US Army Corps of Engineers®
Portland District

WATER QUALITY REPORT

CHIEF JOSEPH RESERVOIR, RUFUS WOODS LAKE
COLUMBIA RIVER BASIN
COLUMBIA RIVER, IDAHO

Chief Joseph Reservoir, Rufus Woods Lake

Water Quality Report
August 2020

EXECUTIVE SUMMARY

The Columbia River drains over 670,000 square kilometers of the Pacific Northwest in the United States and Canada. The Snake, Kootenai, and Pend Oreille-Clark Fork systems are the largest tributaries of the Columbia River. The hydrology of the Columbia River System has been modified during the past 100 years due to the construction of numerous hydroelectric, irrigation, flood control, and transportation projects. The construction of these projects on the mainstem of and tributaries to the Columbia River created numerous reservoirs that have resulted in a significant alteration of the natural flow regime, river geometry, river velocity, and water residence time in the Columbia River. A consequence of the creation of reservoirs is that the water residence times, water temperatures, nutrient loadings, and sediment transport patterns of the Columbia River System have been altered, likely influencing water, sediment, and biological quality in the reservoirs formed by the dams.

The U.S. Army Corps of Engineers (Corps) Seattle District operates one dam on the Mid-Columbia River, Chief Joseph Dam. Rufus Woods Lake, the reservoir formed by Chief Joseph Dam, is located immediately downstream of Grand Coulee Dam and Lake Roosevelt, and upstream of Wells Dam and Lake Pateros. Limited physical, chemical, and biological water quality data has been collected in Rufus Woods Lake.

From the early 1900s through the 1990s, contaminants were introduced to the Columbia River upstream of Rufus Woods Lake and Grand Coulee Dam from a variety of sources. Two major sources of contamination to the water and sediments were the Teck-Cominco Smelter in Trail, British Columbia, about 15 kilometers upstream of the international border, and the Zellstoff Celgar Ltd. bleached kraft pulp mill located in Castlegar, British Columbia, about 50 kilometers upstream of the border (U.S. Environmental Protection Agency [EPA] 2008). Although most sources of contamination were reduced or eliminated by the 1990s, several aquaculture operations exist in Rufus Woods Lake. The potential effects of aquaculture on fresh water and sediment quality are largely related to waste produced by the facilities via fish feed and feces (Environment Canada 2009).

Water quality data collected in Rufus Woods Lake and the Columbia River downstream of Chief Joseph Dam is summarized in order to better understand the limnological functioning of this system. The majority of data discussed in this report is derived from a large-scale water quality monitoring study conducted by the Corps during calendar years 2011 to 2013. This limnological study was designed to investigate the interaction of physical, chemical, and biological processes in the lake and river to better understand the possible water quality impacts of Chief Joseph Dam operations on Rufus Woods Lake and the Columbia River. The scope of this summary of existing conditions is extensive and will include: (1) fate and transport of nutrients and trace metals in Rufus Woods Lake and the Columbia River immediately downstream of Chief Joseph Dam, (2) assessment of the temporal and spatial variability in key water quality parameters, and (3) the biological condition of Rufus Woods Lake.

CONTENTS

EXECUTIVE SUMMARY i
TABLE OF CONTENTS iii
ACRONYMS vii

SECTION 1 - INTRODUCTION 1-8

1.1 STUDY AREA 1-8
1.2 CLIMATE AND GEOLOGY 1-9
1.3 LAND USE 1-10
1.4 CONTAMINANT SOURCES 1-10
1.5 AQUACULTURE FACILITIES 1-11
1.6 PREVIOUS INVESTIGATIONS 1980S TO 2000S 1-13
1.7 CURRENT INVESTIGATION 2011 TO 2013 1-14
1.8 WATER QUALITY CRITERIA 1-20
1.9 EXISTING 303(D) AND TOTAL MAXIMUM DAILY LOADS 1-21
1.10 WASHINGTON DEPARTMENT OF HEALTH TOXIC CYANOBACTERIA GUIDANCE 1-22
1.11 DATA ANALYSIS 1-22

