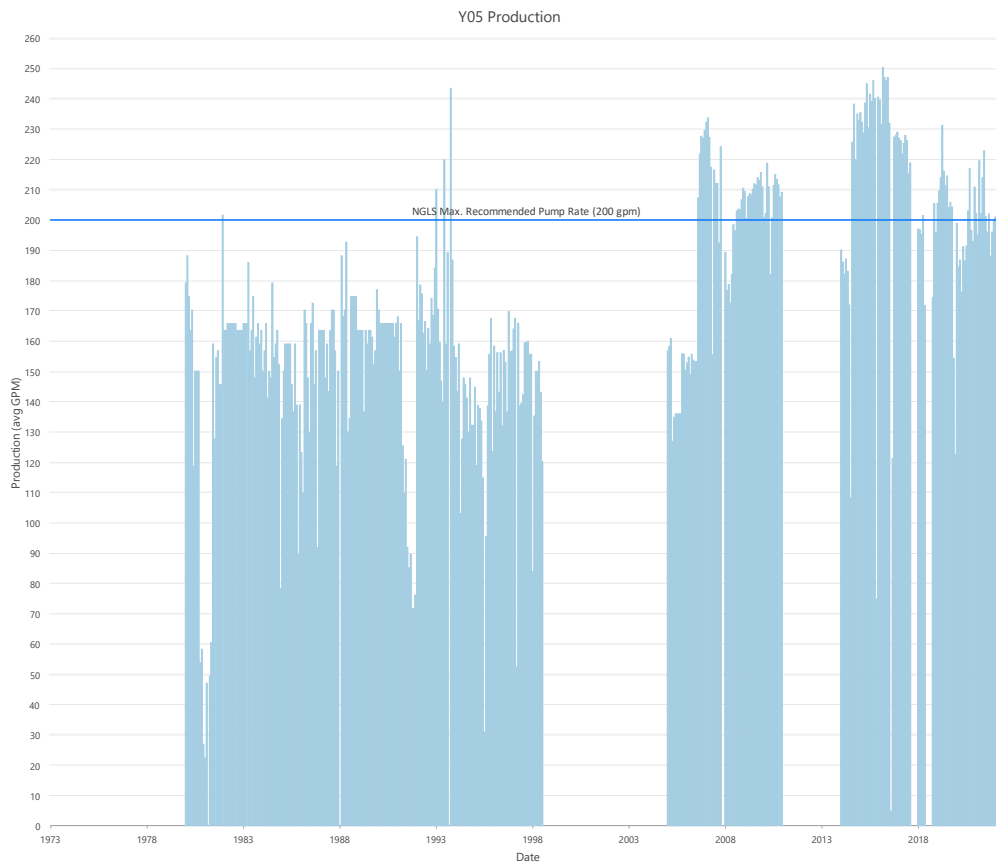


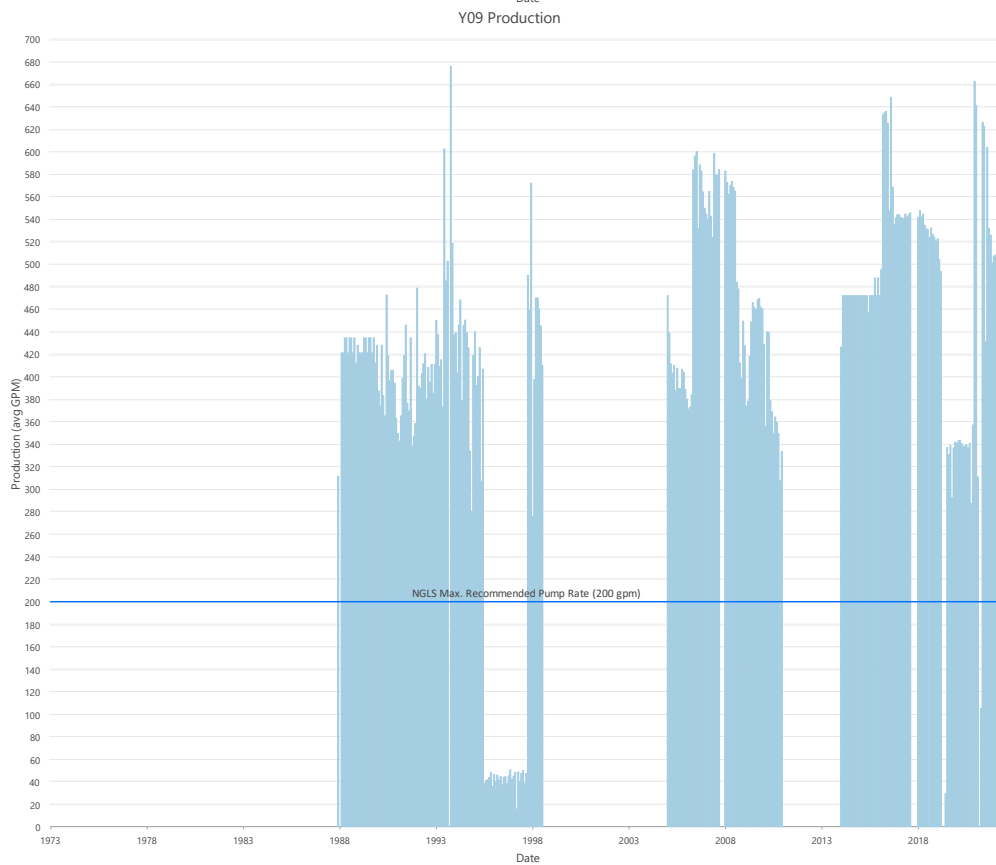
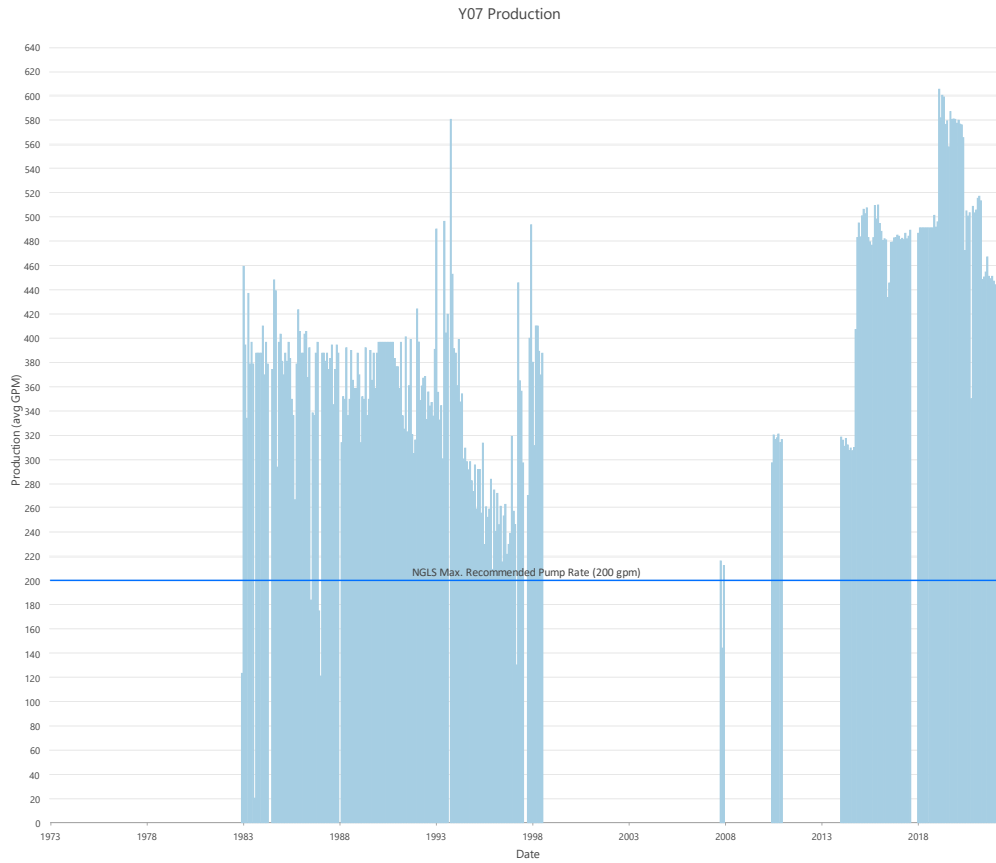


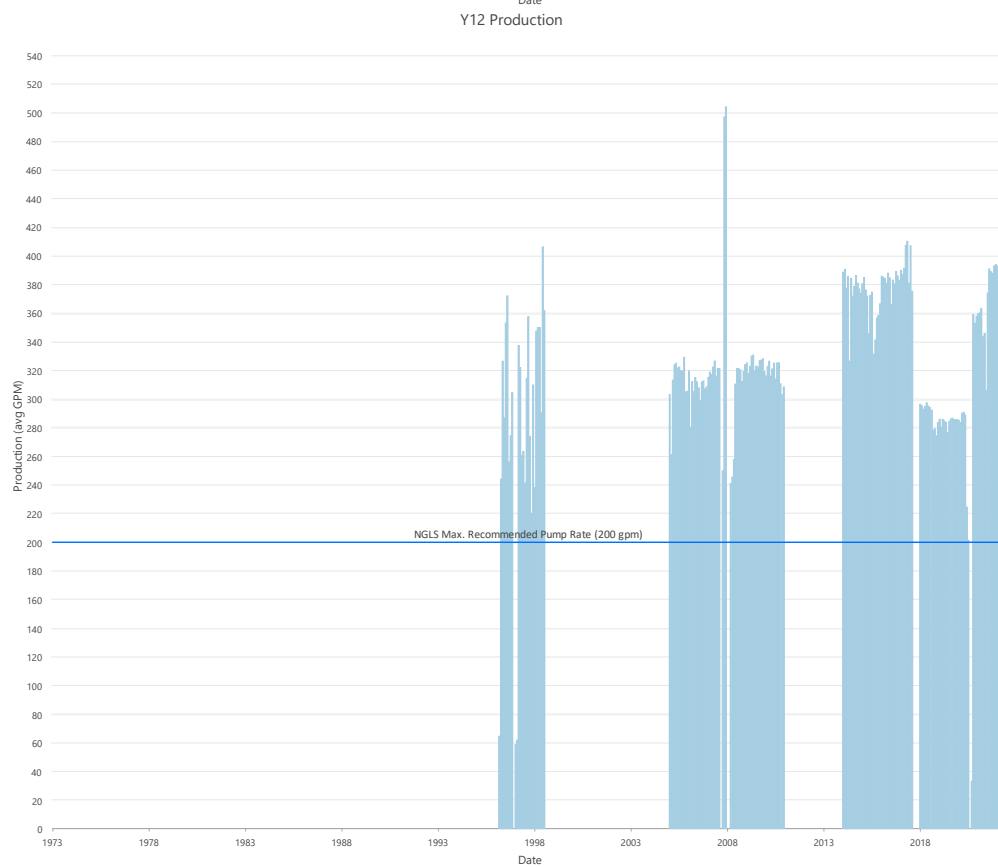
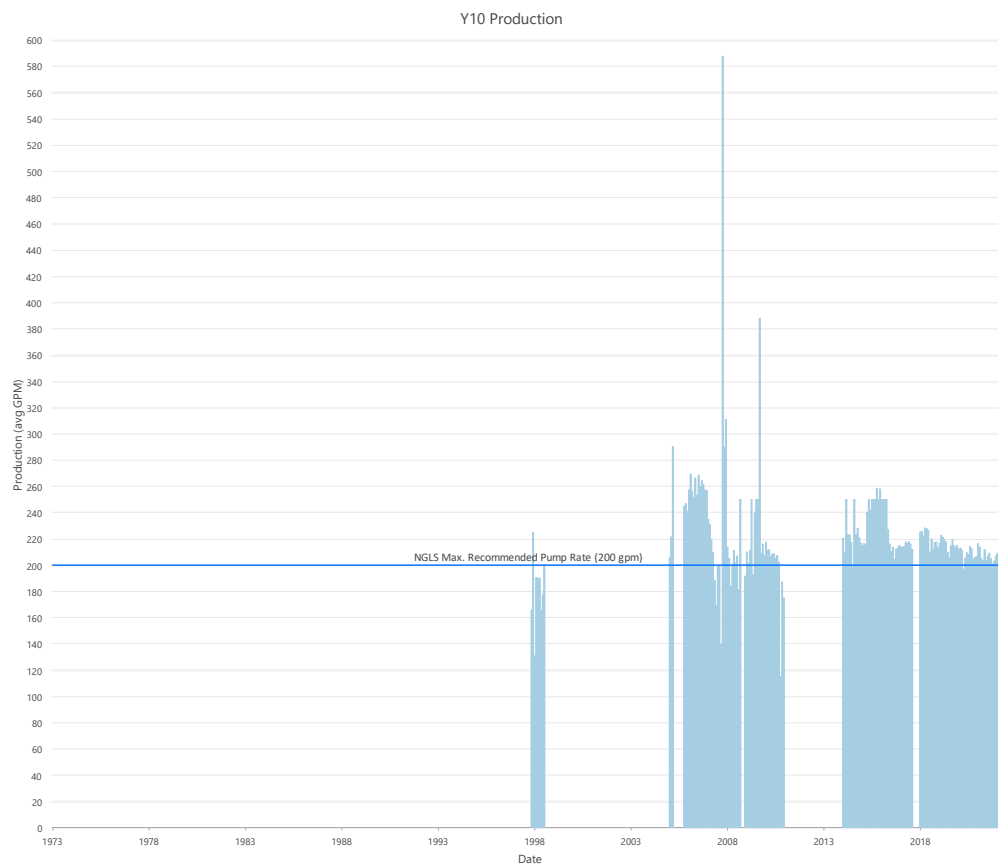


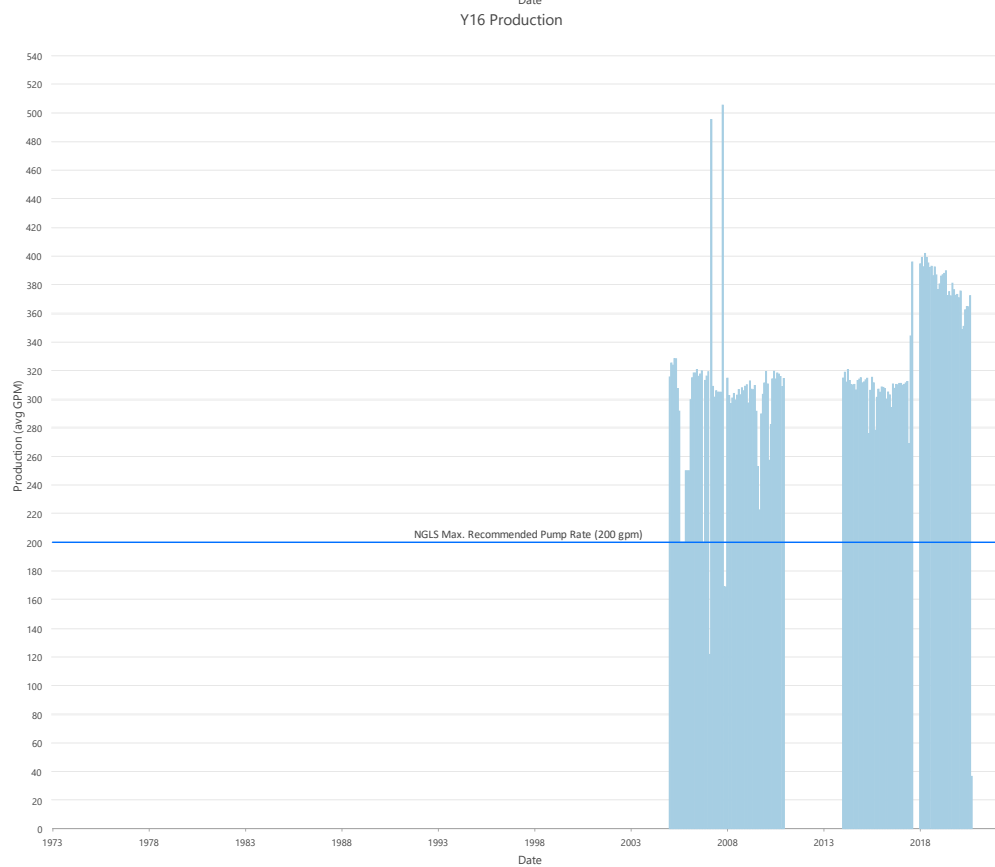
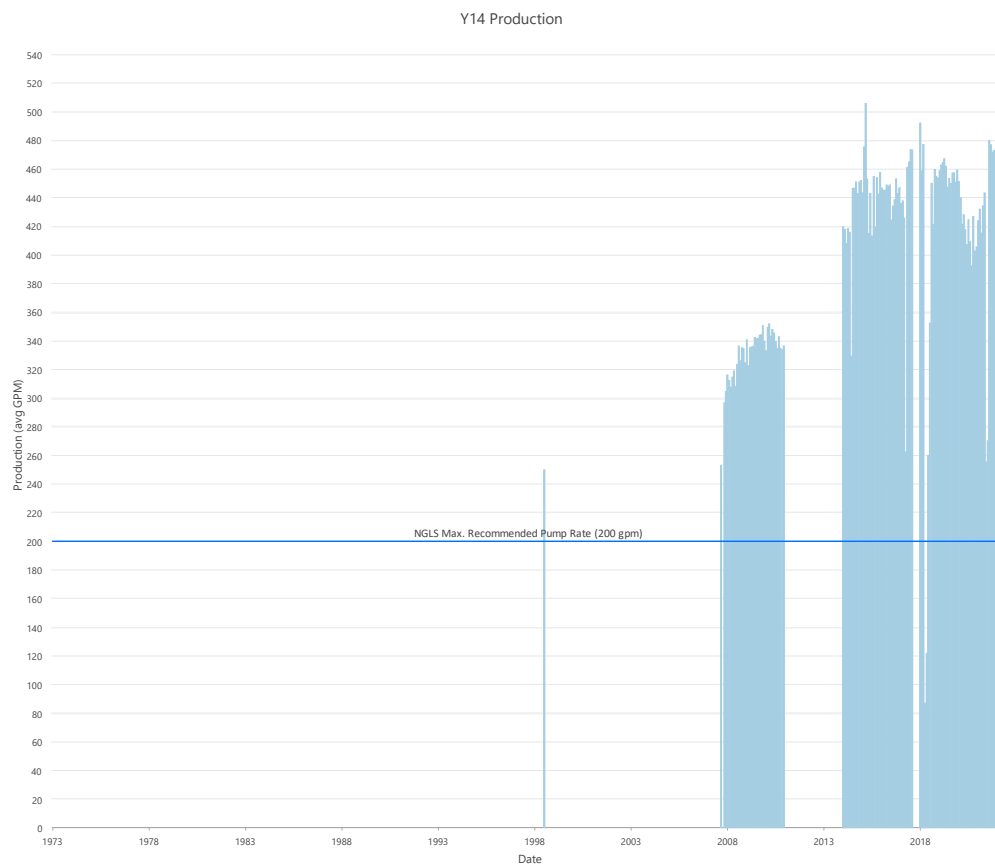




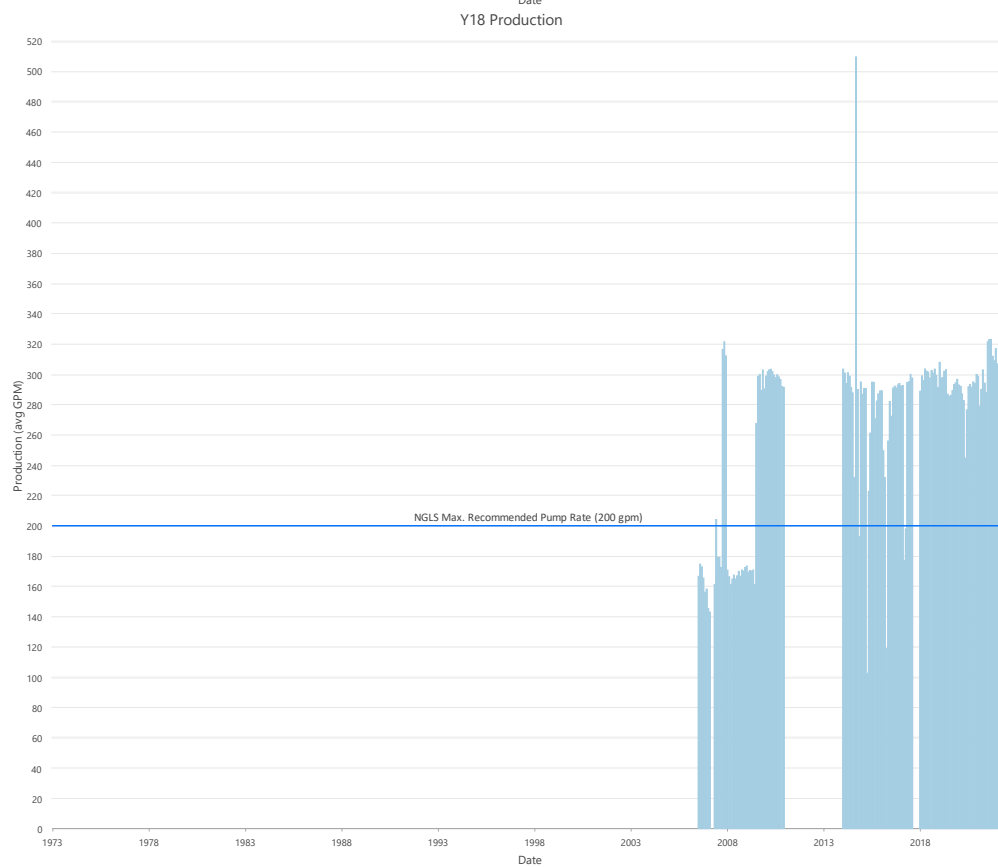
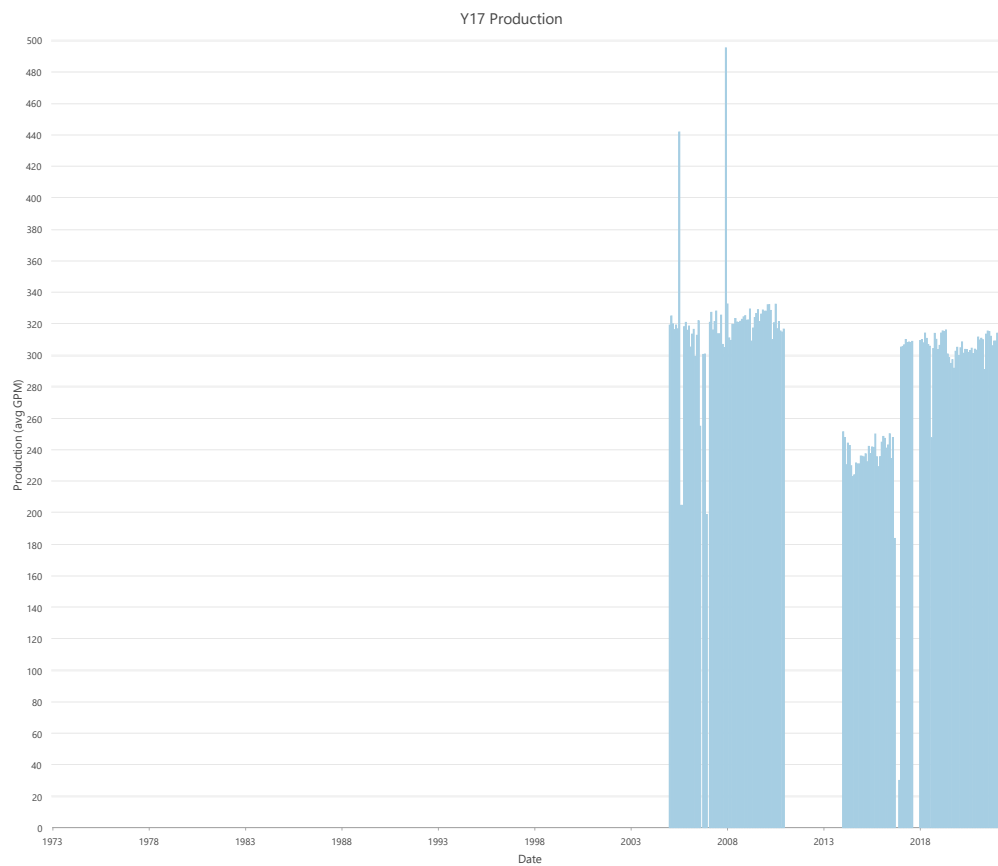