SECTION 2 - WATER QUALITY 2-1

2.1 HYDROLOGICAL CHARACTERIZATION 2-1
2.1.1 Flow and Retention Time 2-1
2.1.2 Spillway Flows 2-4
2.2 LAKE PHYSICAL AND CHEMICAL CONDITIONS 2-6
2.2.1 Water Temperature 2-10
2.2.2 Transparency 2-14
2.2.3 Dissolved Oxygen 2-19
2.2.4 Alkalinity, Hardness and pH 2-22
2.2.5 Specific Conductivity 2-24
2.2.6 Nutrients 2-24
2.2.7 Chlorophyll a 2-48
2.2.8 Trophic State 2-50
2.2.9 Major Anions (SO_4, Cl) and Cations (Ca, Mg, Na, K) 2-52
2.2.10 Trace Metals 2-53
2.2.11 Fats, Oils, and Grease 2-57
2.2.12 Total Organic Carbon 2-57
2.2.13 Total Dissolved Gas 2-59
2.2.14 Statistical Analysis 2-61
2.3 LAKE BIOLOGICAL CONDITIONS 2-64
2.3.1 Phytoplankton 2-64
2.3.2 Periphyton 2-76
2.3.3 Harmful Algae Blooms 2-79
2.3.4 Zooplankton 2-89

SECTION 3 - CONCLUSIONS AND RECOMMENDATIONS 3-1

3.1 CONCLUSIONS 3-1
3.2 RECOMMENDATIONS 3-2

SECTION 4 - REFERENCES 4-1

TABLES

Table 1-1. Water Quality Sampling Locations in Rufus Woods Lake from 2011 to 2013 1-15
Table 1-2. Methods and Detection Limits for Water Quality Analyses 1-16
Table 1-3. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake 2011 1-18
Table 1-4. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake 2012 1-19
Table 1-5. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake 2013 ... 1-19
Table 1-6. Periphyton Sampling Locations in Rufus Woods Lake 2011 1-20
Table 1-7. Washington State Department of Ecology and Confederated Tribes of the Colville Reservation General Water Quality Standards 1-20
Table 1-8. Washington State Department of Ecology and Colville Tribes Metals and Ammonia Water Quality Standards 1-21
Table 2-1. Rufus Woods Lake Water Quality Data for 2011 2-7
Table 2-2. Rufus Woods Lake Water Quality Data for 2012 2-8
Table 2-3. Rufus Woods Lake Water Quality Data for 2013 2-9
Table 2-4. Trophic Classification Values for Rufus Woods Lake from 2011 to 2013 .. 2-51
Table 2-5. Carlson Trophic State Index Values for Rufus Woods Lake from 2011 to 2013 2-51
Table 2-6. OECD Trophic State Classification Total Phosphorus, Chlorophyll a, and Transparency Values for Rufus Woods Lake from 2011 to 2013 2-52
Table 2-7. Statistical Summary for Mann-Whitney Test Upstream and Downstream of Aquaculture Facilities in Rufus Woods Lake from 2011 to 2013 2-62
Table 2-8. Kendall Rank Correlation Coefficients for June to October Rufus Woods Lake Water Quality and Phytoplankton Data from 2011 to 2013 2-63
Table 2-9. Phytoplankton Species List for Rufus Woods Lake from 2011 to 2013 2-67
Table 2-10. Periphyton Data for July 11, 2011, Rufus Woods Lake Samples 2-77
Table 2-11. Harmful Algae Bloom Qualitative Analysis Species List for Rufus Woods Lake from 2011 to 2013 2-82
Table 2-12. Harmful Algae Bloom Quantitative Analysis Species List for Rufus Woods Lake from 2011 to 2013 2-83
Table 2-13. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2011 2-86
Table 2-14. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2012 2-87
Table 2-15. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2013 2-88
Table 2-16. Zooplankton Species List for Rufus Woods Lake from 2011 to 2013 2-91