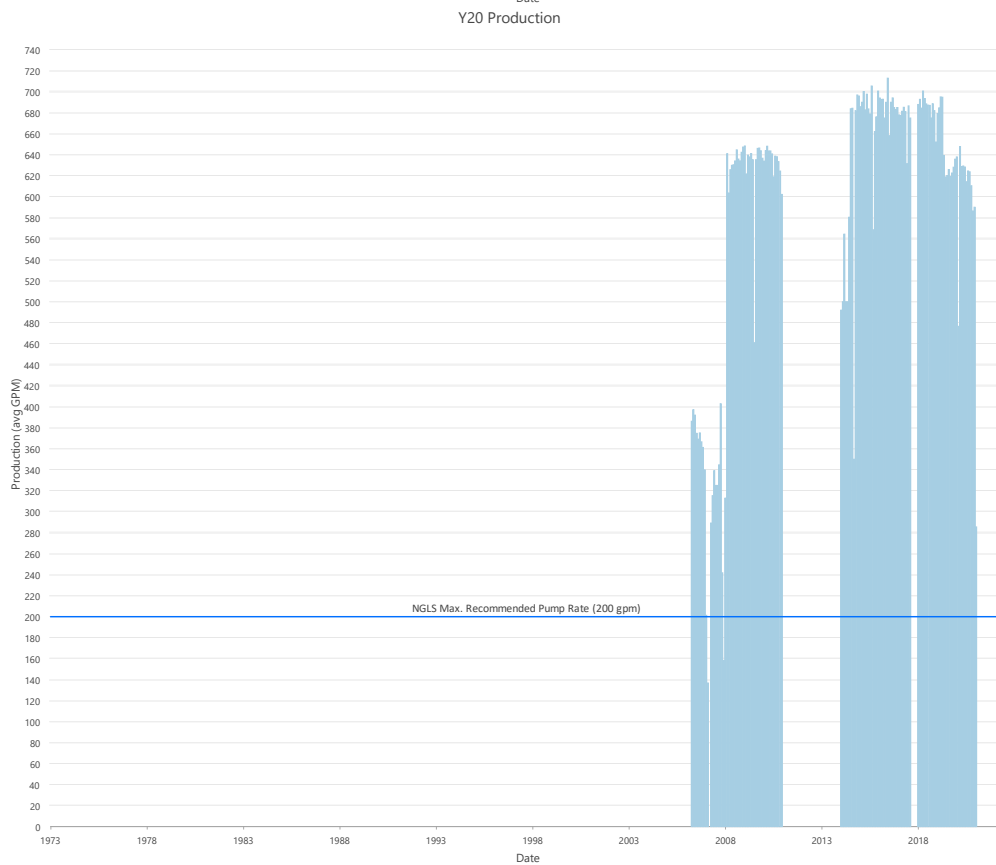
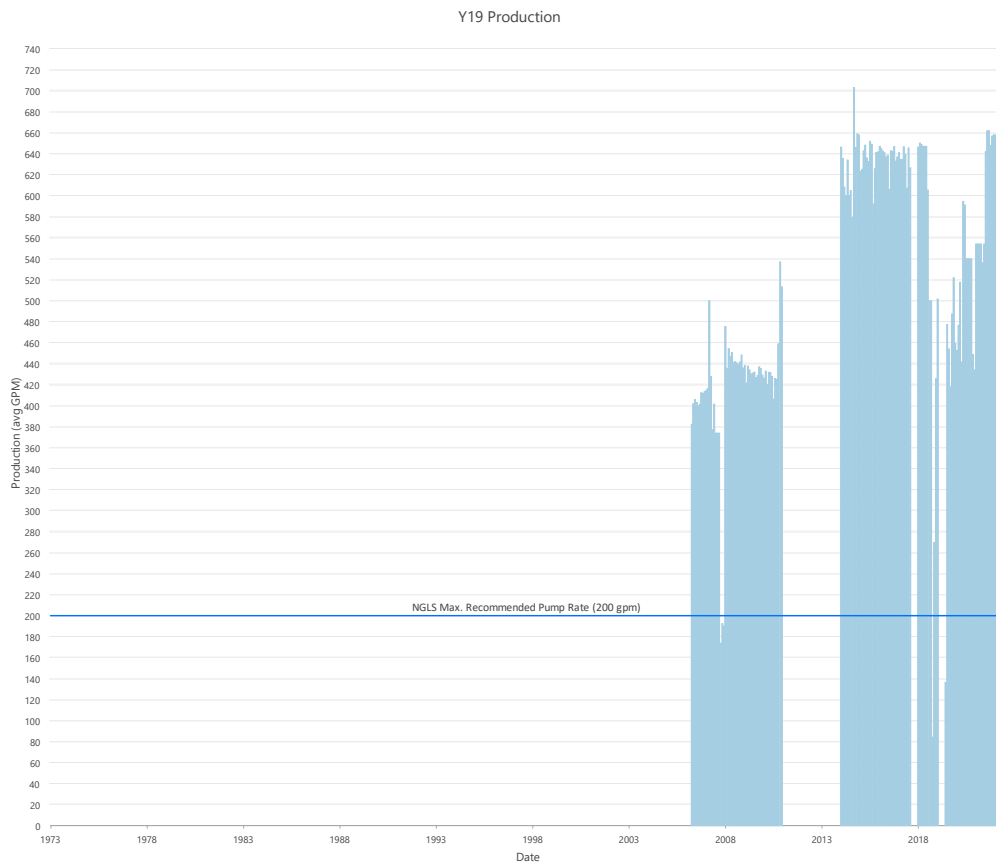


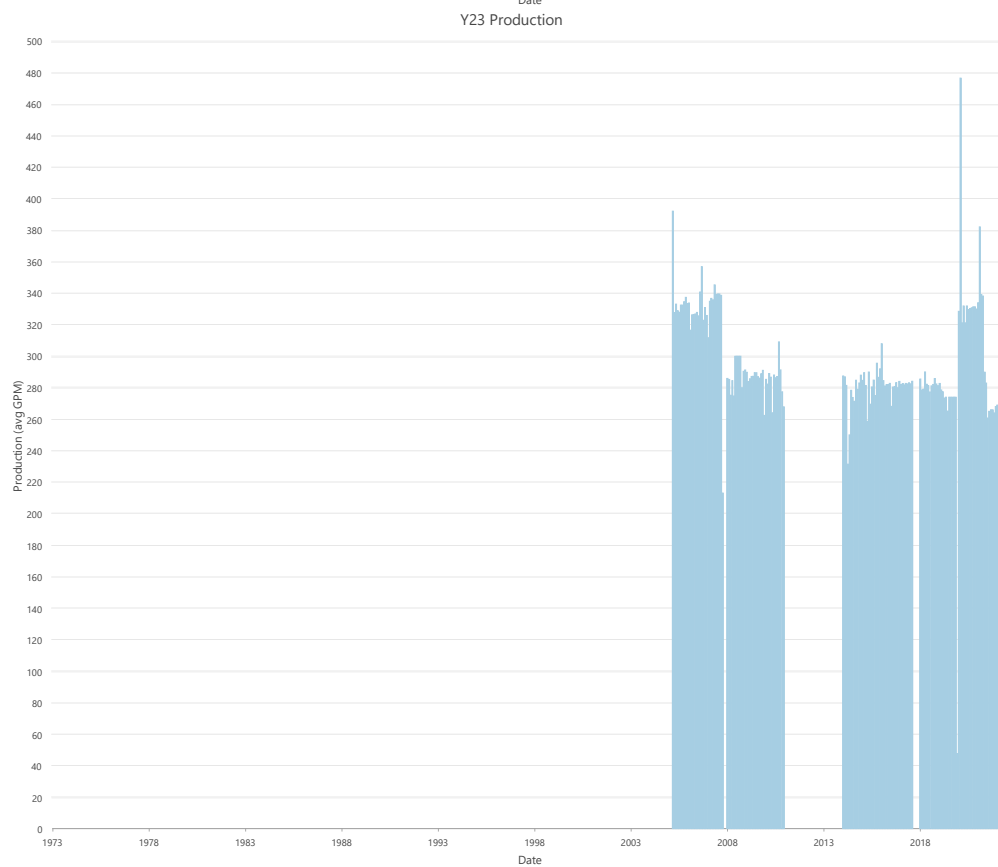
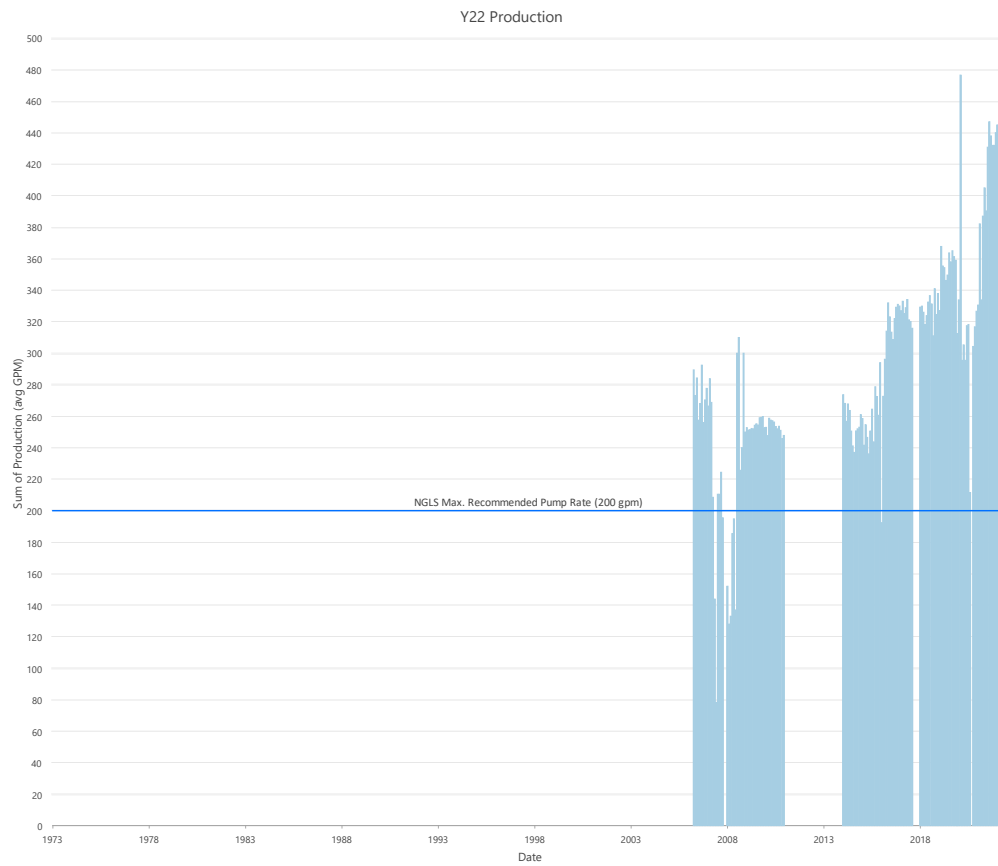












## Appendix E: Linear Regression Summary of the Relationship between Chloride Concentration and Production for Individual Wells

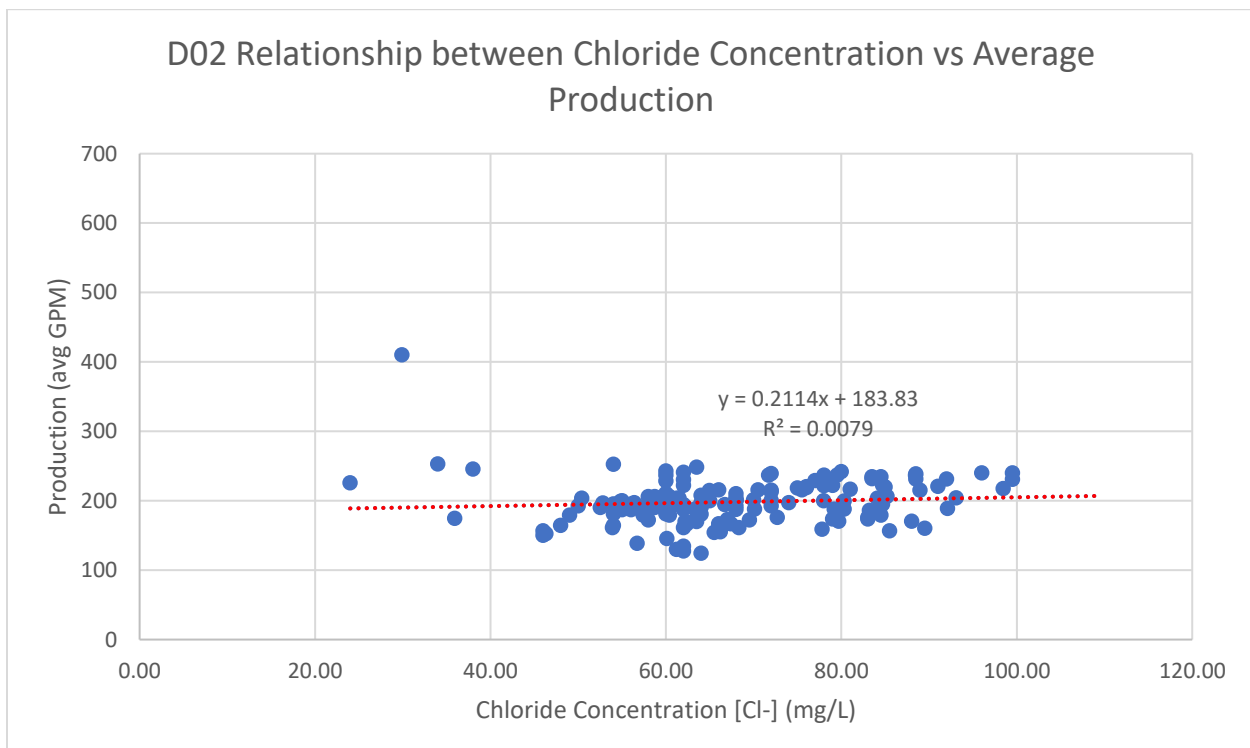
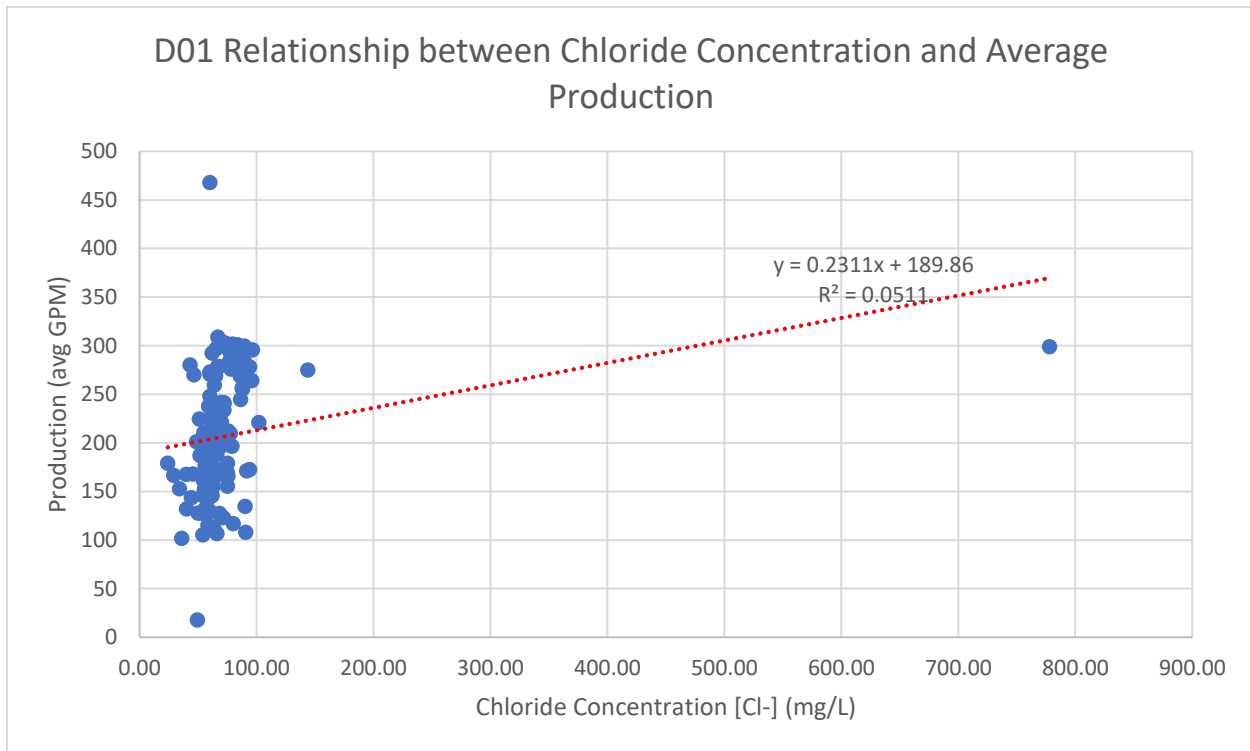
For these summaries, the n = number of data values that had both a chloride concentration and average production reading on that given date. The regression equations showed whether or not there was a significant increase or decrease relationship between chloride concentration and average production.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

Relationship between [Cl-] and avg GPM produced								
Well ID	Regression Equation	r <sup>2</sup>	r	r <sub>crit</sub>	n	df = n - 2	Significant if r > r <sub>crit</sub>	Trend
D01	y = 0.2311x + 189.86	0.0511	0.226053	0.159	152	150	Significant	Increase
D02	y = 0.2114x + 183.83	0.0079	0.088882	0.159	153	151	Not Significant	Increase
D03A	y = -0.19x + 151.65	0.0016	0.04	0.199	98	96	Not Significant	Decrease
D04	y = 3.2117x + 36.583	0.3631	0.602578	0.158	154	152	Significant	Increase
D05	y = -0.1463x + 160.35	0.0022	0.046904	0.175	126	124	Not Significant	Decrease
D06	y = 1.8686x + 90.944	0.2062	0.454093	0.158	155	153	Significant	Increase
D07	y = 1.072x + 102.65	0.2007	0.447996	0.157	157	155	Significant	Increase
D08	y = 0.2344x + 114.88	0.1212	0.348138	0.158	155	153	Significant	Increase
D09	y = 0.3493x + 133.59	0.124	0.352136	0.161	149	147	Significant	Increase
D10	y = 0.7218x + 153.75	0.1252	0.353836	0.165	141	139	Significant	Increase
D11	y = 0.6806x + 134.74	0.0702	0.264953	0.156	158	156	Significant	Increase
D12	y = 0.9317x + 186.11	0.0008	0.028284	0.157	157	155	Not Significant	Increase
D13	y = 0.0347x + 144.58	0.0351	0.18735	0.182	117	115	Significant	Increase
D14	y = 0.9137x + 138.56	0.3266	0.571489	0.156	158	156	Significant	Increase
D15	y = 0.1162x + 168.5	0.0034	0.05831	0.158	155	153	Not Significant	Increase
D16	y = 0.1938x + 186.03	0.0162	0.127279	0.159	153	151	Not Significant	Increase
D17A	y = 0.2786x + 140.45	0.221	0.470106	0.183	115	113	Significant	Increase
D18B	y = 0.2987x + 159.9	0.0192	0.138564	0.2	97	95	Not Significant	Increase
D19	y = -0.1595x + 219.25	0.0045	0.067082	0.191	106	104	Not Significant	Decrease
D20	y = 0.2548x + 0.0194	0.0194	0.139284	0.1898	108	106	Not Significant	Increase
D21	y = 0.4189x + 127.35	0.0107	0.103441	0.191	106	104	Not Significant	Increase
D25	y = 2.1679x + 236.37	0.233	0.482701	0.273	52	50	Significant	Increase
D26	y = -0.1409x + 284.8	0.1822	0.426849	0.285	48	46	Significant	Decrease
D27	y = 0.7942x + 380.46	0.023	0.151658	0.276	51	49	Not Significant	Increase
D28	y = 0.1246x + 191.45	0.0023	0.047958	0.285	48	46	Not Significant	Increase
EX05	y = 3.7502x + 85.609	0.3813	0.617495	0.187	110	108	Significant	Increase
F05	y = 0.4808x + 110.13	0.2535	0.503488	0.161	149	147	Significant	Increase
F06	y = 0.2369x + 96.837	0.286	0.53479	0.164	143	141	Significant	Increase
F07	y = 0.399x + 120.57	0.1511	0.388716	0.159	152	150	Significant	Increase
F09	y = -0.1301x + 168.26	0.0085	0.092195	0.157	156	154	Not Significant	Decrease

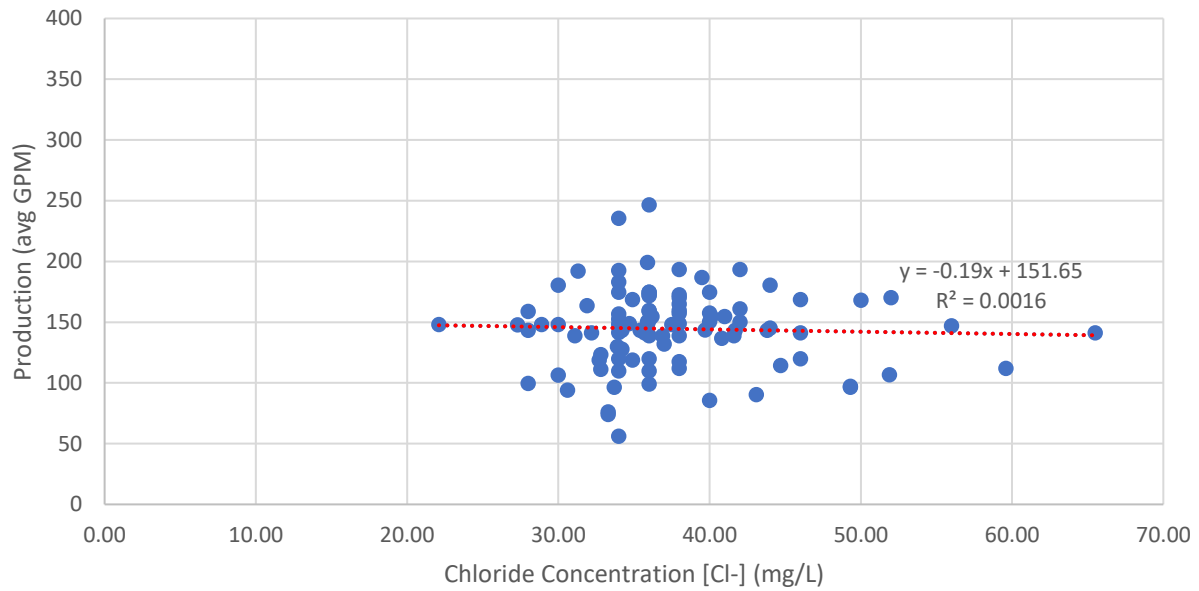
F19	$y = 0.0302x + 204.32$	0.0029	0.053852	0.285	48	46	Not Significant	Increase
F20	$y = 0.0393x + 197.53$	0.003	0.054772	0.285	48	46	Not Significant	Increase
G501	$y = 0.1926x + 177.84$	0.1308	0.361663	0.344	33	31	Significant	Increase
H01	$y = 0.5988x + 153.25$	0.2683	0.517977	0.179	120	118	Significant	Increase
M05	$y = 0.7641x + 129.72$	0.0943	0.307083	0.16	151	149	Significant	Increase
M06	$y = 0.2003x + 140.57$	0.036	0.189737	0.165	141	139	Significant	Increase
M07	$y = 0.3328x + 168.54$	0.0156	0.1249	0.16	151	149	Not Significant	Increase
M12	$y = -0.102x + 108.42$	0.006	0.07746	0.182	117	115	Not Significant	Decrease
M14	$y = 0.5805x + 168.83$	0.1138	0.337343	0.199	98	96	Significant	Increase
M15	$y = 0.6829x + 155.33$	0.1349	0.367287	0.181	118	116	Significant	Increase
M17A	$y = 0.4449x + 177.08$	0.0161	0.126886	0.308	41	39	Not Significant	Increase
M17B	$y = -0.2364x + 300.61$	0.0021	0.045826	0.211	87	85	Not Significant	Decrease
M18	$y = -0.3798x + 298.95$	0.0083	0.091104	0.344	33	31	Not Significant	Decrease
M20A	$y = -0.079x + 276.83$	0.0005	0.022361	0.246	64	62	Not Significant	Decrease
M21	$y = 0.4659x + 212.88$	0.0597	0.244336	0.261	57	55	Not Significant	Increase
Y01	$y = 1.5358x + 116.1$	0.1771	0.420833	0.16	150	148	Significant	Increase
Y02	$y = 0.6162x + 148.19$	0.0549	0.234307	0.158	154	152	Significant	Increase
Y03	$y = 1.2613x + 110.28$	0.0772	0.277849	0.157	156	154	Significant	Increase
Y04A	$y = 2.1367x + 93.078$	0.3186	0.564447	0.187	111	109	Significant	Increase
Y05	$y = 0.9502x + 112.7$	0.2351	0.484871	0.158	155	153	Significant	Increase
Y06	$y = 1.5474x + 125.41$	0.107	0.327109	0.16	151	149	Significant	Increase
Y07	$y = 4.6533x + 269.07$	0.2431	0.493052	0.199	98	96	Significant	Increase
Y09	$y = 4.5994x + 271.09$	0.1173	0.342491	0.202	95	93	Significant	Increase
Y10	$y = 0.5049x + 189.18$	0.0716	0.267582	0.261	57	55	Significant	Increase
Y12	$y = 0.3854x + 297.45$	0.0113	0.106301	0.252	61	59	Not Significant	Increase
Y14	$y = 2.3672x + 247.02$	0.1792	0.42332	0.291	46	44	Significant	Increase
Y16	$y = 0.5565x + 289.78$	0.0152	0.123288	0.279	50	48	Not Significant	Increase
Y17	$y = 0.2997x + 284.27$	0.0084	0.091652	0.263	56	54	Not Significant	Increase
Y18	$y = 1.572x + 194.49$	0.0991	0.314802	0.282	49	47	Significant	Increase
Y19	$y = 1.0995x + 468.53$	0.0092	0.095917	0.279	50	48	Not Significant	Increase
Y20	$y = 2.6431x + 485.36$	0.045	0.212132	0.297	44	42	Not Significant	Increase
Y22	$y = -2.0778x + 365.49$	0.0498	0.223159	0.279	50	48	Not Significant	Decrease
Y23	$y = -0.1246x + 303.02$	0.0013	0.036056	0.266	55	53	Not Significant	Decrease
Maui Well	$y = 0.9975x + 586.43$	0.0406	0.201494	0.444	20	18	Not Significant	Increase

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

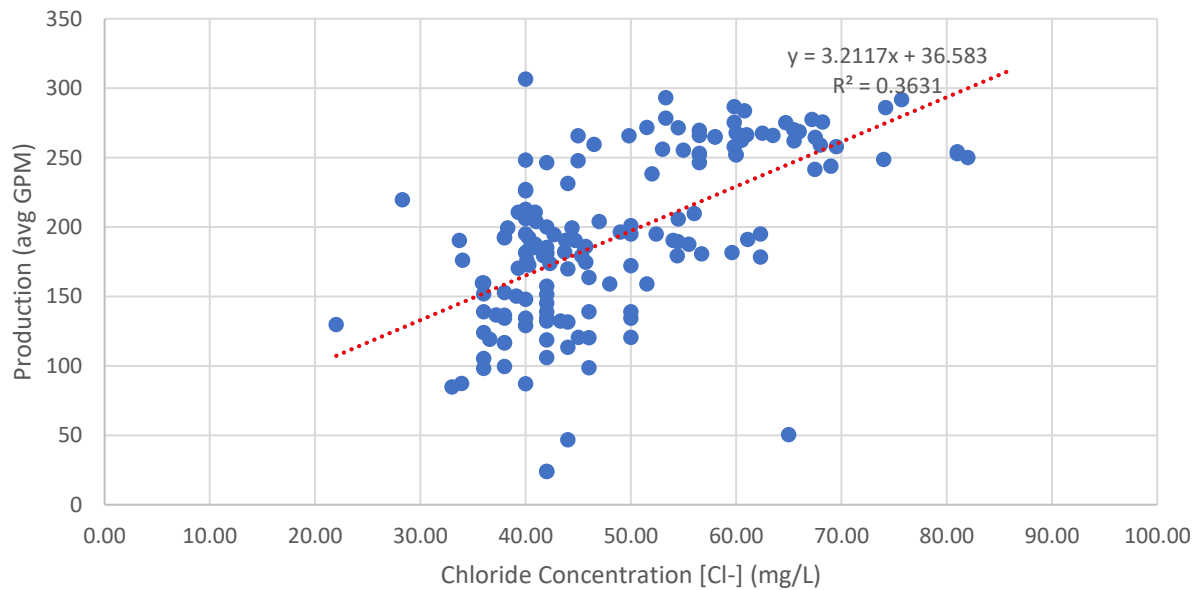
Only data points with both the chloride concentration and production were graphed. The x-axis is chloride concentration (mg/L) and the y-axis is the average production (avg GPM).



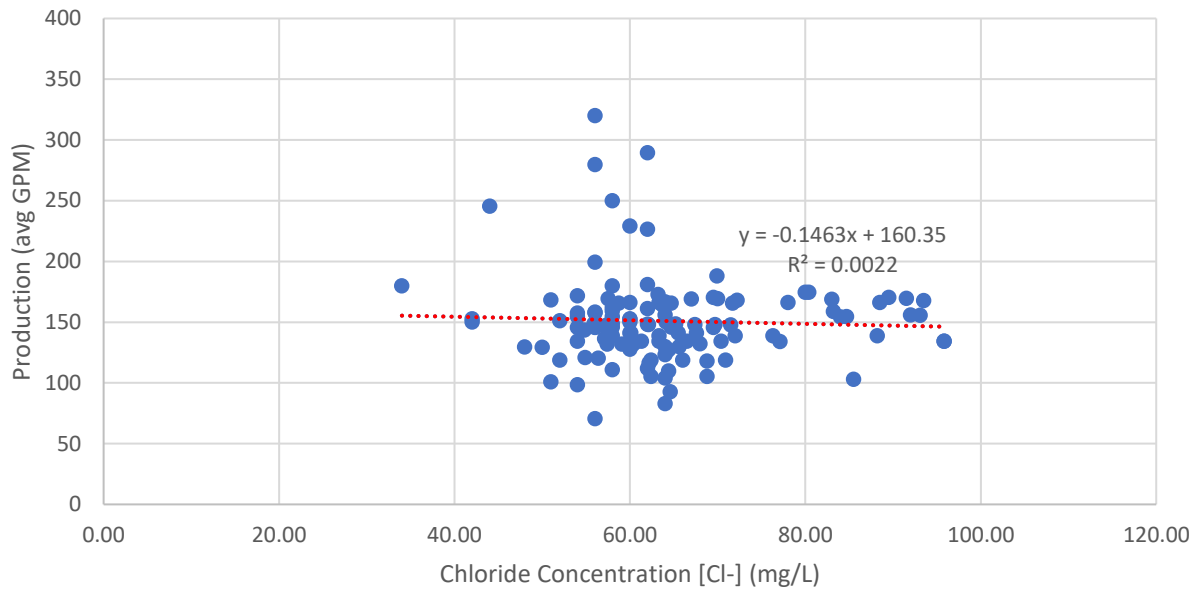
D03A Relationship between Chloride Concentration vs Average Production



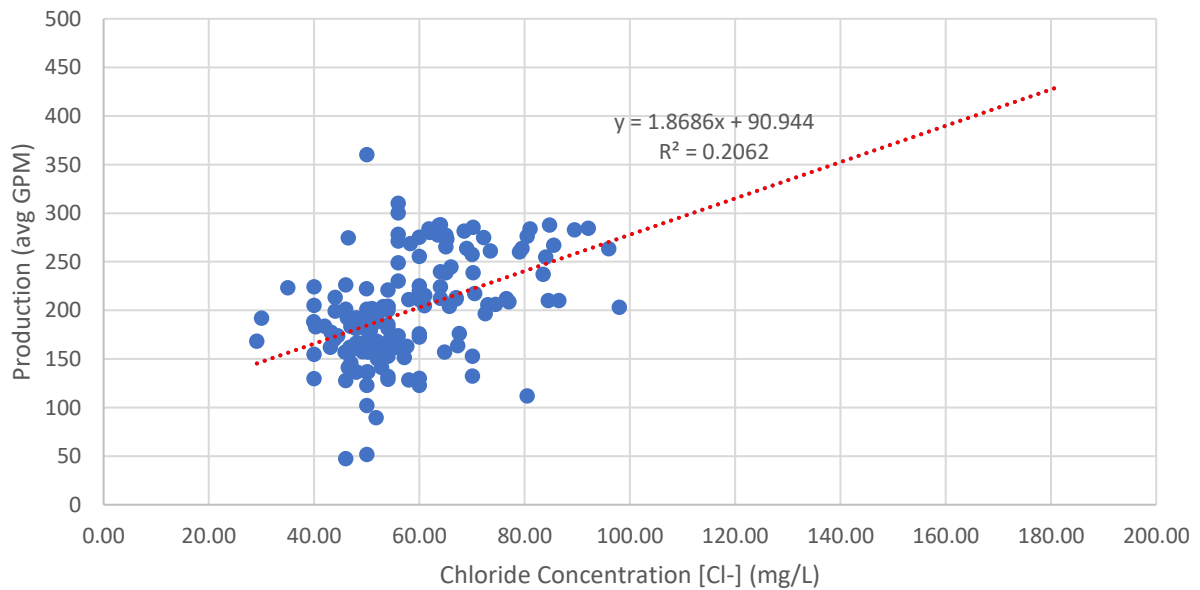
D04 Relationship between Chloride Concentration vs Average Production



D05 Relationship between Chloride Concentration vs Average Production

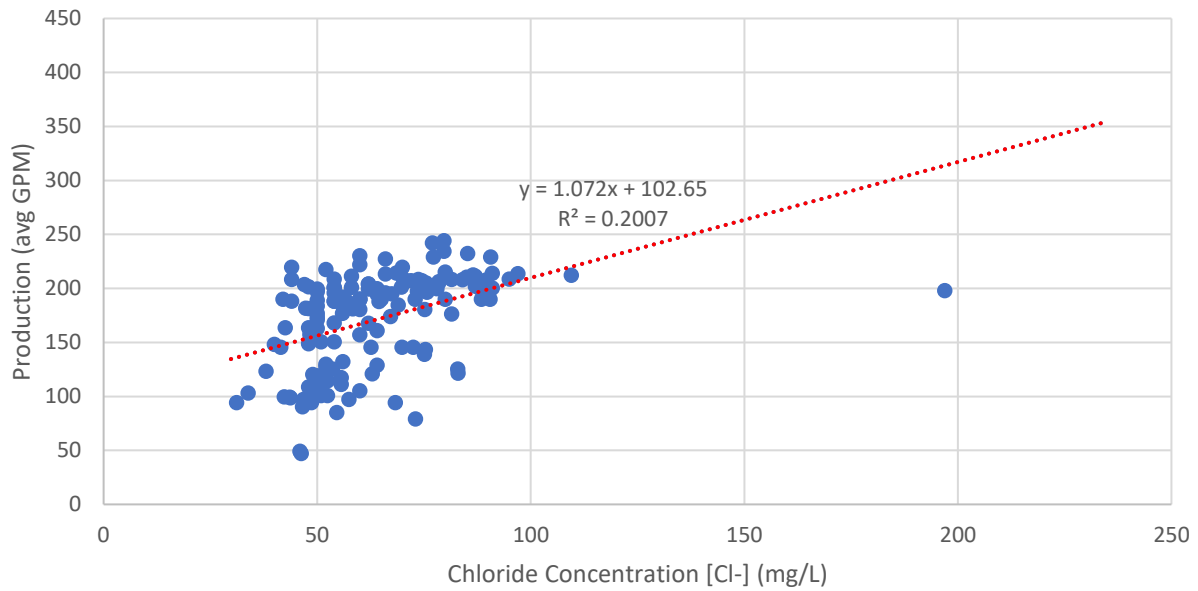


D06 Relationship between Chloride Concentration vs Average Production

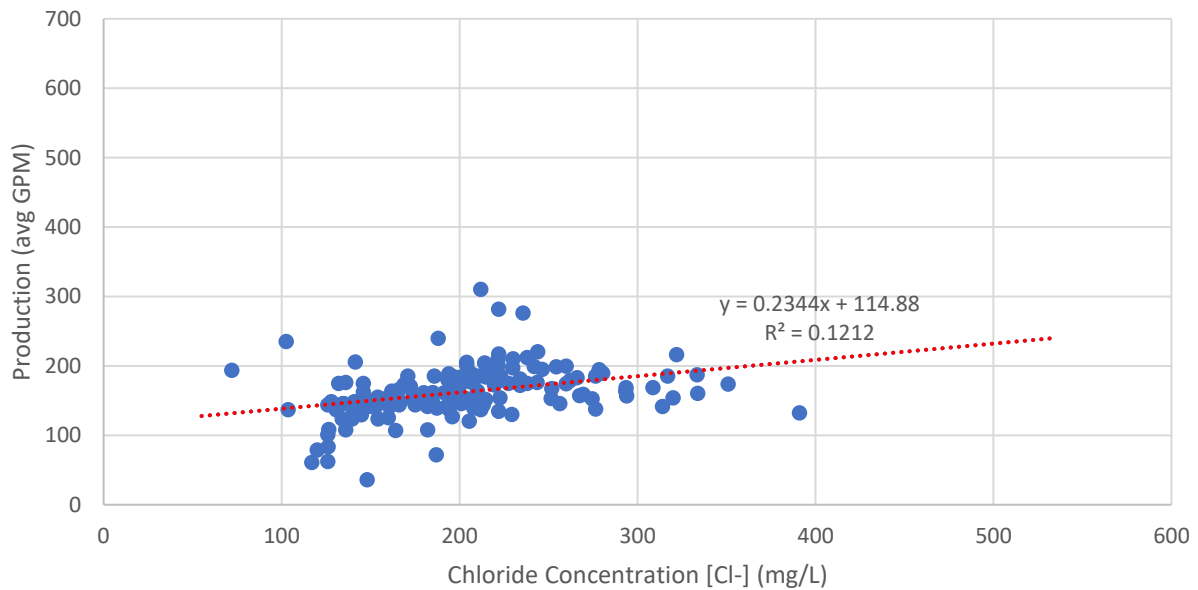




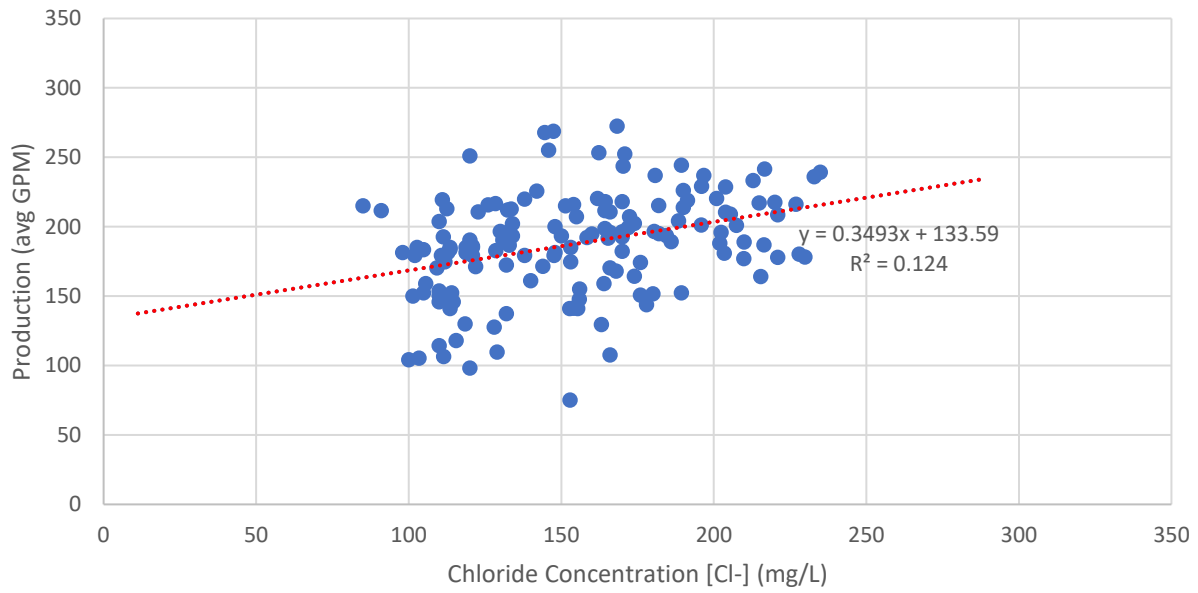
D07 Relationship between Chloride Concentration vs Average Production



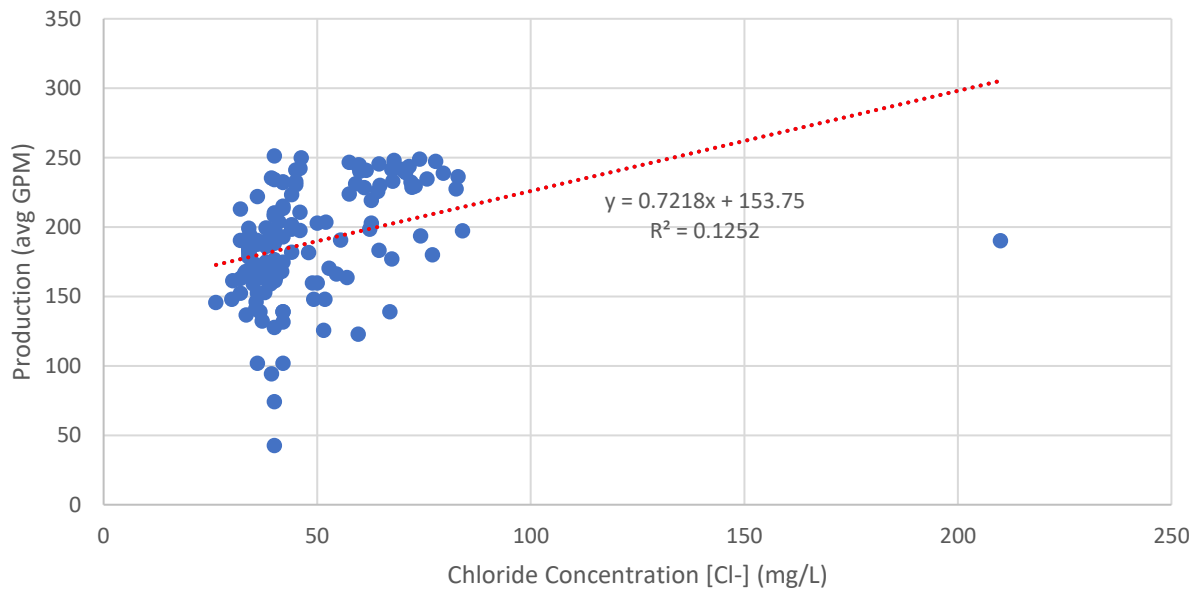
D08 Relationship between Chloride Concentration vs Average Production



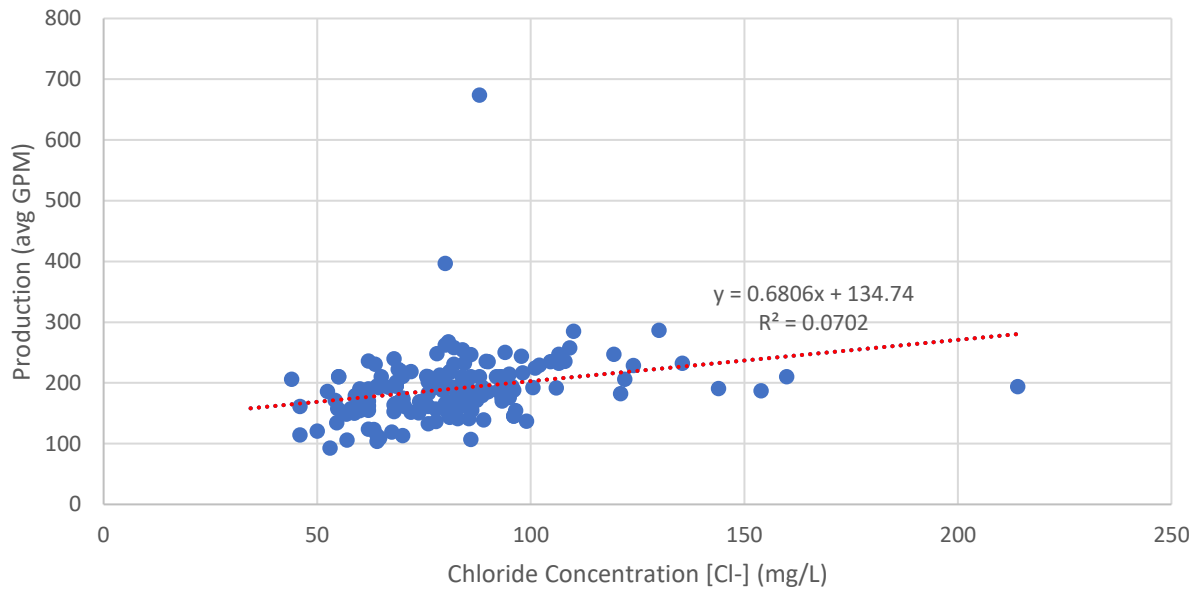
D09 Relationship between Chloride Concentration vs Average Production



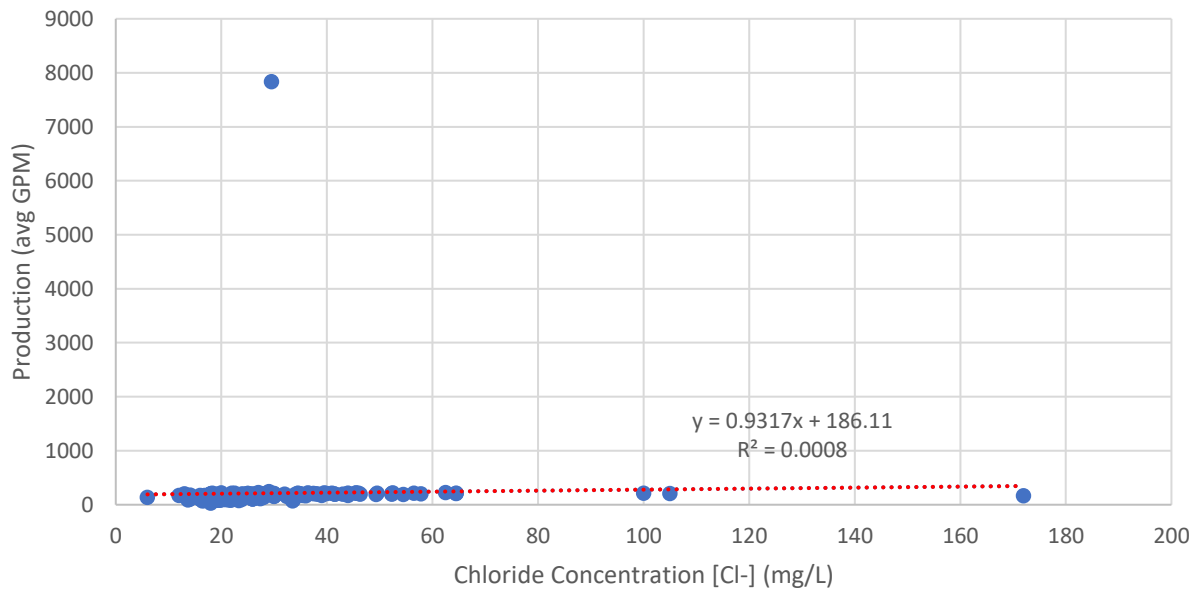
D10 Relationship between Chloride Concentration vs Average Production