FIGURES

Figure 1-1. Location of Chief Joseph Dam in the Columbia River Basin Watershed... 1-8
Figure 1-2. Locations of Water Quality Monitoring Stations in Rufus Woods Lake and the Columbia River 1-9
Figure 1-3. Locations of Harmful Algae Bloom Monitoring Stations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake for 2011 to 2013 1-17
Figure 1-4. Locations of Periphyton Monitoring Stations in Rufus Woods Lake in 2011 1-18
Figure 2-1. Comparison of the Historic Daily Flow for the Columbia River at Chief Joseph Dam from 1975 to 2010 with the Average Daily Flows for 2011, 2012, and 2013 2-2
Figure 2-2. Comparison of the Average Daily Flows and Retention Times for 2011, 2012, and 2013 2-3
Figure 2-3. Average Daily Flow and Spill for Grand Coulee Dam and Chief Joseph Dam in 2011, 2012, and 2013 2-5
Figure 2-4. Rufus Woods Lake Water Temperature Profiles at Stations CHJUP, CHJMID, and CHJFB for 2011 to 2013 2-11
Figure 2-5. Continuous Hourly Temperature, Flow and Spill at Long-Term Stations CHJ and CHQW for 2011, 2012, and 2013 2-13
Figure 2-6. Rufus Woods Lake Transparencies for 2011, 2012, and 2013 2-15
Figure 2-7. Rufus Woods Lake Chlorophyll a for 2011, 2012, and 2013 2-16
Figure 2-8. Statistical Summary of Annual (March to October) Transparency in Rufus Woods Lake for 2011, 2012, and 2013 2-18
Figure 2-9. Rufus Woods Lake Dissolved Oxygen Profiles at Stations CHJUP, CHJMID, and CHJFB for 2011 to 2013 2-20
Figure 2-10. Columbia River Monthly Dissolved Oxygen Concentrations at Station CHJTW 2-21
Figure 2-11. Data Summary of Annual (March to October) Alkalinity Concentrations in Rufus Woods Lake for 2011, 2012, and 2013 2-23
Figure 2-12. Rufus Woods Lake Total Phosphorus Concentrations for 2011 to 2013 2-26
Figure 2-13. Rufus Woods Lake Data Summary of Annual (March to October) Total Phosphorus Concentrations for 2011 to 2013 2-28
Figure 2-14. Rufus Woods Lake Data Summary of Summer (June to October) Total Phosphorus and Soluble Reactive Phosphorus Concentrations for 2011 to 2013 2-29
Figure 2-15. Rufus Woods Lake Soluble Reactive Phosphorus Concentrations for 2011 to 2013 2-31
Figure 2-16. Rufus Woods Lake Data Summary of Annual (March to October) Soluble Reactive Phosphorus Concentrations for 2011 to 2013 2-33
Figure 2-17. Rufus Woods Lake Total Nitrogen Concentrations for 2011, 2012, and 2013 2-36
Figure 2-18. Rufus Woods Lake Data Summary of Annual (March to October) Total Nitrogen Concentrations for 2011 to 2013 2-37
Figure 2-19. Rufus Woods Lake Data Summary of Summer (June to October) Total Nitrogen, Nitrate+Nitrite, and Ammonia Concentrations for 2011 to 2013 2-39
Figure 2-20. Rufus Woods Lake Nitrate Concentrations for 2011 to 2013 2-40

Figure 2-21. Rufus Woods Lake Data Summary of Annual (March to October) Nitrate+Nitrite Concentrations for 2011 to 2013 2-42
Figure 2-22. Rufus Woods Lake Ammonia Concentrations for 2011 to 2013..... 2-43
Figure 2-23. Rufus Woods Lake Data Summary of Annual (March to October) Ammonia Concentrations from 2011 to 2013 2-44
Figure 2-24. Rufus Woods Lake Total Nitrogen to Total Phosphorus Ratios for 2011 to 2013 2-46
Figure 2-25. Rufus Woods Lake Data Summary of Summer (June to October) Total Nitrogen to Total Phosphorus Ratios by Station from 2011 to 2013..... 2-47
Figure 2-26. Rufus Woods Lake Data Summary of Annual (March to October) Chlorophyll a Concentrations from 2011 to 2013 2-49
Figure 2-27. Rufus Woods Lake Total Copper Concentrations for 2011, 2012, and 2013 2-54
Figure 2-28. Rufus Woods Lake Total Zinc Concentrations for 2011, 2012, and 2013 2-56
Figure 2-29. Rufus Woods Lake Temporal Variation in Total Organic Carbon Concentrations for 2011, 2012, and 2013 2-58
Figure 2-30. Rufus Woods Lake Temporal Variation in Total Dissolved Gas Saturations from 2011 to 2013 2-60
Figure 2-31. Rufus Woods Lake Temporal Variation in Phytoplankton Biovolume and Density from 2011 to 2013 2-70
Figure 2-32. Rufus Woods Lake Average Phytoplankton Percent Composition by Biovolume 2-73
Figure 2-33. Rufus Woods Lake Average Phytoplankton Percent Composition by Density 2-74
Figure 2-34. Photos of Rufus Woods Lake Harmful Algae Bloom in Forebay During 2011 2-80
Figure 2-35. Rufus Woods Lake Harmful Algae Bloom Algal Percent Composition by Biovolume for 2011 and 2012 2-85
Figure 2-36. Rufus Woods Lake Zooplankton Density by Station from 2011 to 2013 2-92
Figure 2-37. Rufus Woods Lake Whole Lake Zooplankton Density and Percent Composition from 2011 to 2013 2-94