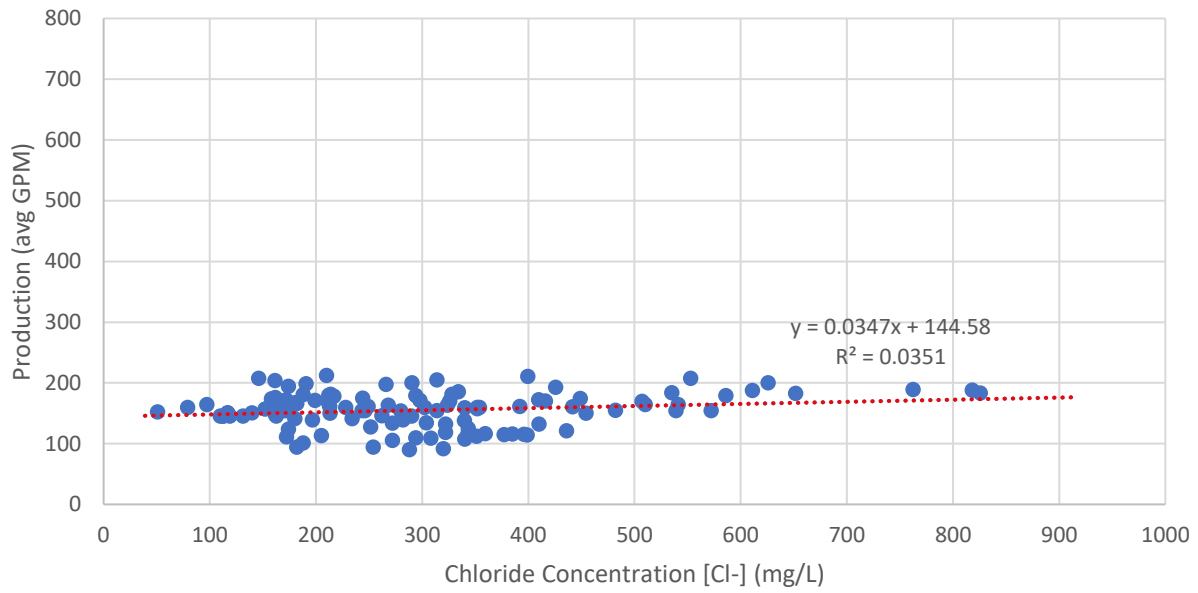
D11 Relationship between Chloride Concentration vs Average Production



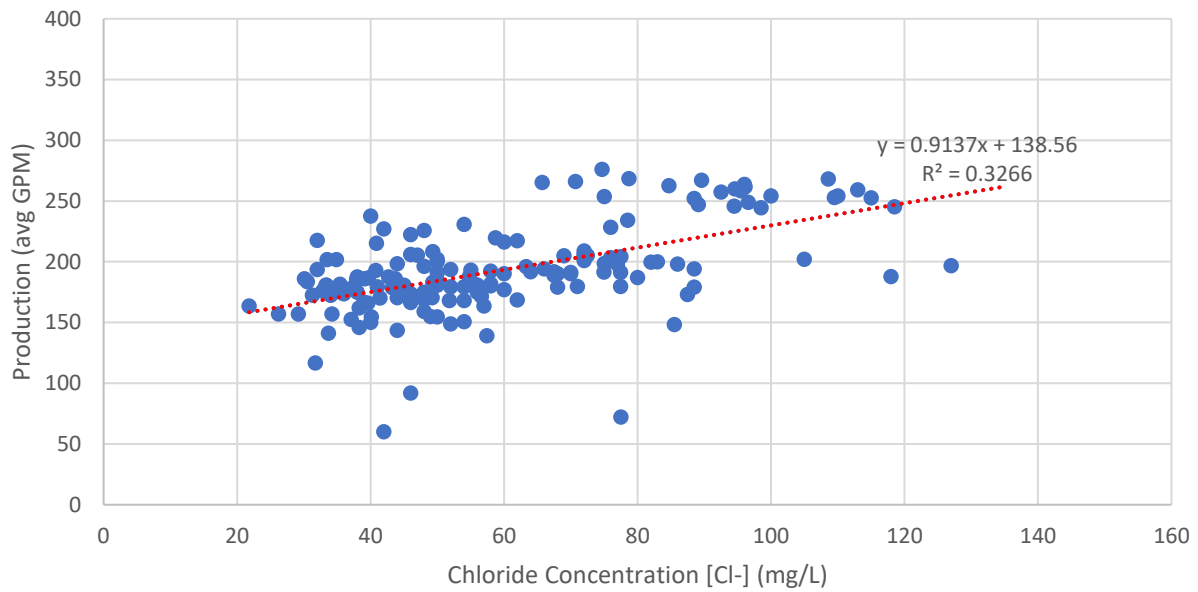
D12 Relationship between Chloride Concentration vs Average Production



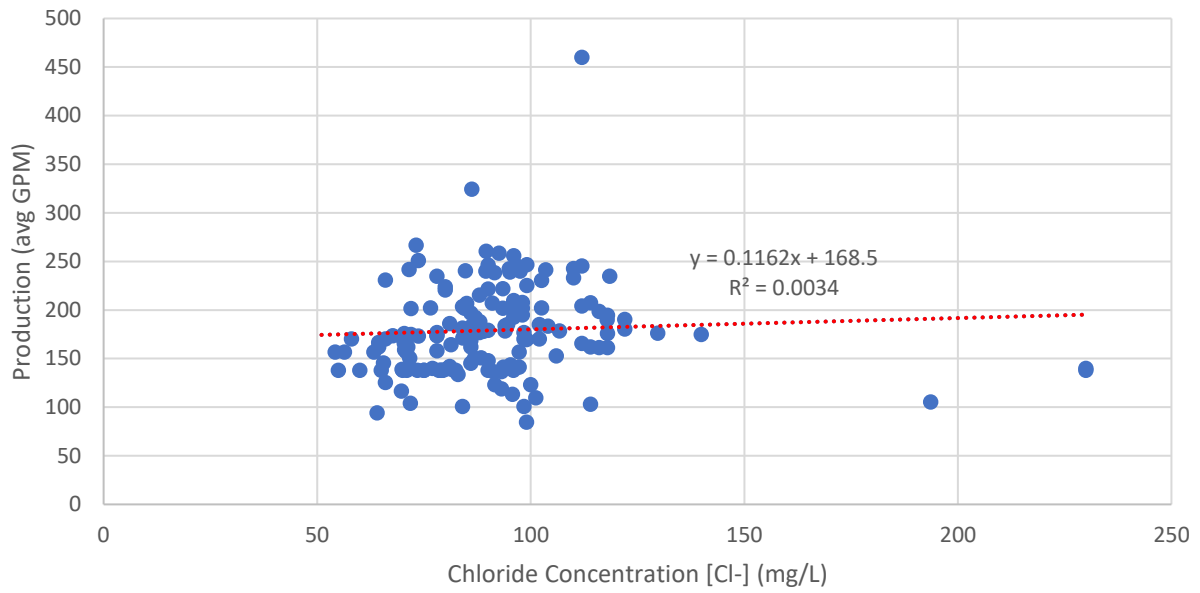
D13 Relationship between Chloride Concentration vs Average Production



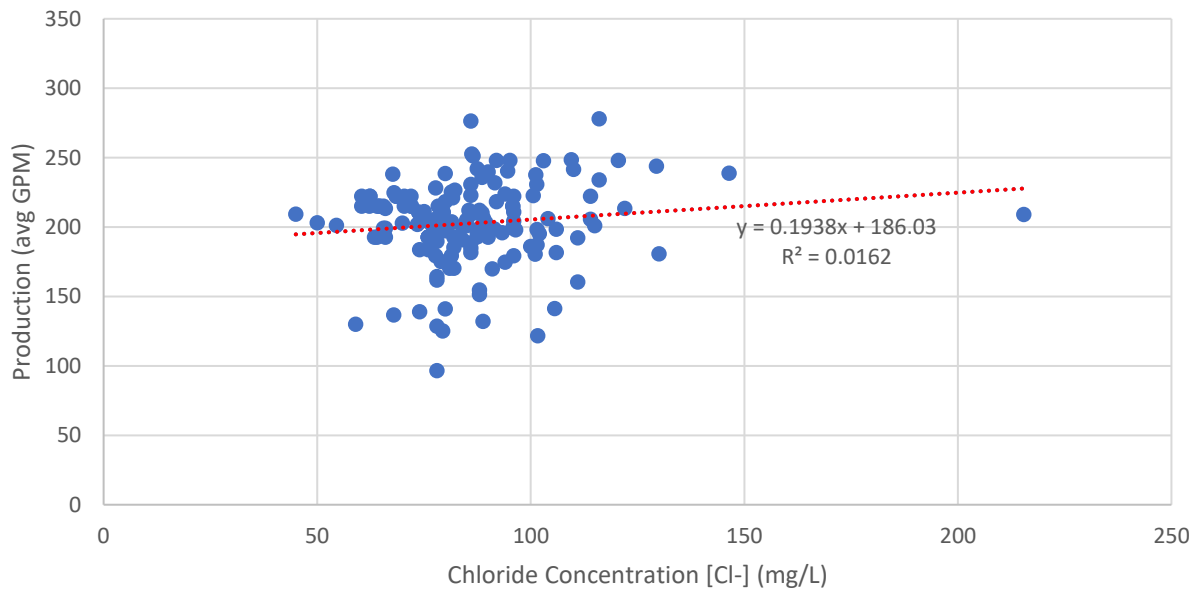
D14 Relationship between Chloride Concentration vs Average Production



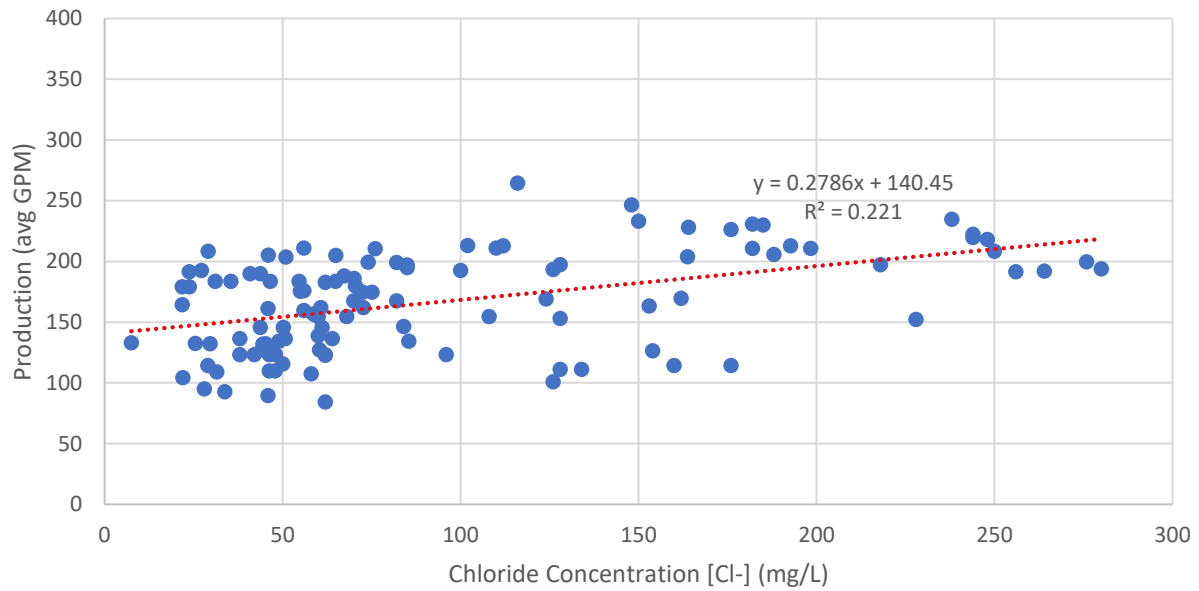
D15 Relationship between Chloride Concentration vs Average Production



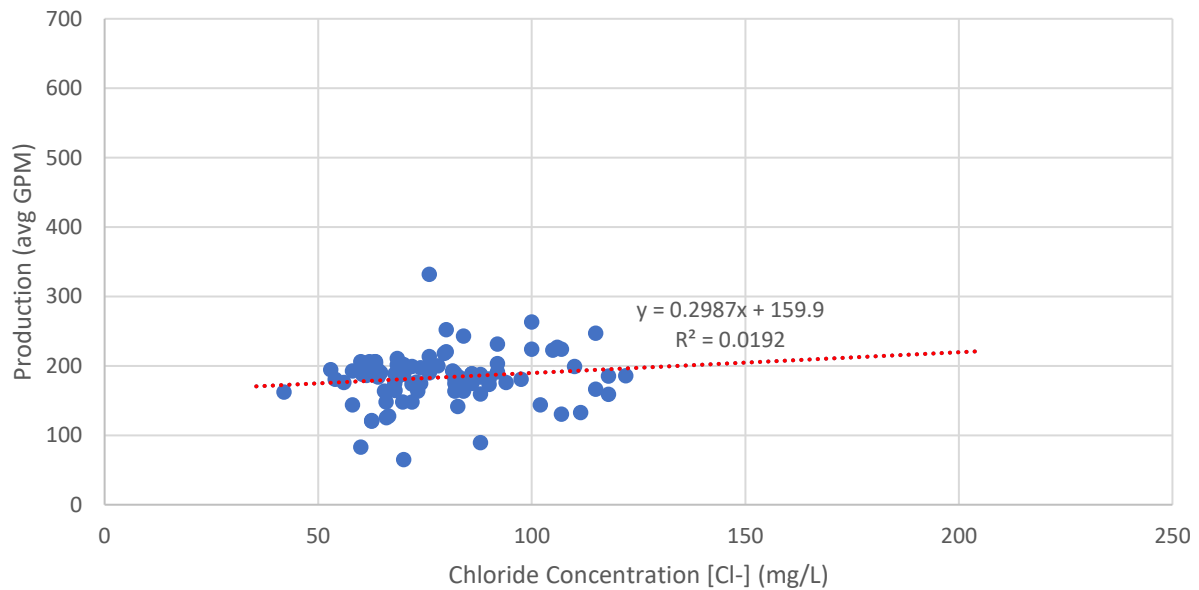
D16 Relationship between Chloride Concentration vs Average Production



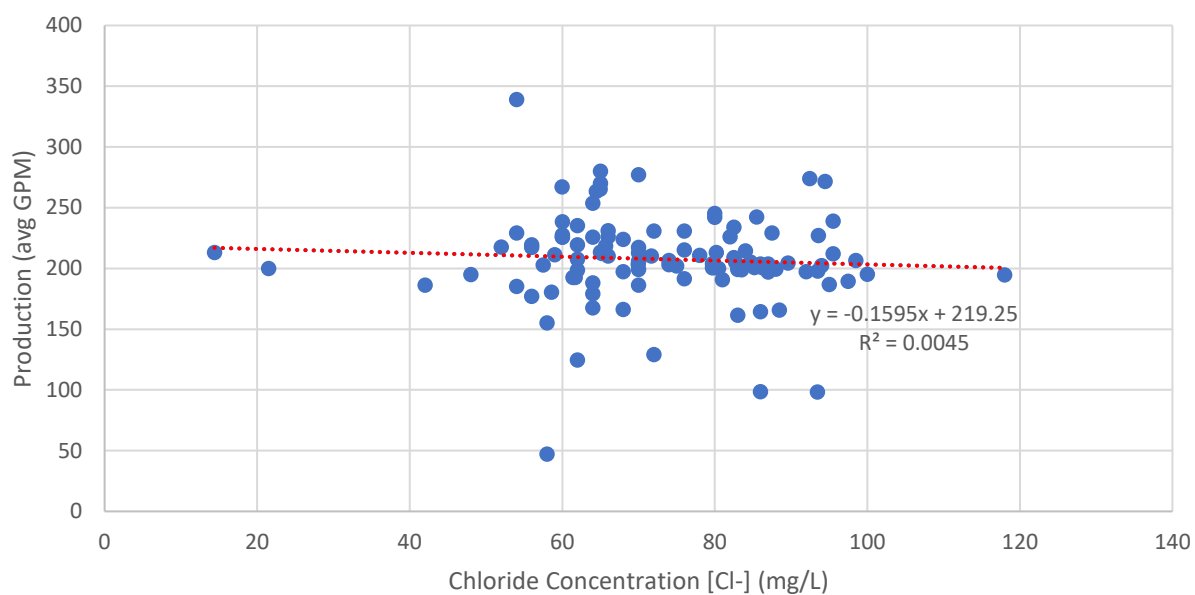
D17A Relationship between Chloride Concentration vs Average Production



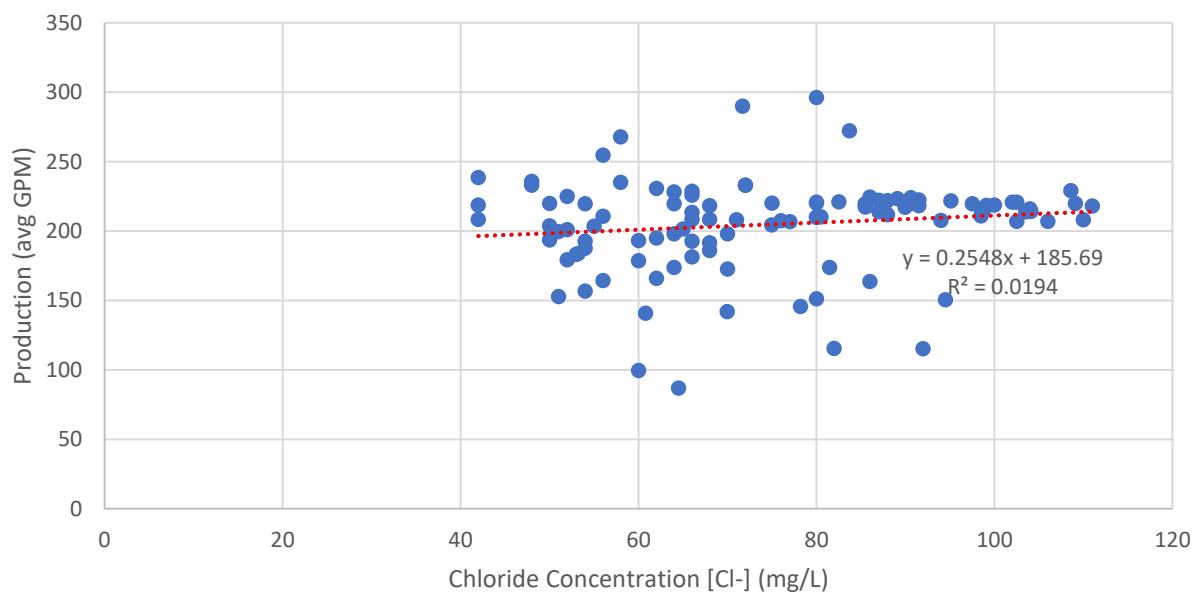
D18B Relationship between Chloride Concentration vs Average Production



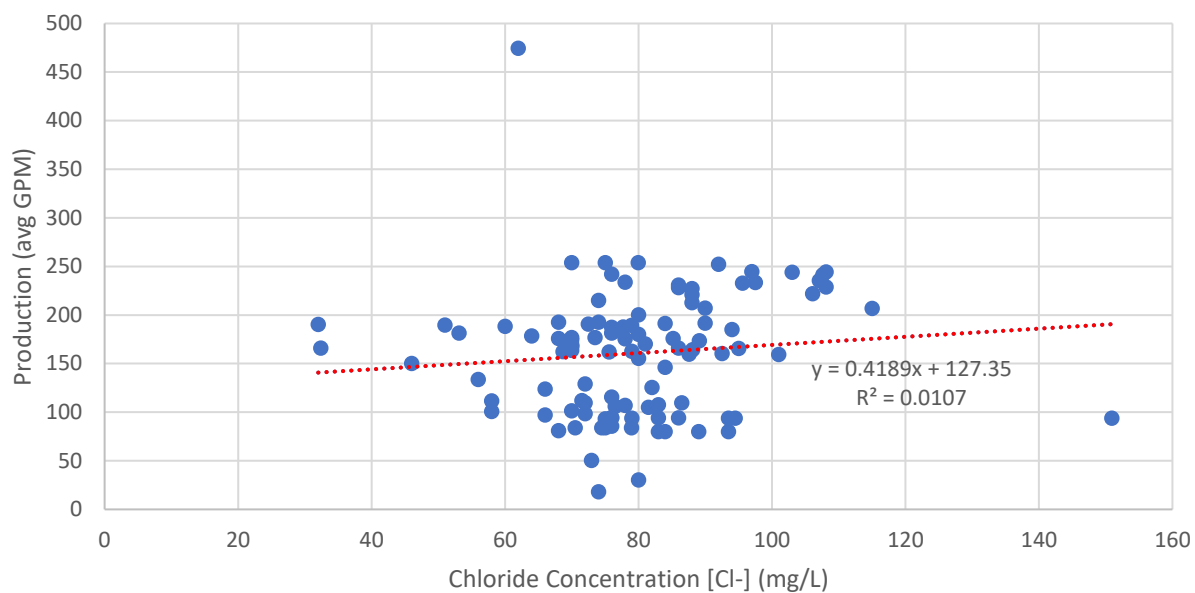
D19 Relationship between Chloride Concentration vs Average Production



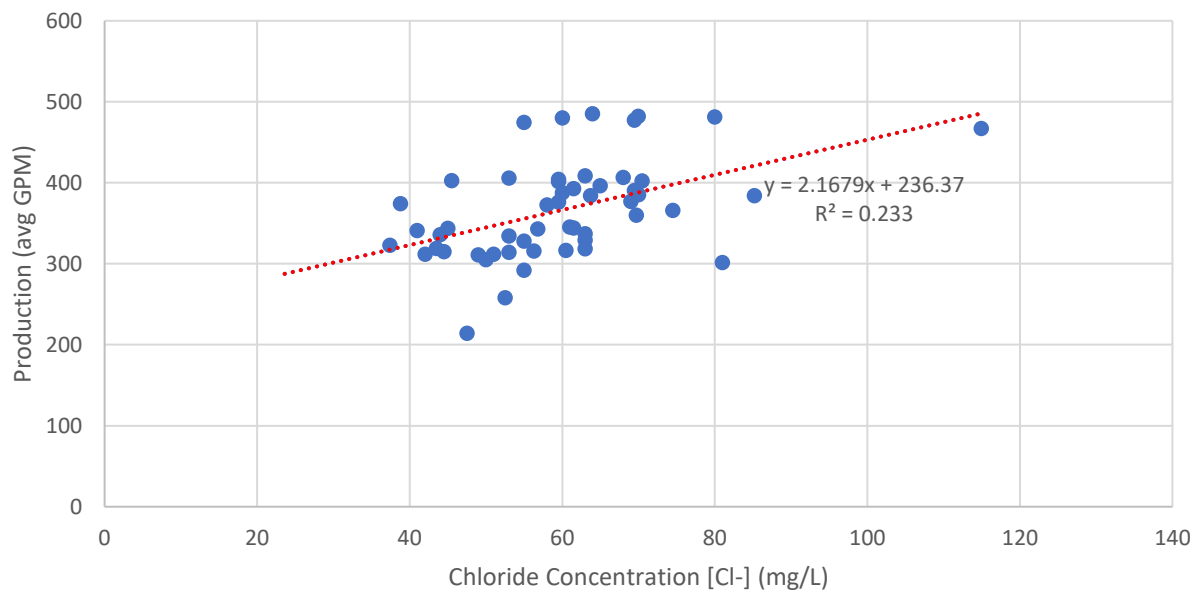
D20 Relationship between Chloride Concentration vs Average Production



D21 Relationship between Chloride Concentration vs Average Production

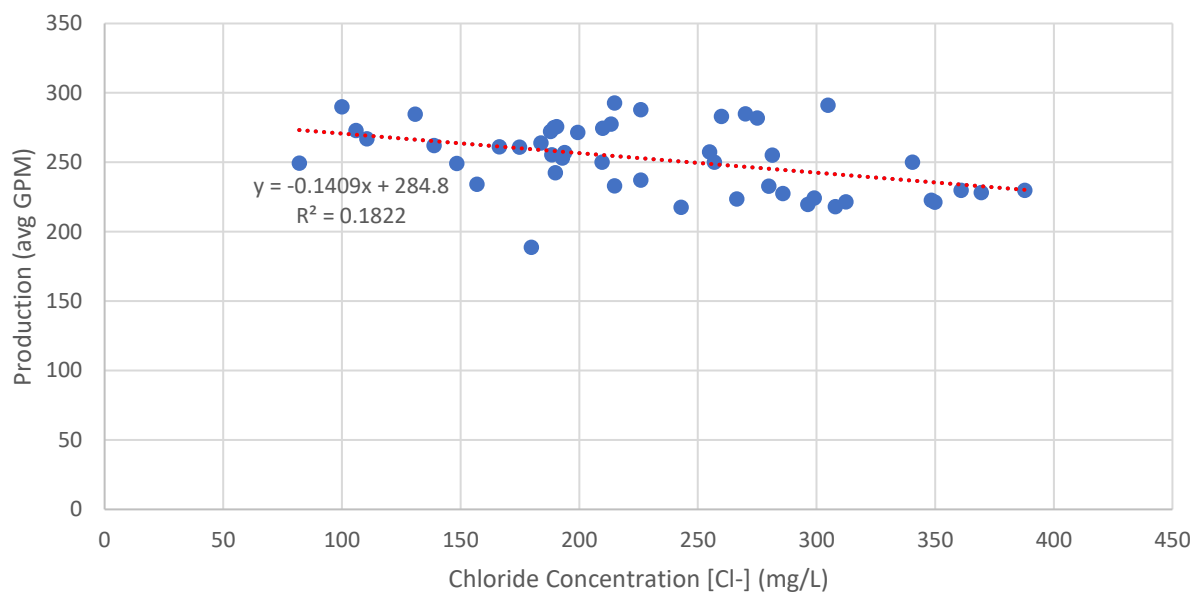


D25 Relationship between Chloride Concentration vs Average Production

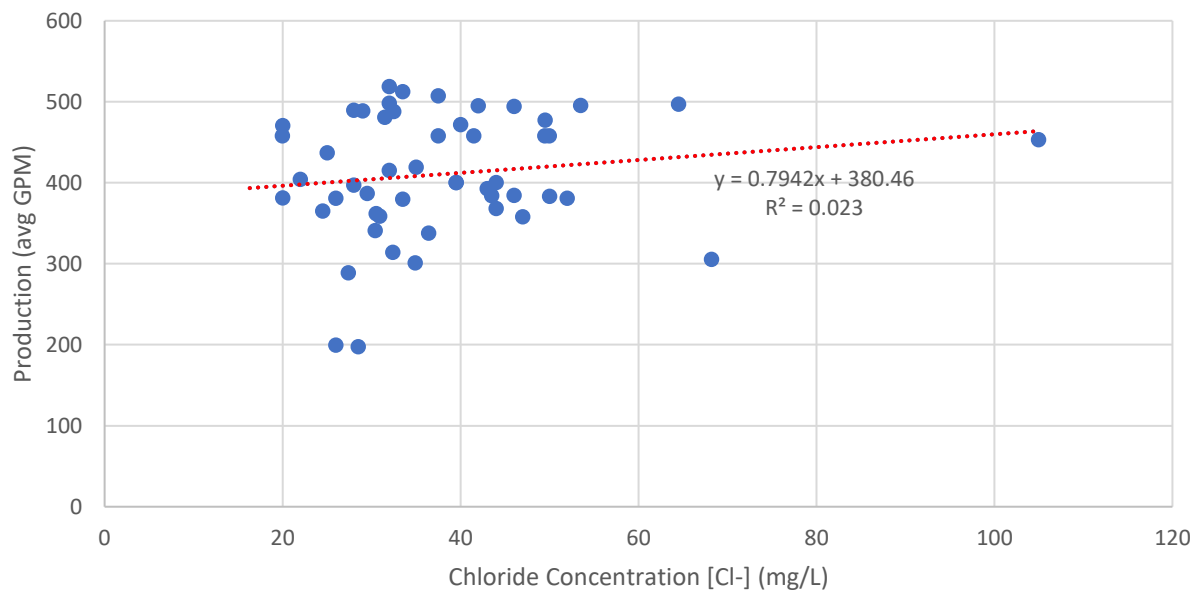




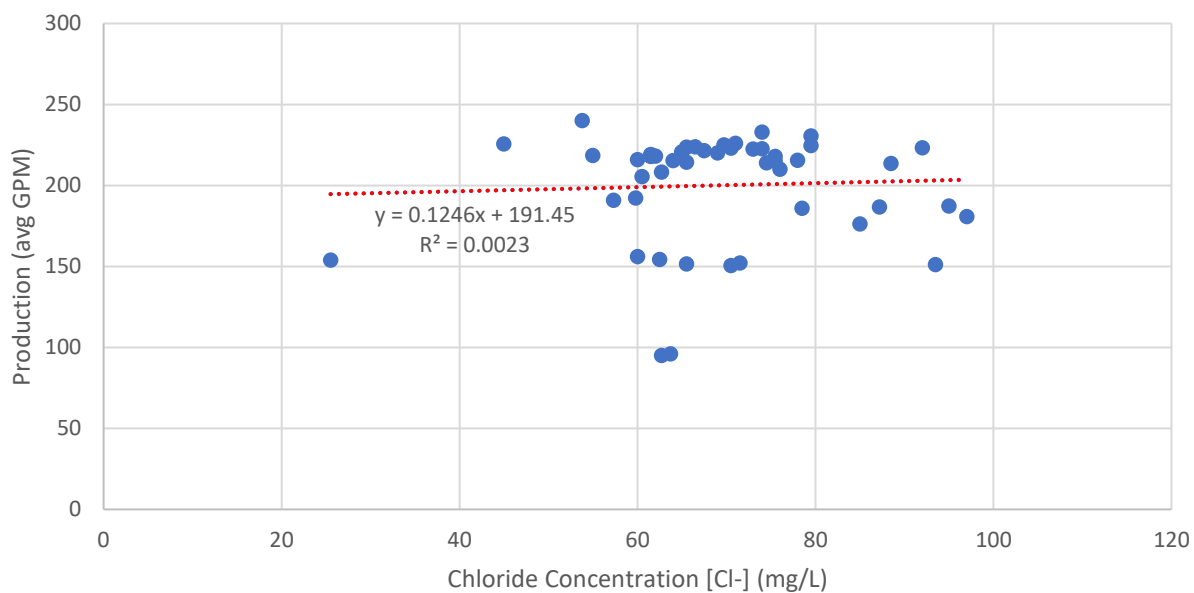
D26 Relationship between Chloride Concentration vs Average Production



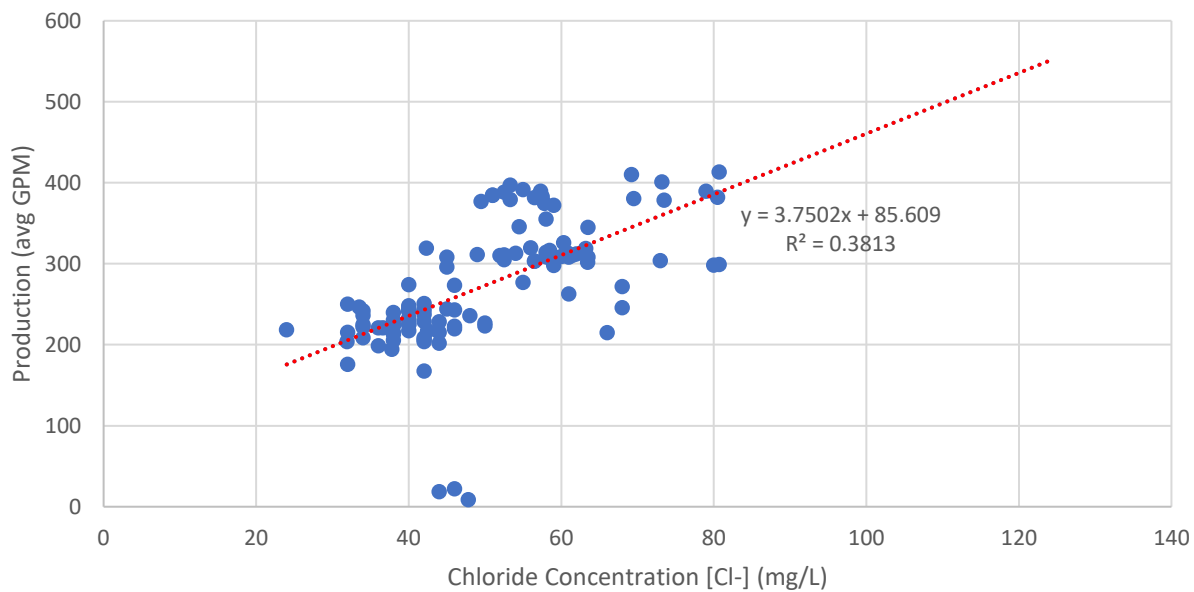
D27 Relationship between Chloride Concentration vs Average Production



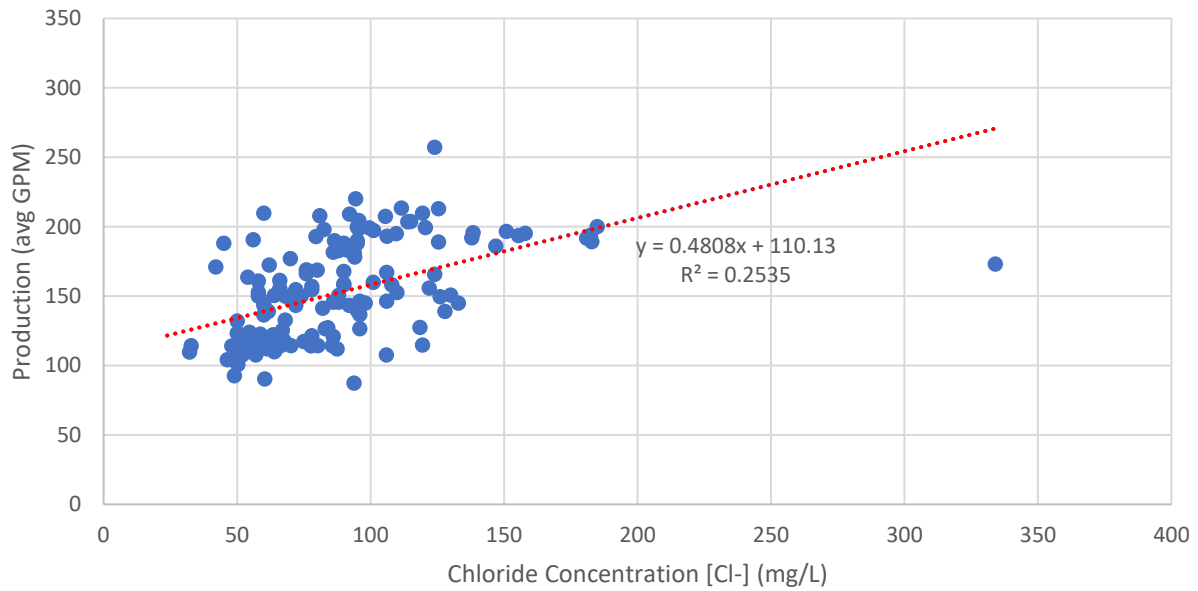
D28 Relationship between Chloride Concentration vs Average Production



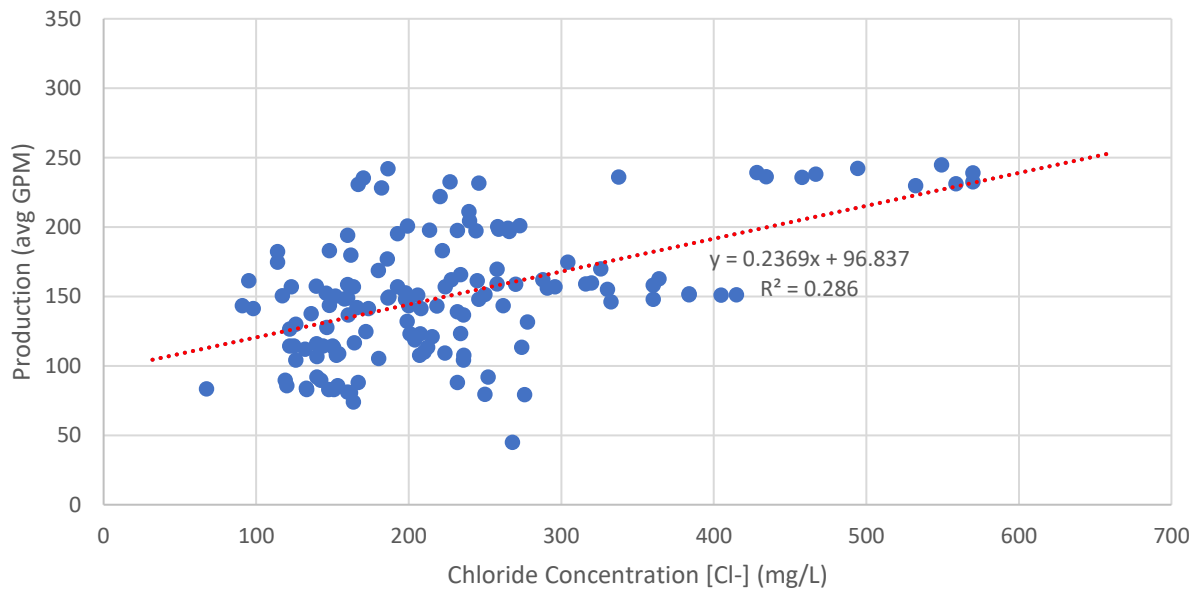
EX05 Relationship between Chloride Concentration vs Average Production



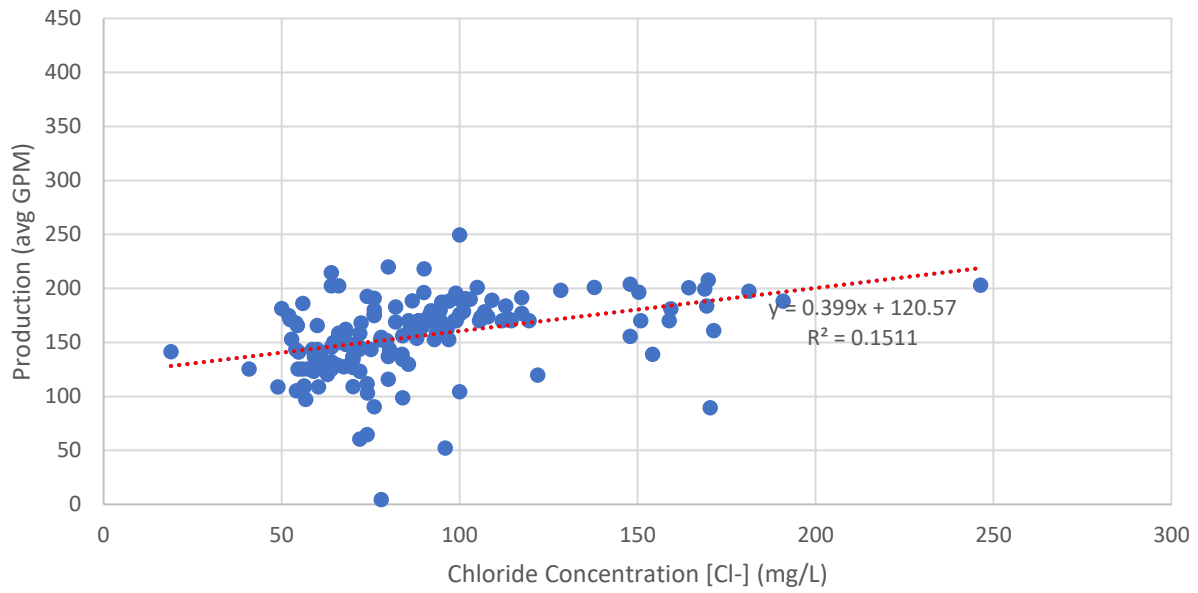
F05 Relationship between Chloride Concentration vs Average Production



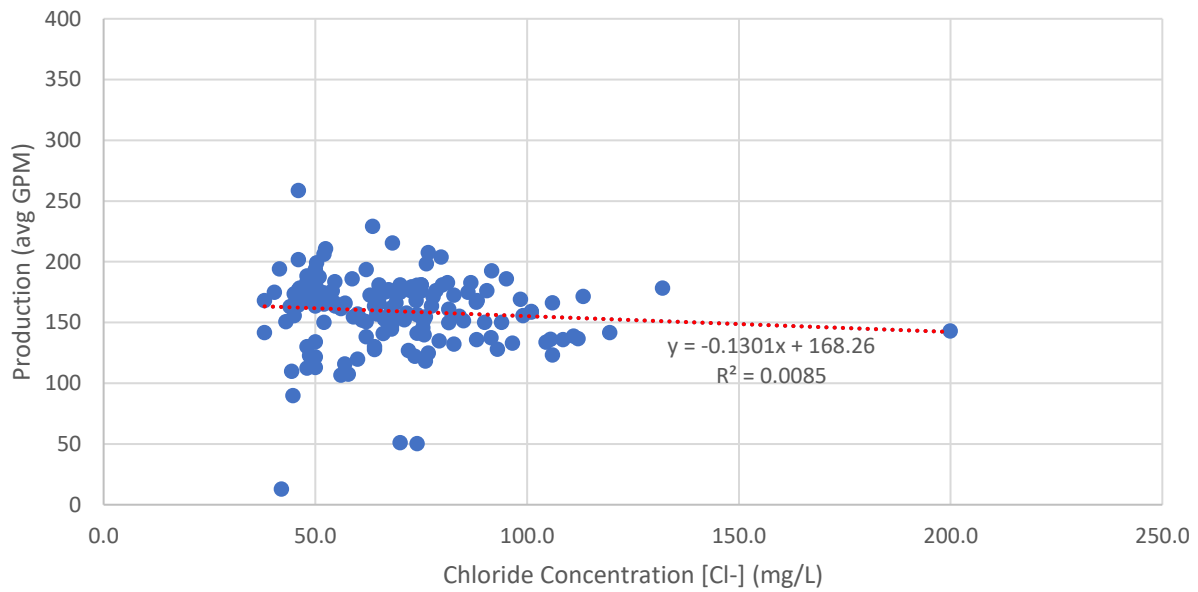
F06 Relationship between Chloride Concentration vs Average Production



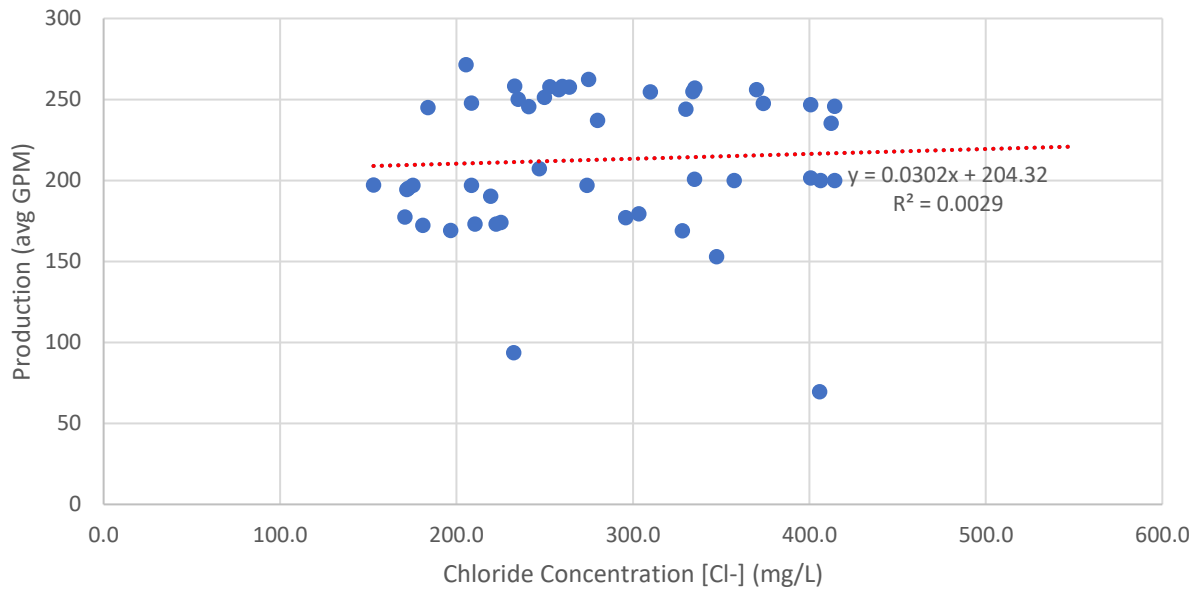
F07 Relationship between Chloride Concentration vs Average Production



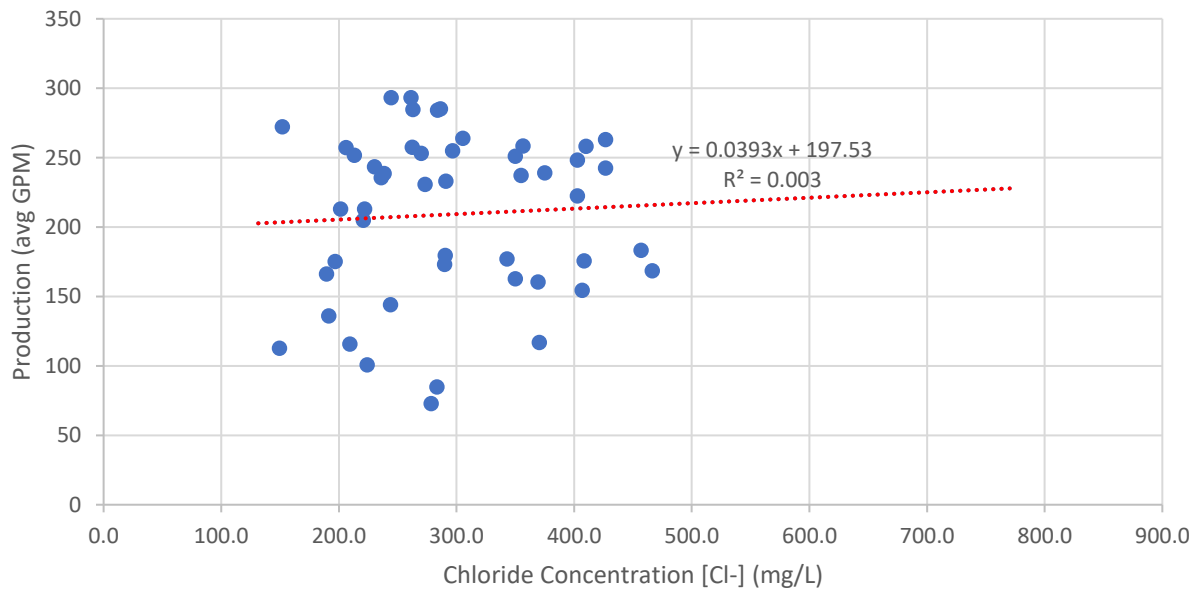
F09 Relationship between Chloride Concentration vs Average Production