ACRONYMS

Acronym	Description
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
CaCO3	calcium carbonate
cfs	cubic feet per second
CHJFB	monitoring station in the forebay of Chief Joseph Dam
CHJMID	mid-reservoir monitoring station
CHJNSP	in-lake monitoring station downstream of Grand Coulee Dam and upstream of the upstream of the aquaculture facilities
CHJNSP-1	monitoring station immediately downstream of the aquaculture facilities
CHJNSP-2	monitoring station immediately downstream of the aquaculture facilities
CHJNSP-3	monitoring station immediately downstream of the aquaculture facilities
CHJNSP-4	monitoring station immediately downstream of the aquaculture facilities
CHJTW	tailwater monitoring station located on the Columbia River and collected from the right bank about 2 kilometers downstream of Chief Joseph Dam
CHJUP	in-lake monitoring station downstream of Grand Coulee Dam and upstream of the upstream of the aquaculture facilities
Colville Tribes	Confederated Tribes of the Colville Reservation
Corps	U.S. Army Corps of Engineers
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FOG	fats, oils, and grease
HAB	harmful algae bloom
mg/L	milligrams per liter
mg/m2	milligrams per square meter
OECD	Organization for Economic Co-Operation and Development
TDG	total dissolved gases
TMDL	total maximum daily load
TN:TP	total nitrogen to total phosphorus ratio
TSI	trophic state index
USGS	U.S. Geological Survey
Washington State DNR	Washington State Department of Natural Resources

SECTION 1 - INTRODUCTION

1.1 STUDY AREA

The Columbia River originates in the Rocky Mountains of British Columbia at an elevation exceeding 3,000 meters and flows northward for several hundred kilometers before flowing southward through a series of lakes and reservoirs toward the State of Washington (Figure 1-1). The Kootenai (spelled Kootenay in Canada) River and the Pend Oreille River enter the Columbia River north of the international border, and the Columbia River flows into Lake Roosevelt immediately south of the border. Lake Roosevelt is the 210–kilometer–long reservoir formed by Grand Coulee Dam, a Bureau of Reclamation project located at River Kilometer 960. Downstream of Grand Coulee Dam, the river enters Rufus Woods Lake, the 80–kilometer–long reservoir formed by Chief Joseph Dam, a Corps project. Chief Joseph Dam is a run-of-river dam located at river kilometer 876 on the Columbia River in Washington, about 84 kilometers downstream of Grand Coulee Dam. The dam is a concrete gravity dam, 72 meters high, with 19 spillway bays that abut the right bank. Rufus Woods Lake has a gross storage capacity of 728 million cubic meters, a maximum depth of about 70 meters, and a mean water residence time of about 3 days. This study was conducted in Rufus Woods Lake from Grand Coulee Dam downstream to Chief Joseph Dam and in the Columbia River immediately downstream of Chief Joseph Dam (Figure 1-2).