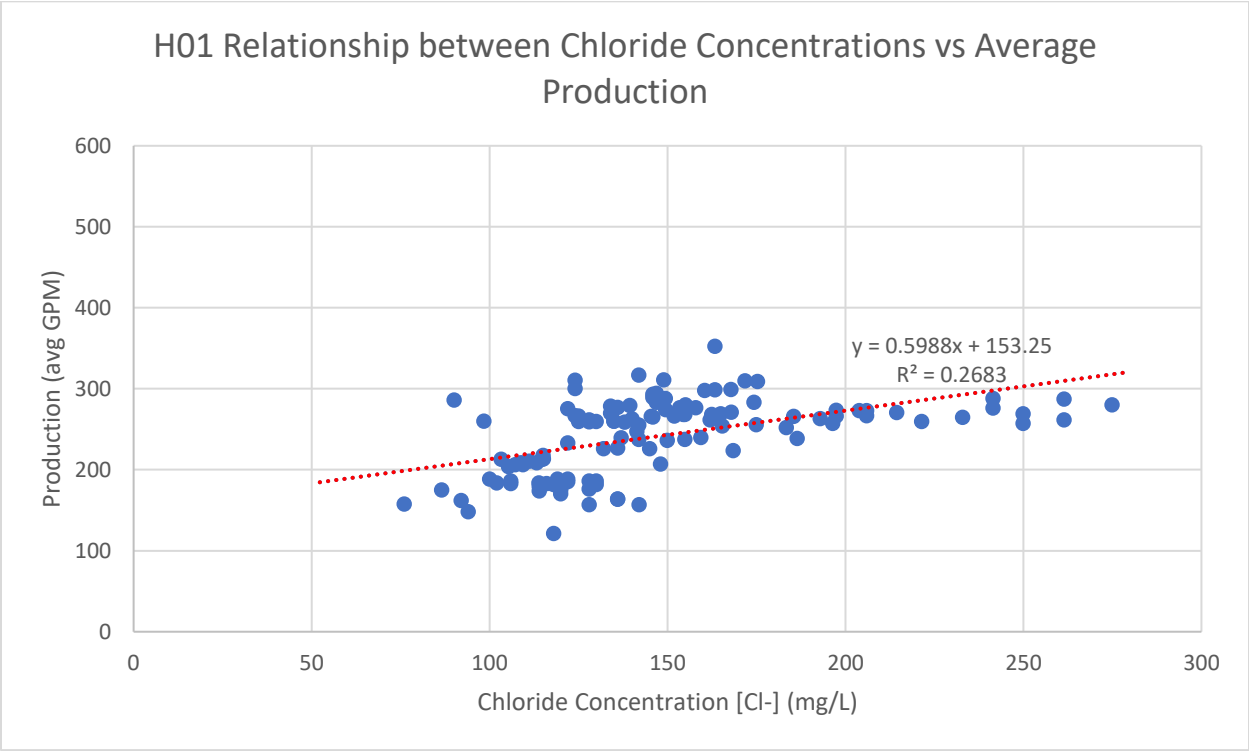
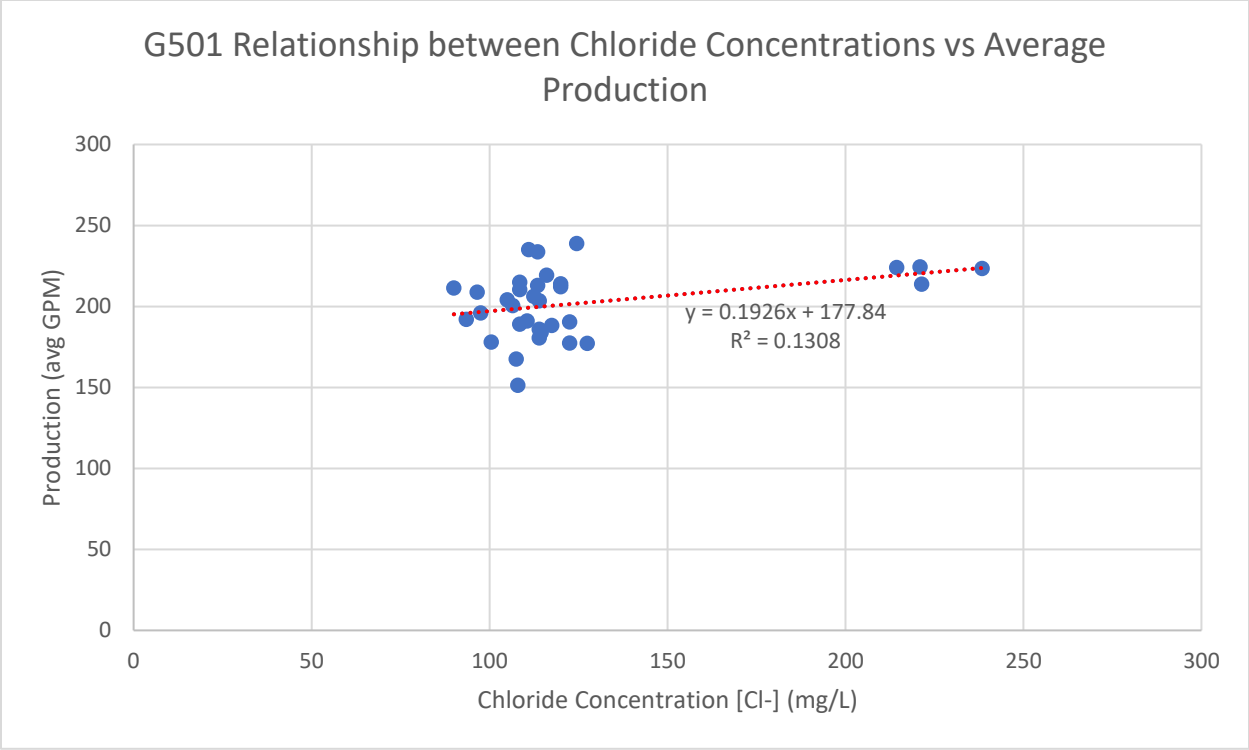


F19 Relationship between Chloride Concentrations vs Average Production

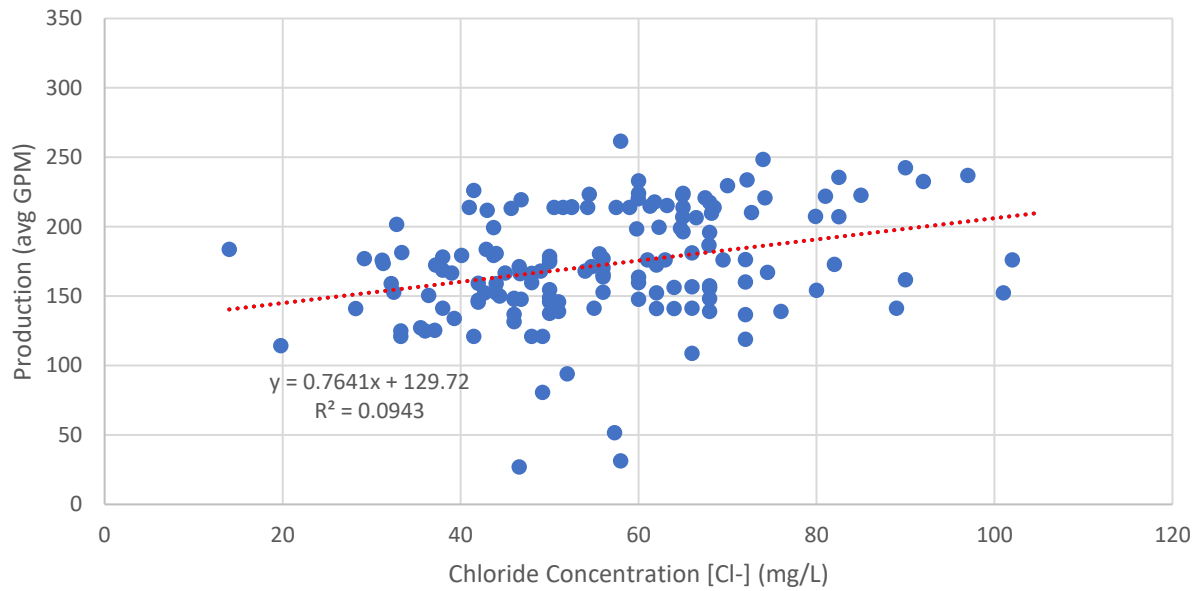


F20 Relationship between Chloride Concentrations vs Average Production

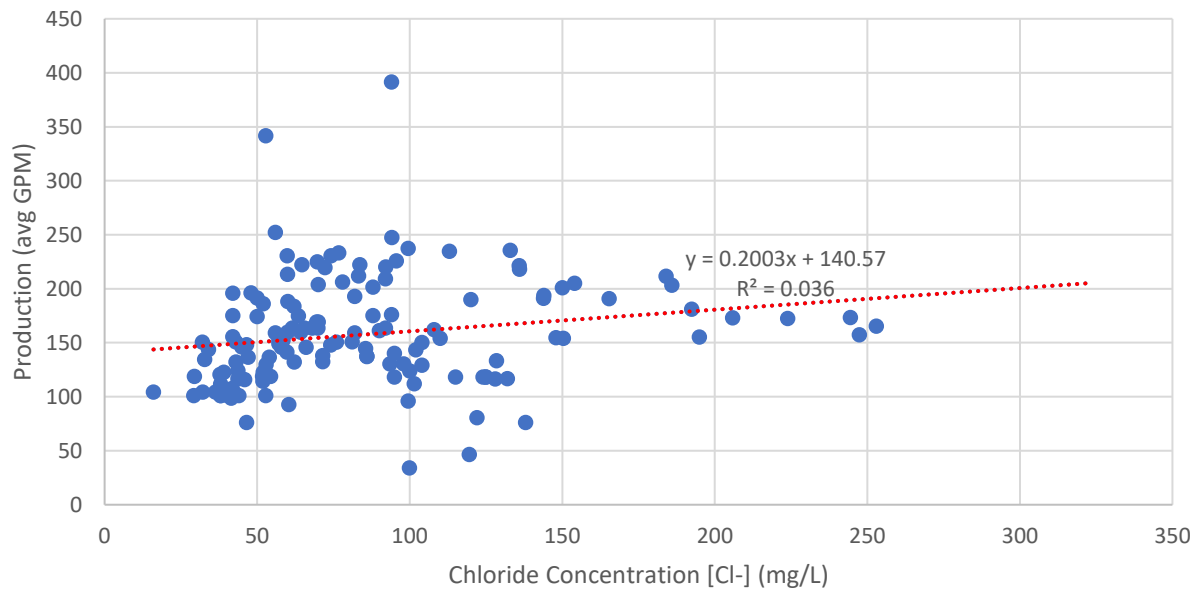




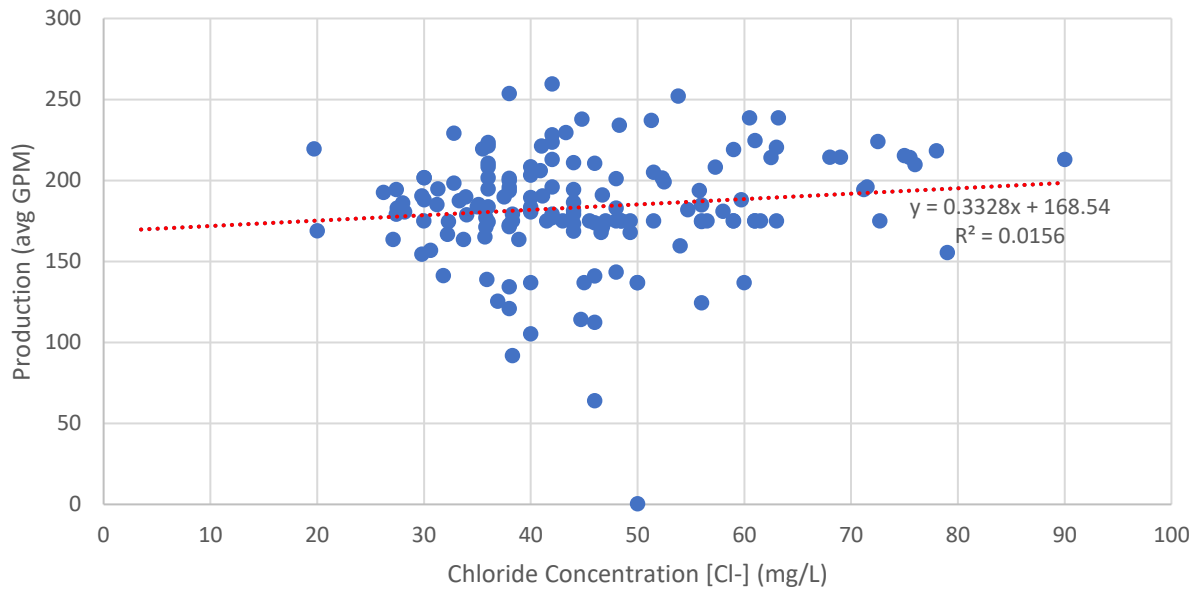
M05 Relationship between Chloride Concentrations vs Average Production



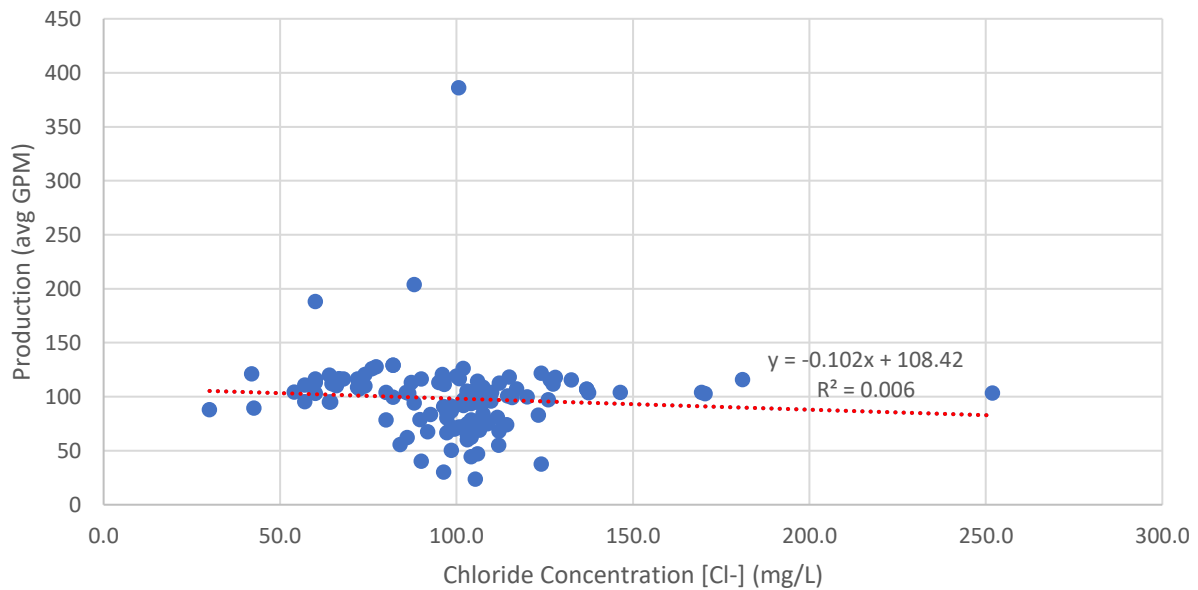
M06 Relationship between Chloride Concentrations vs Average Production



M07 Relationship between Chloride Concentrations vs Average Production

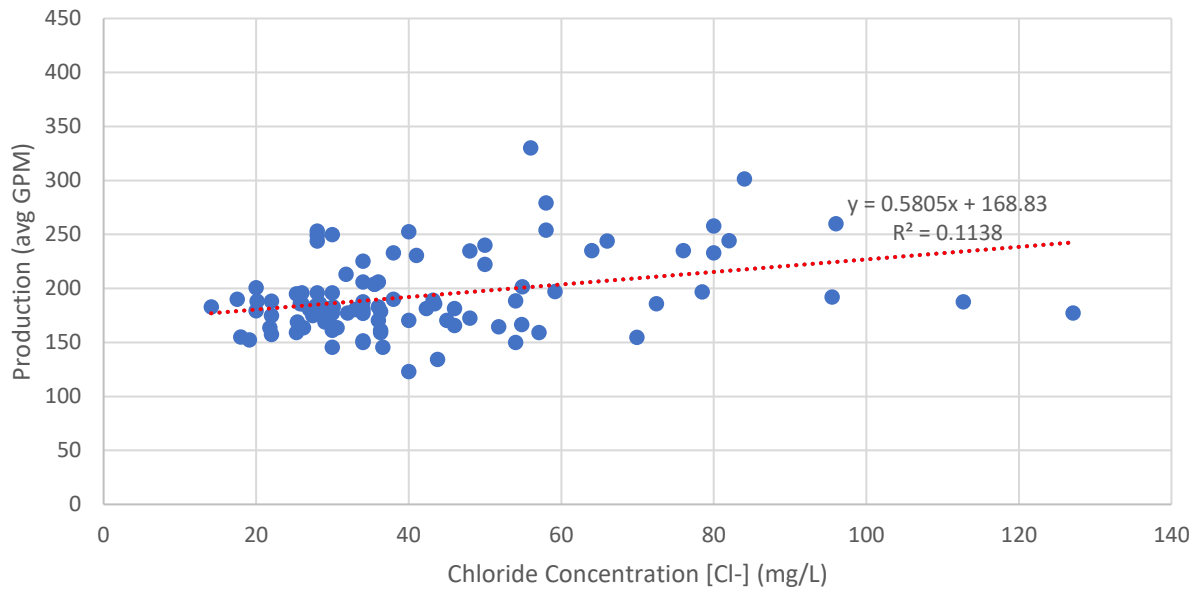


M12 Relationship between Chloride Concentrations vs Average Production

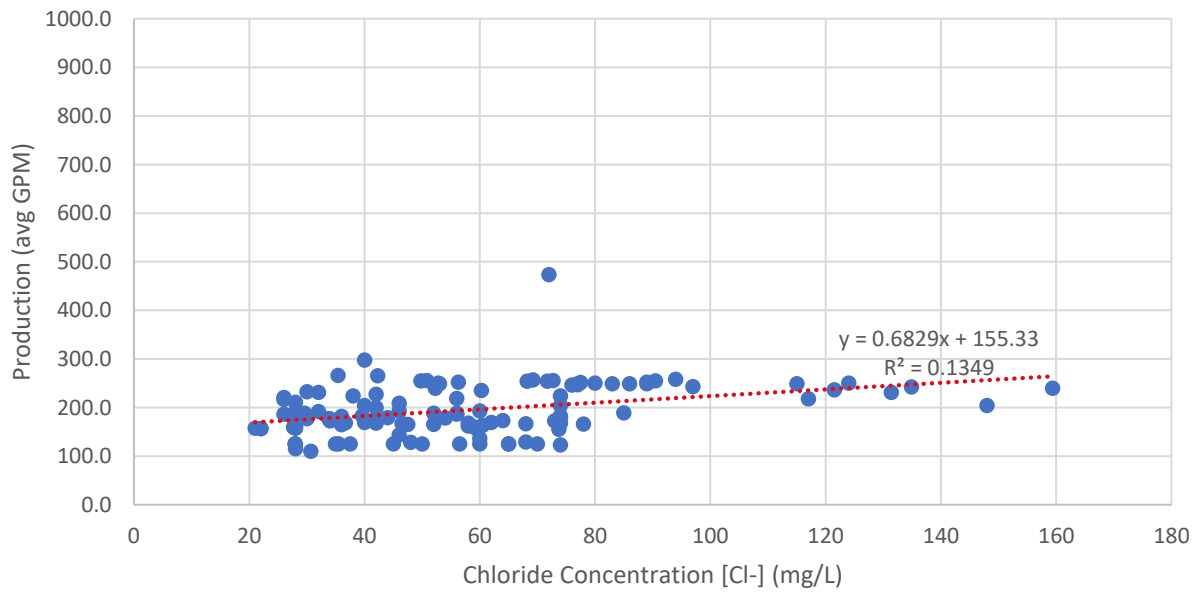




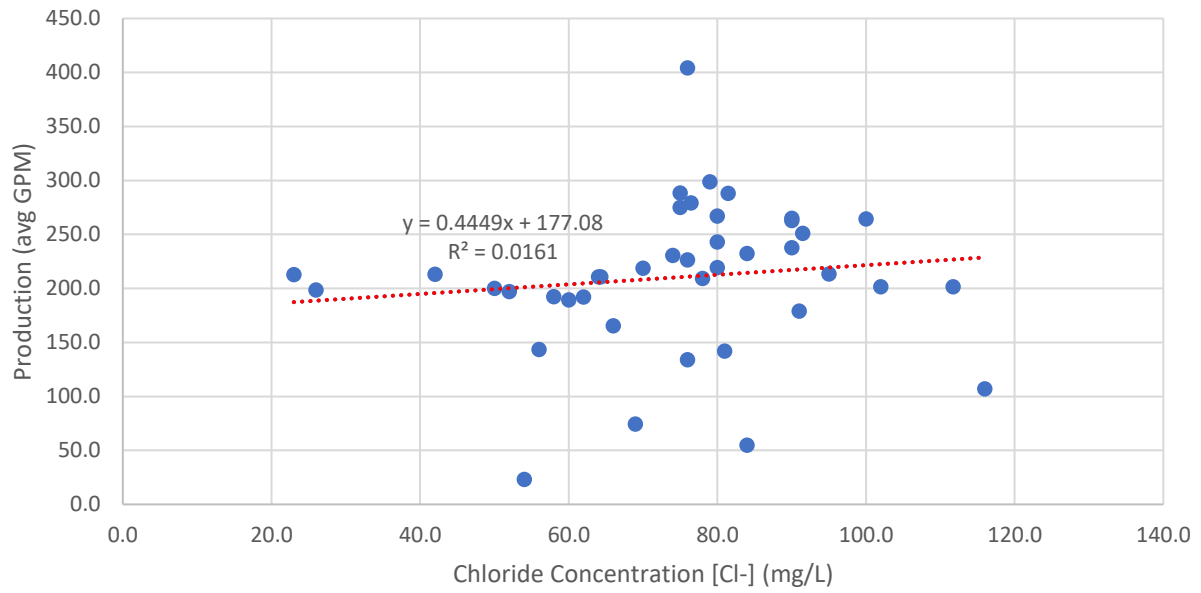
M14 Relationship between Chloride Concentrations vs Average Production



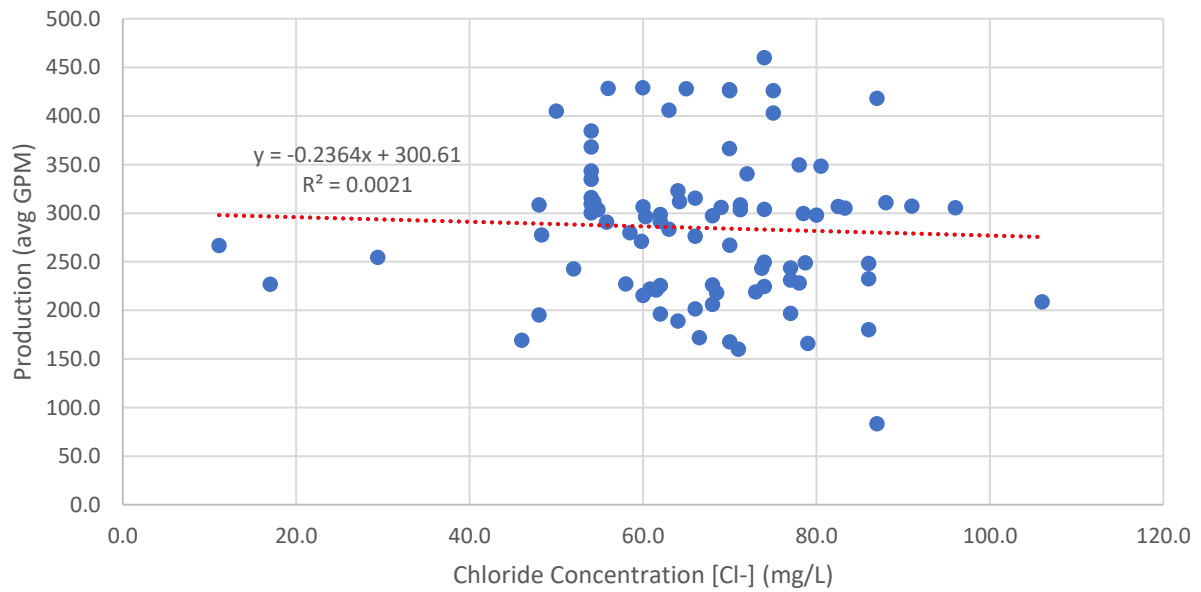
M15 Relationship between Chloride Concentrations vs Average Production



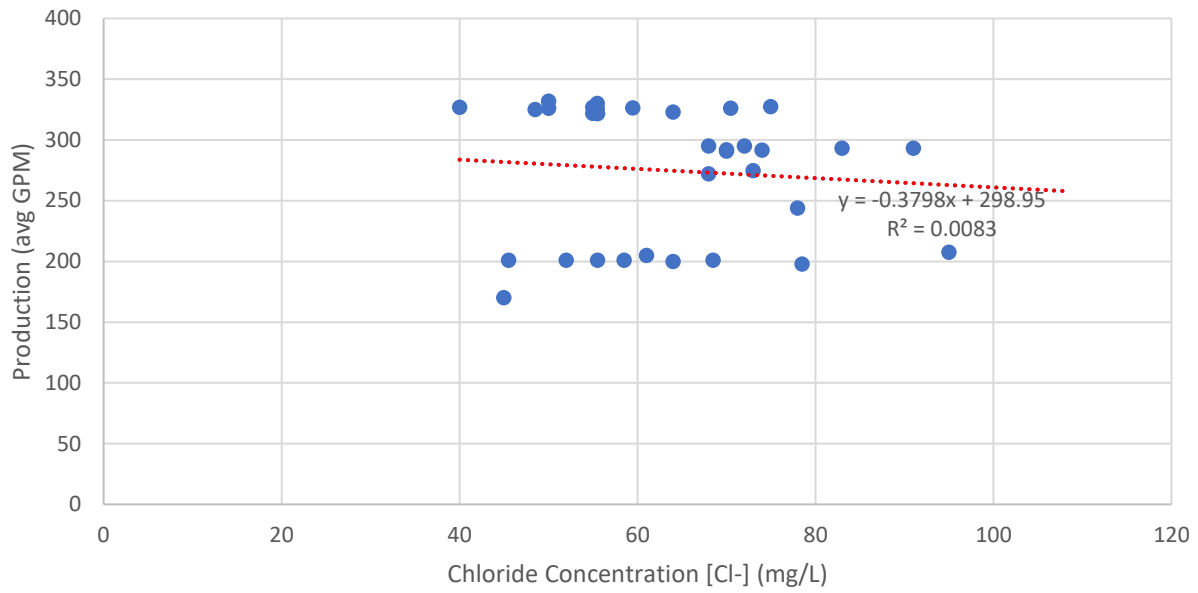
M17A Relationship between Chloride Concentrations vs Average Production