Figure 1-1. Location of Chief Joseph Dam in the Columbia River Basin Watershed

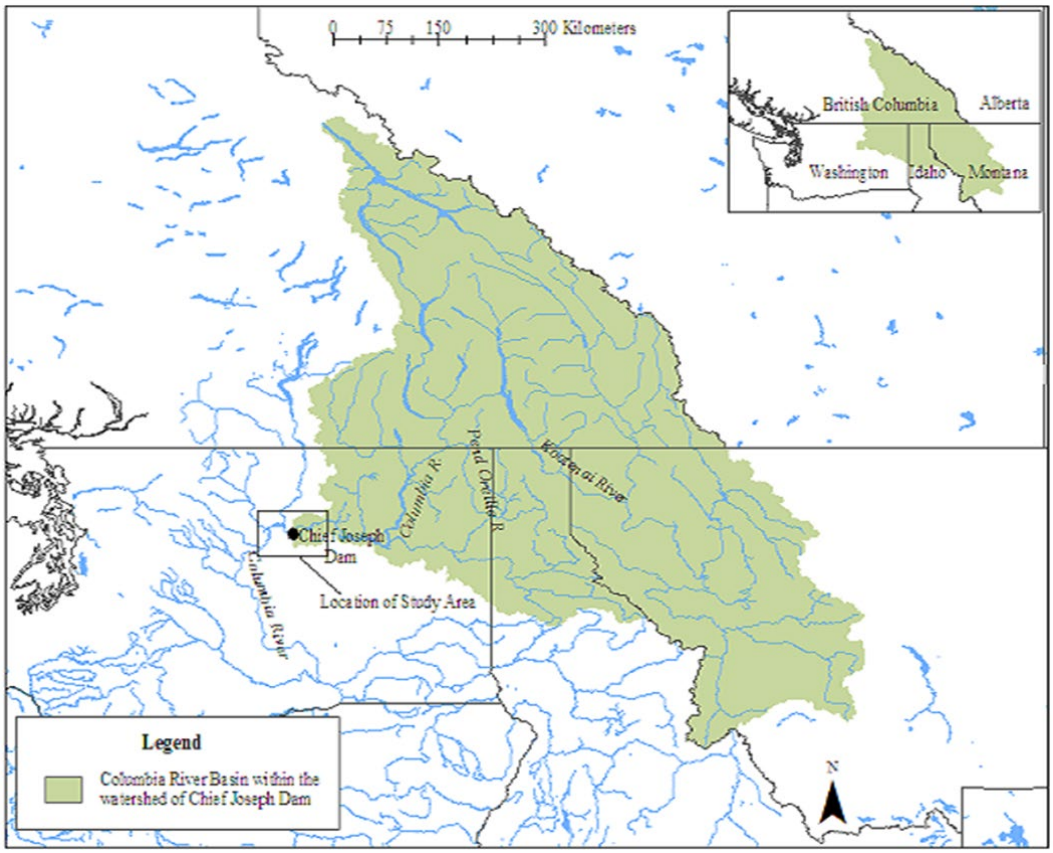
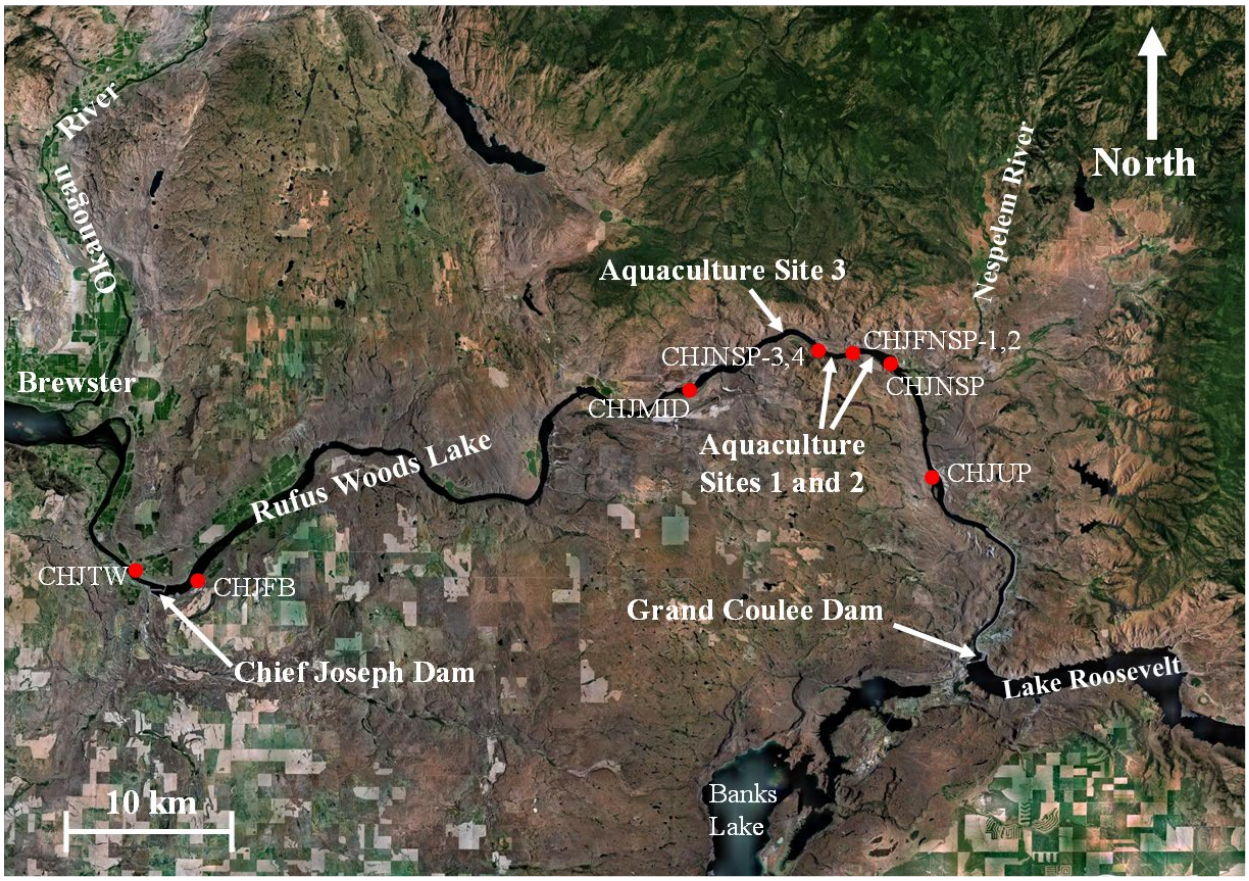