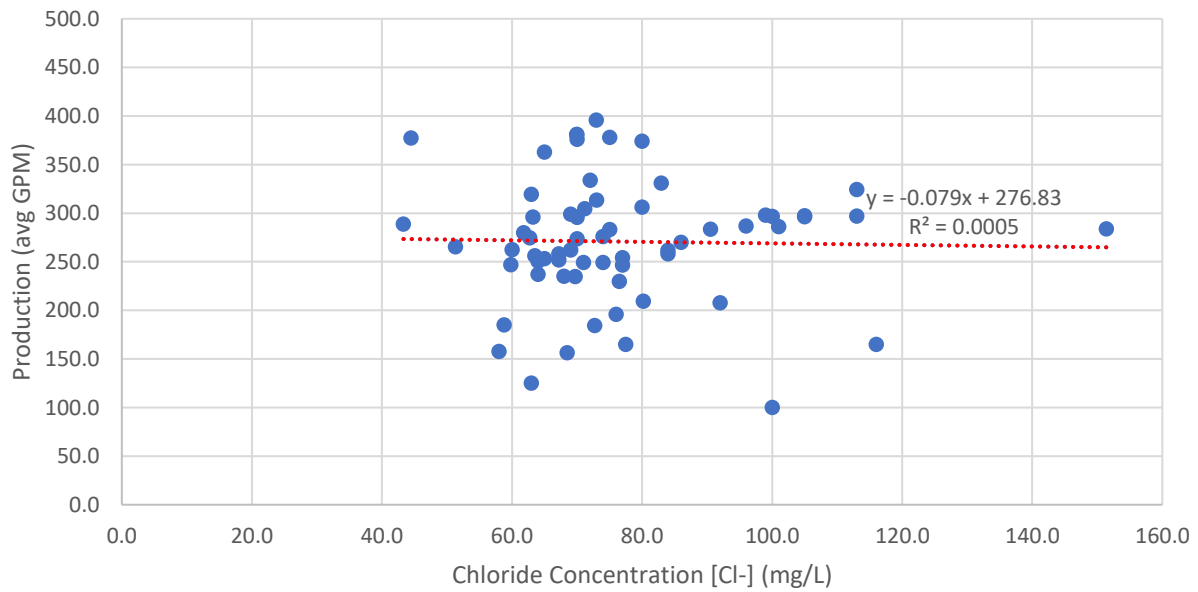
M17B Relationship between Chloride Concentrations vs Average Production



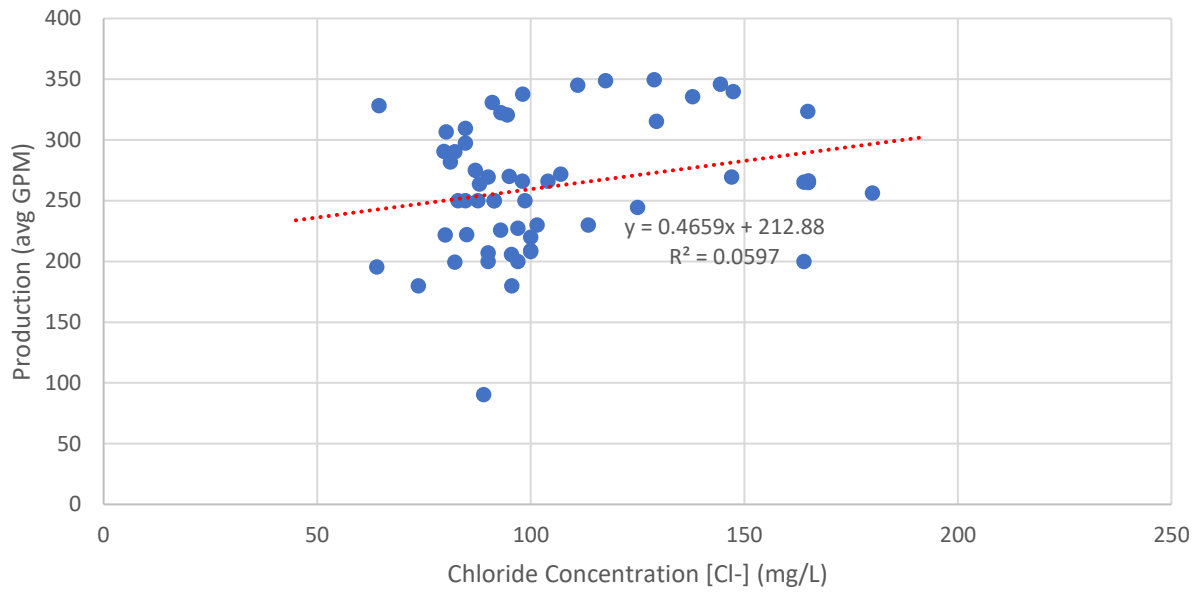
M18 Relationship between Chloride Concentrations vs Average Production



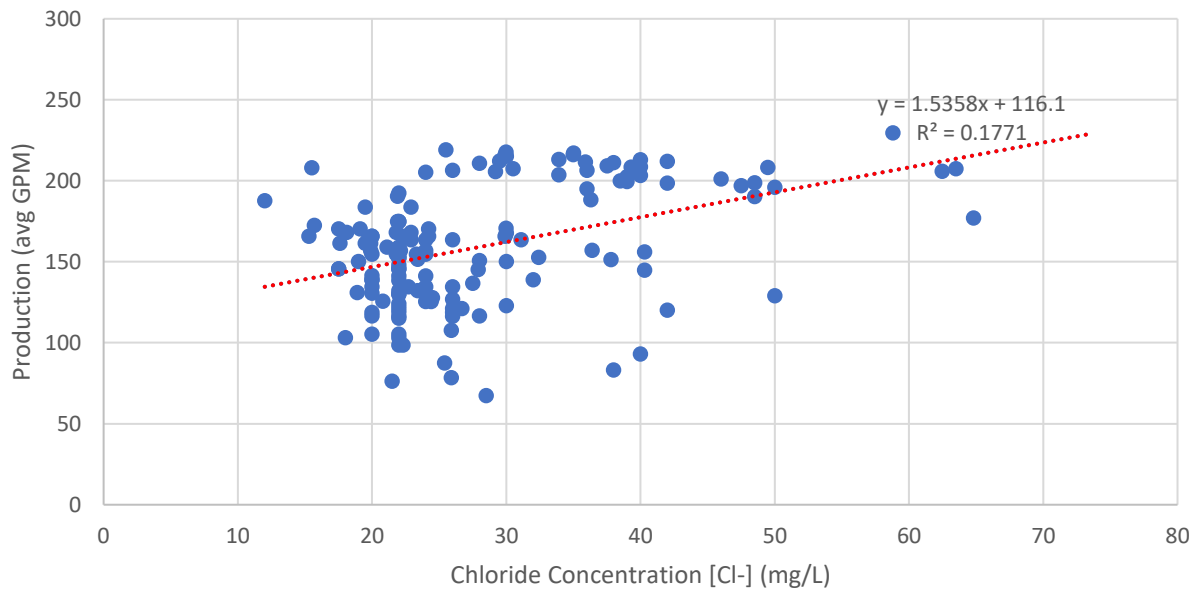
M20A Relationship between Chloride Concentrations vs Average Production



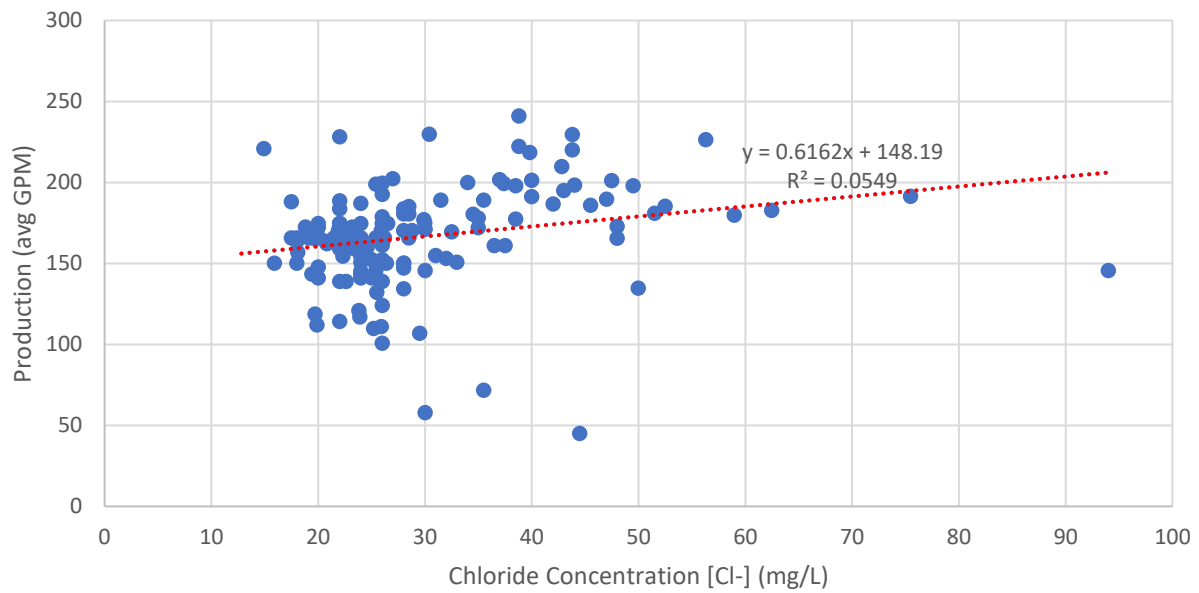
M21 Relationship between Chloride Concentrations vs Average Production



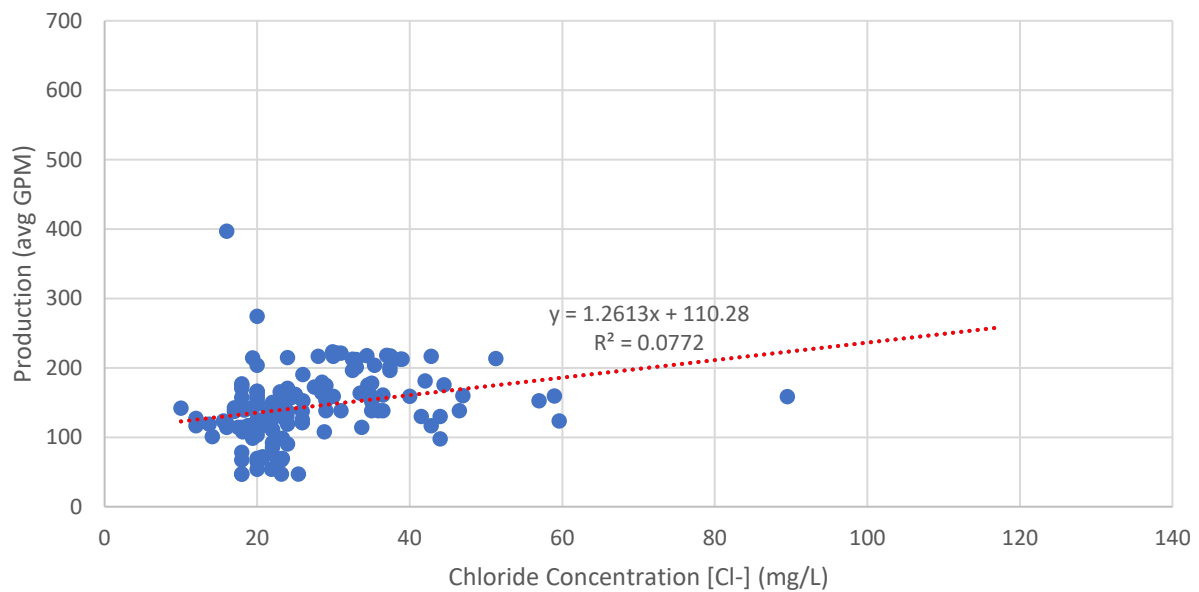
Y01 Relationship between Chloride Concentrations vs Average Production

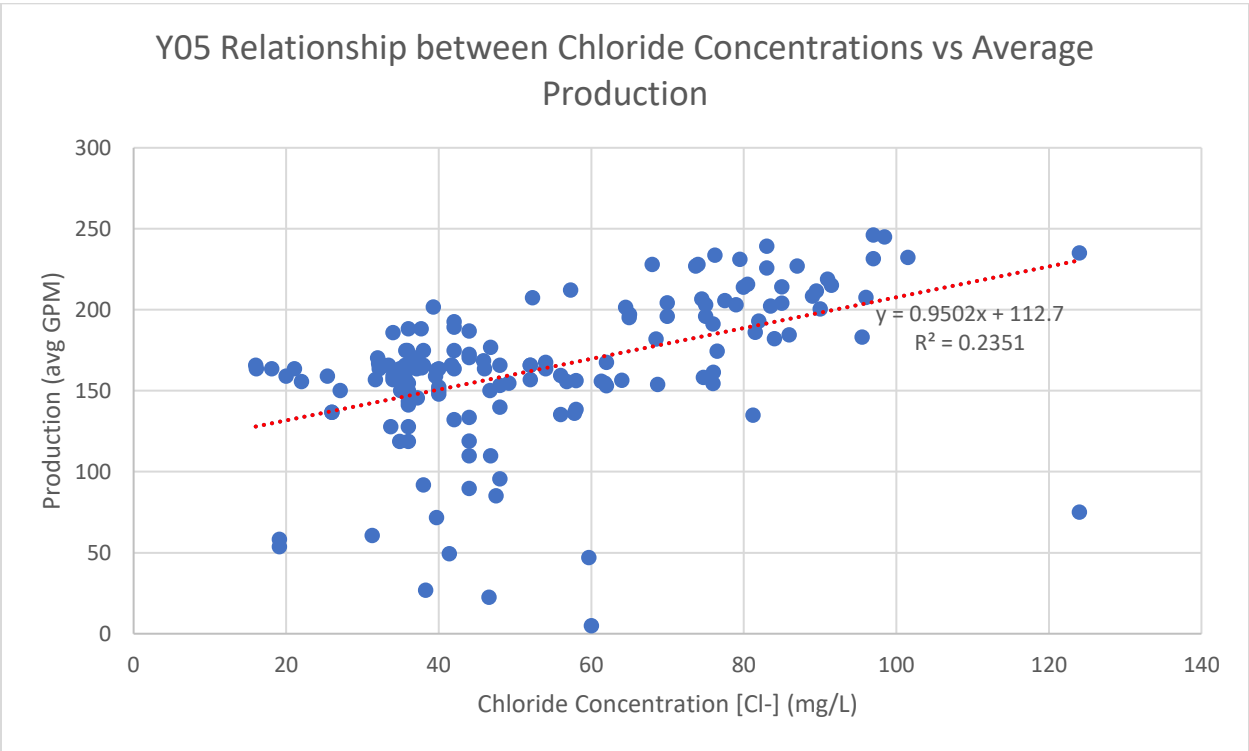
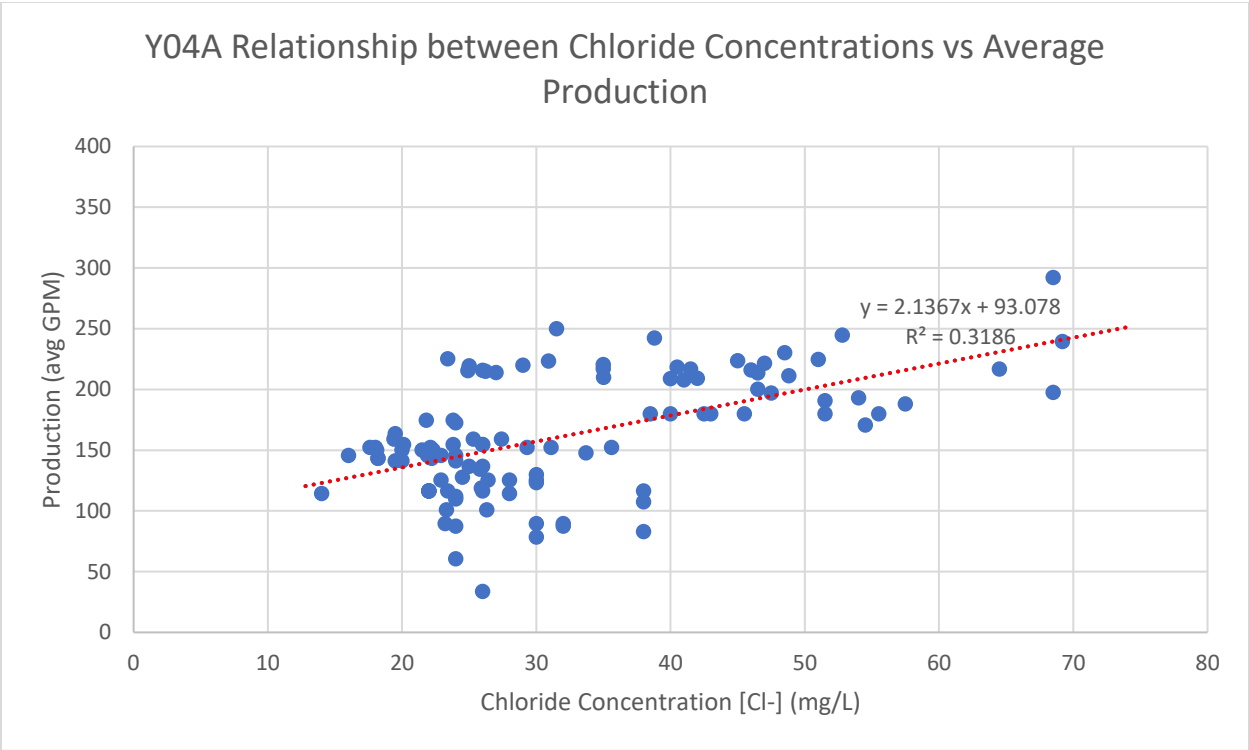


Y02 Relationship between Chloride Concentrations vs Average Production

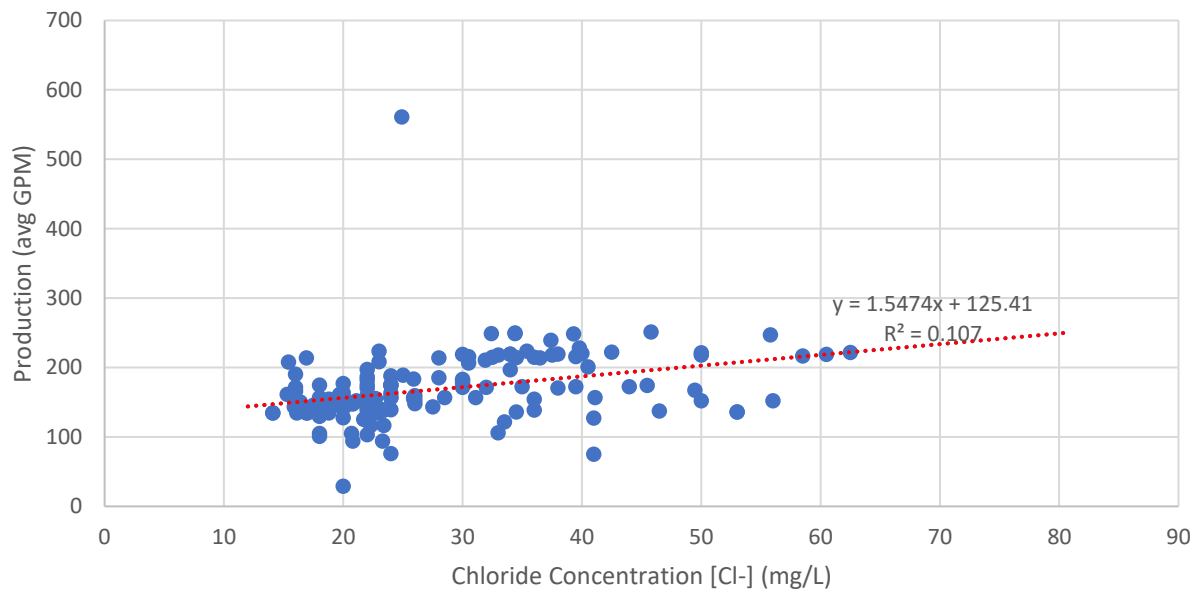


Y03 Relationship between Chloride Concentrations vs Average Production

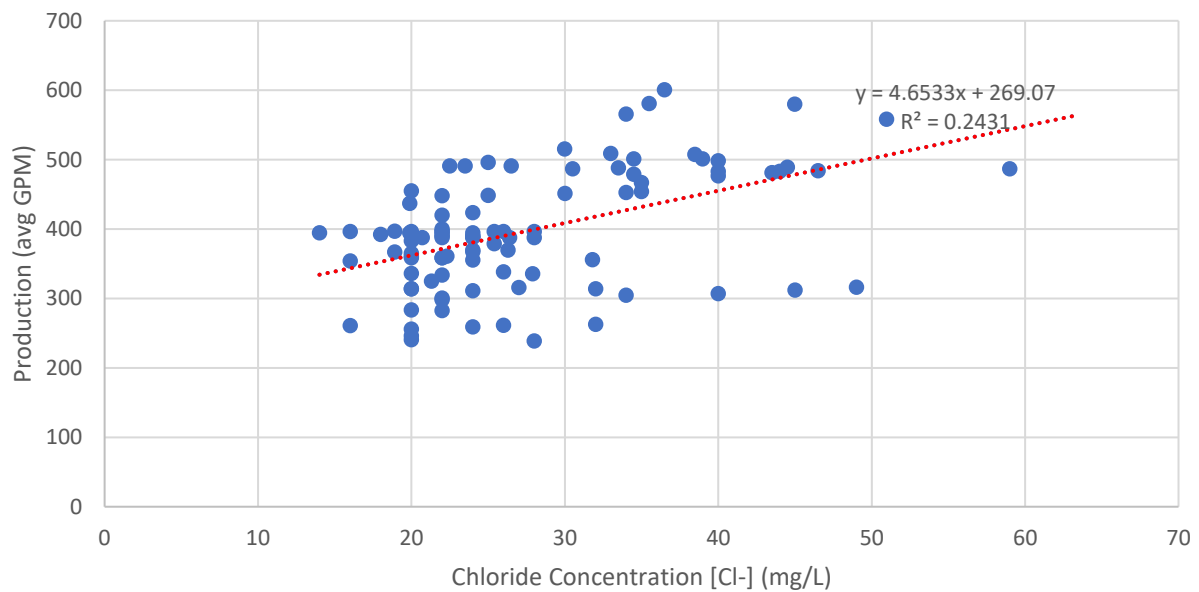




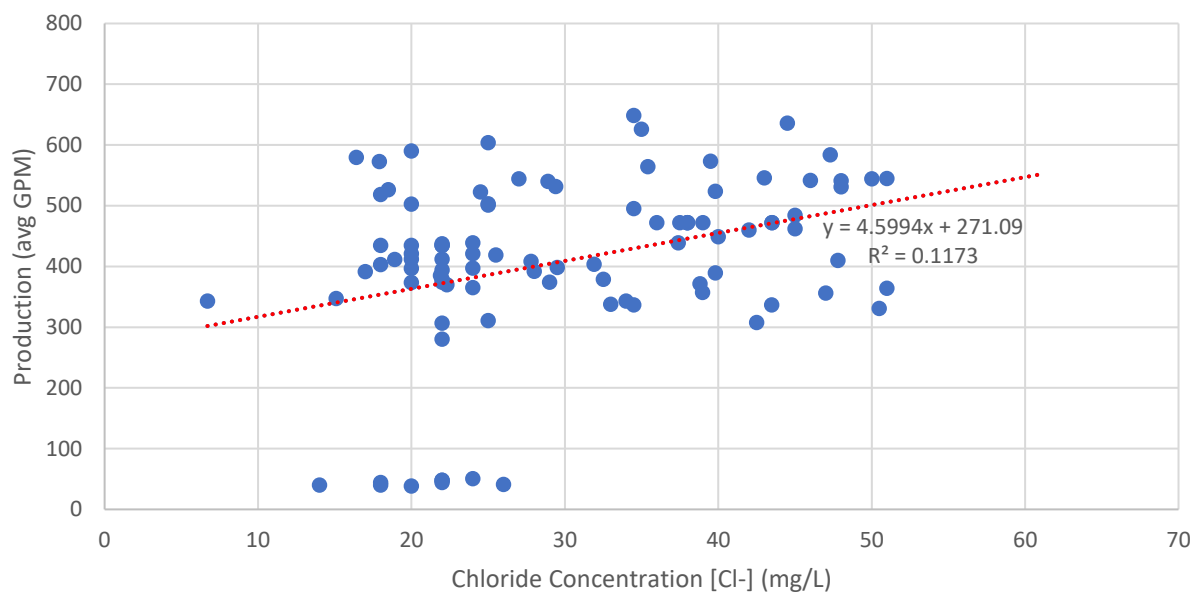
Y06 Relationship between Chloride Concentrations vs Average Production



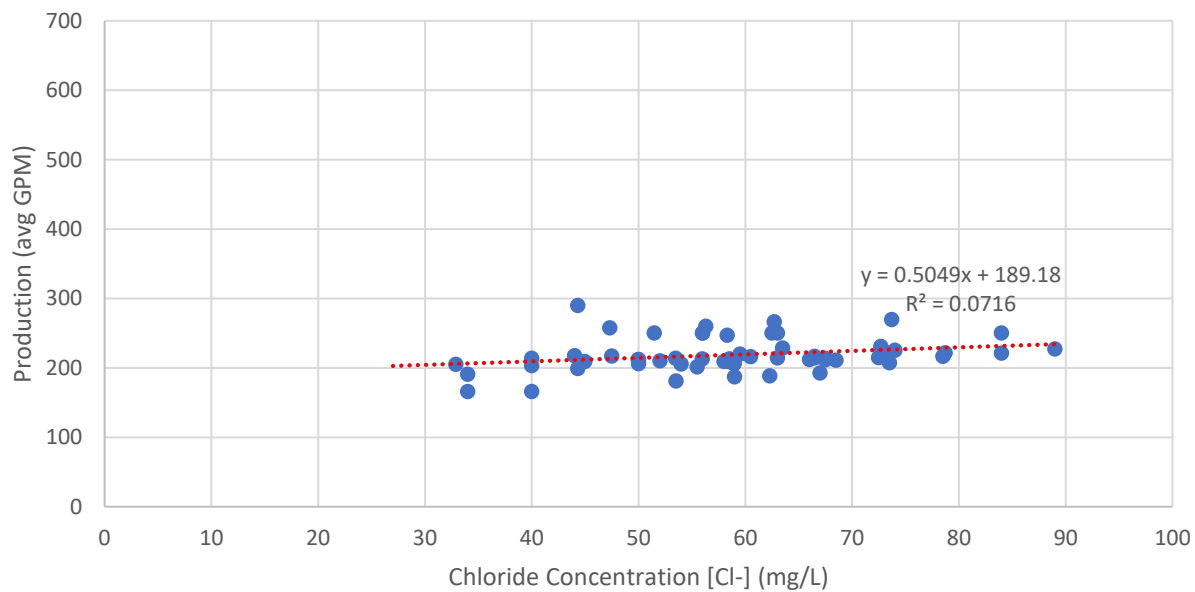
Y07 Relationship between Chloride Concentrations vs Average Production



Y09 Relationship between Chloride Concentrations vs Average Production

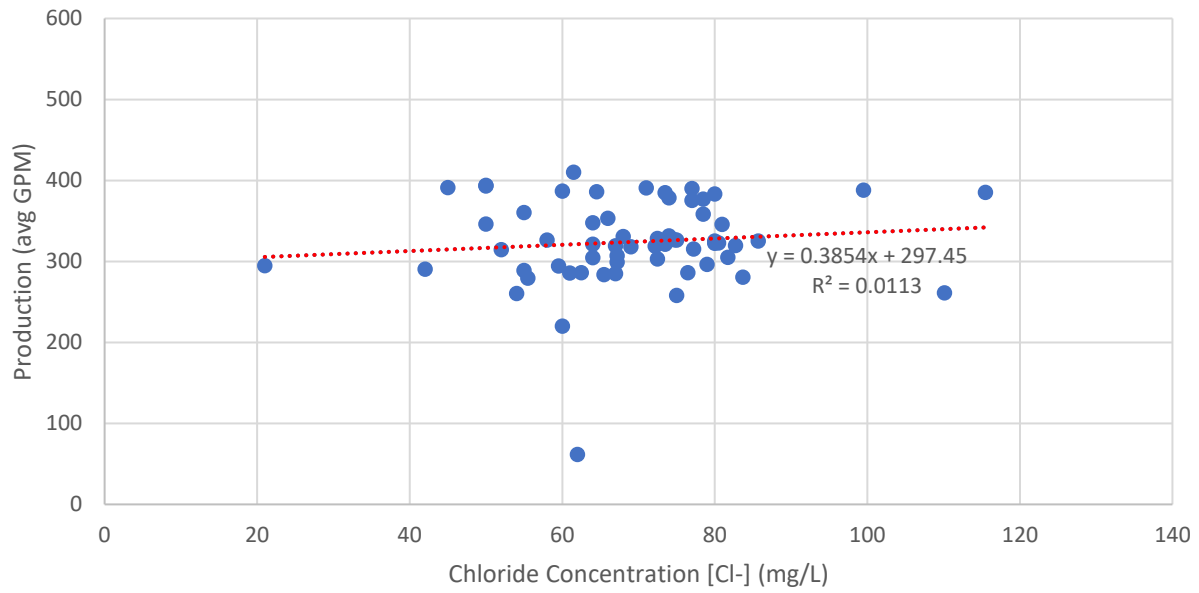


Y10 Relationship between Chloride Concentrations vs Average Production

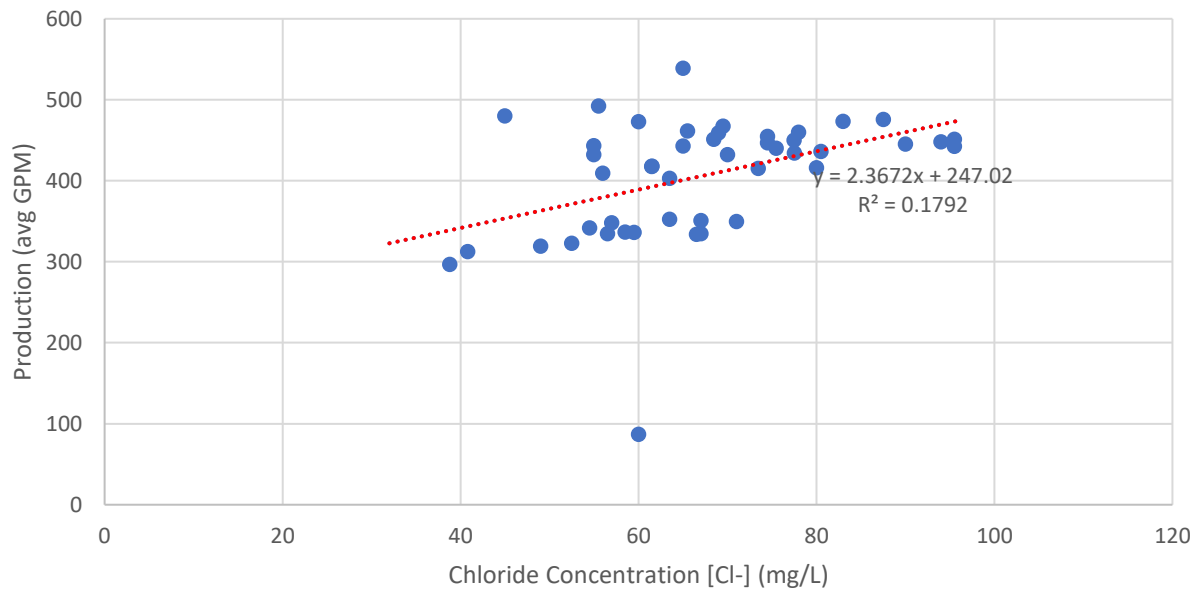




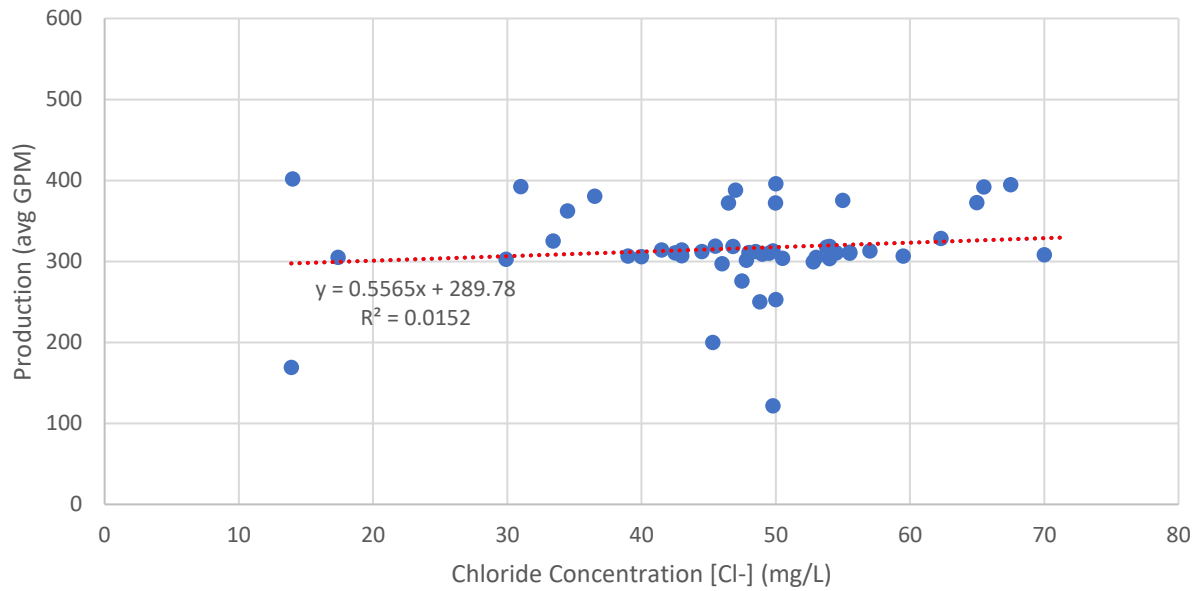
Y12 Relationship between Chloride Concentrations vs Average Production



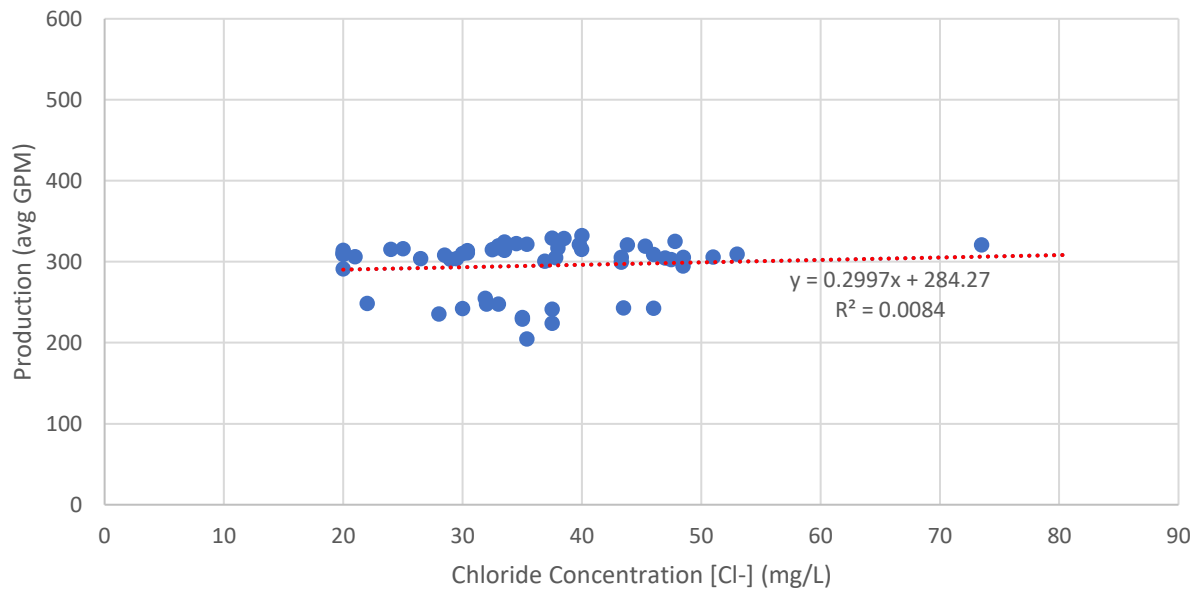
Y14 Relationship between Chloride Concentrations vs Average Production



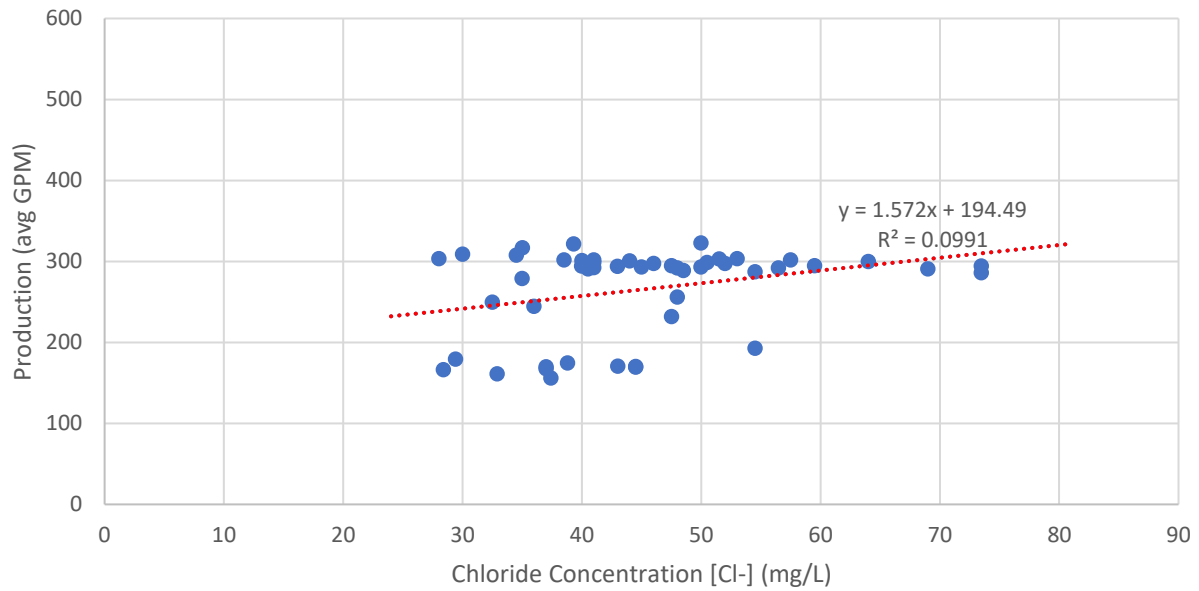
Y16 Relationship between Chloride Concentrations vs Average Production



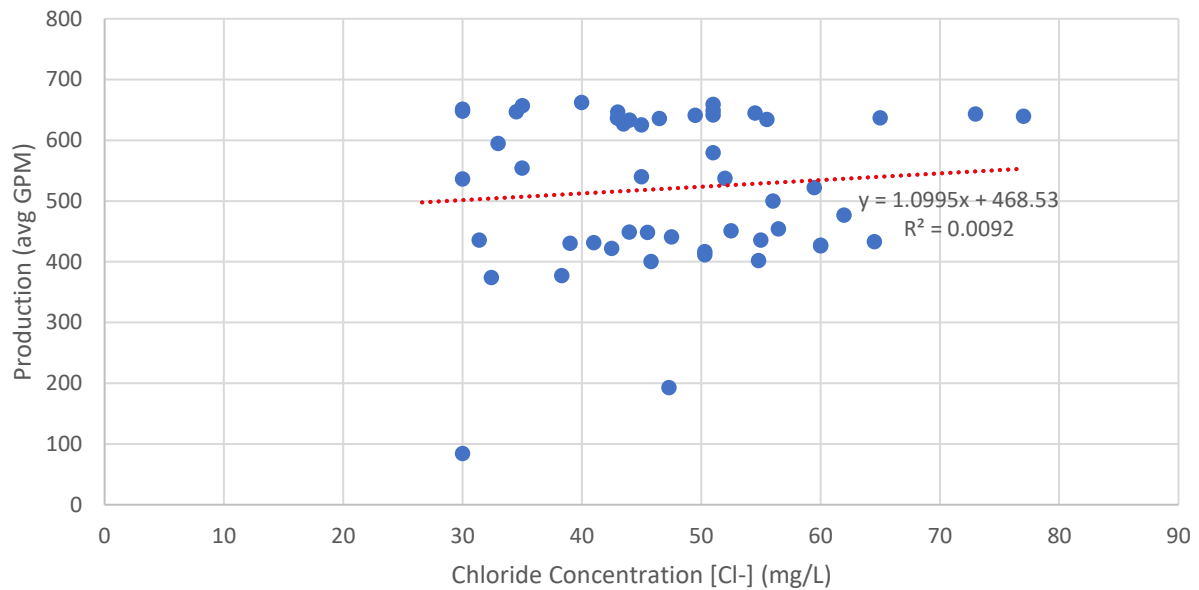
Y17 Relationship between Chloride Concentrations vs Average Production



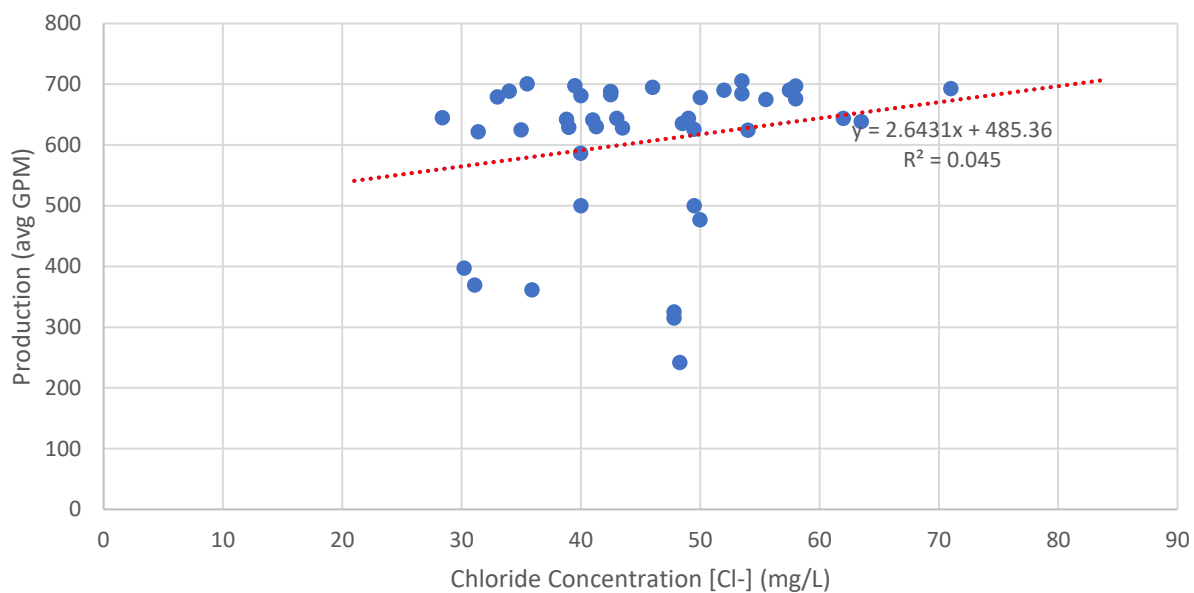
Y18 Relationship between Chloride Concentrations vs Average Production



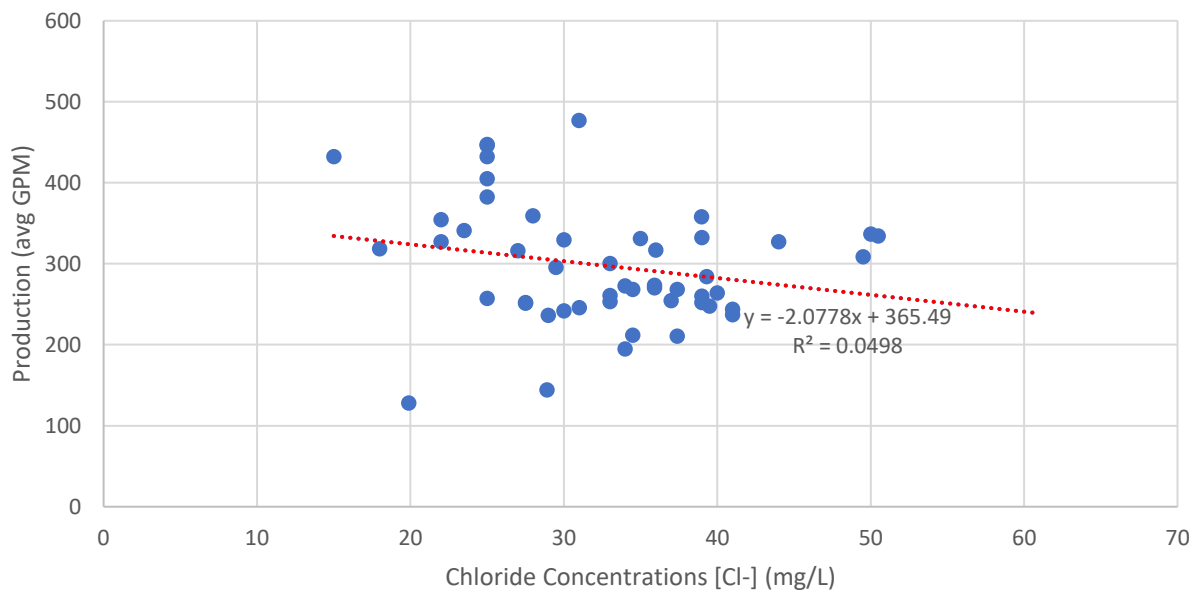
Y19 Relationship between Chloride Concentrations vs Average Production



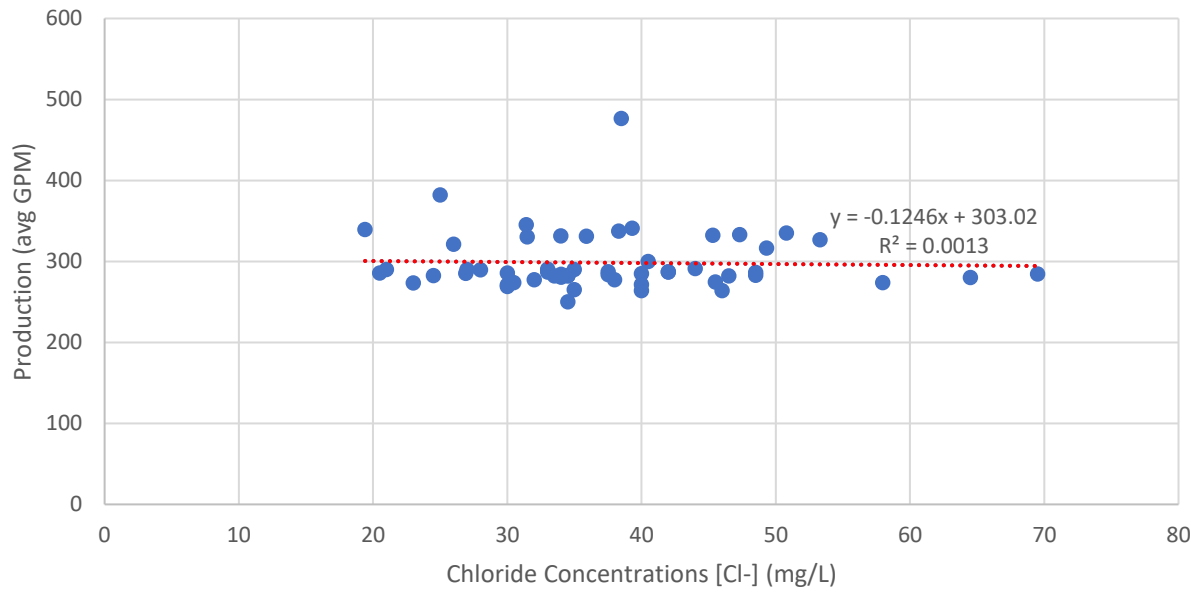
Y20 Relationship between Chloride Concentrations vs Average Production



Y22 Relationship between Chloride Concentrations vs Average Production



Y23 Relationship between Chloride Concentrations vs Average Production



Maui Well Relationship between Chloride Concentrations vs Average Production