Figure 1-2. Locations of Water Quality Monitoring Stations in Rufus Woods Lake and the Columbia River



1.2 CLIMATE AND GEOLOGY

Rufus Woods Lake lies within the high-steppe, semiarid desert region of central Washington. The Columbia River in the study area forms the boundary between two distinct geologic provinces in the State of Washington, the Okanogan Highlands to the north and the Columbia Plateau to the south (Washington State Department of Natural Resources [DNR] 2004). The Okanogan Highlands are characterized by rounded mountains and narrow valleys and are dominated by metasedimentary rocks. The Columbia Plateau is characterized by incised rivers, extensive plateaus, and anticlinal ridges. The Plateau region is dominated by basalt flows laid down by successive volcanic eruptions during the Miocene (Washington State DNR 2004). Elevations range from about 236 meters at the Columbia River immediately downstream of Chief Joseph Dam to more than 1,000 meters in the mountainous terrain that rises up from the water in the mid- to upper reaches of the reservoir. Land use in the study area is dominated by rangeland, irrigated cropland, and orchards (Corps 2009).

The climate of the study area is influenced by easterly moving weather systems from the Pacific Ocean. Winters are generally cool with November through March being the wettest months. Summers are warm and dry with little to no precipitation falling from June through September. The mean annual precipitation in the vicinity of the dam is

about 25 centimeters. Total annual snowfall varies with elevation throughout the study area, with about 40 centimeters near the dam. The mean annual temperature at the dam is 10°C, with extremes recorded in the vicinity of the dam of -30°C and 43°C (Corps 2009).

1.3 LAND USE

The Columbia River watershed upstream of Chief Joseph Dam and Rufus Woods Lake encompasses about 195,000 square kilometers of northeastern Washington, northwestern Montana, northern Idaho, and southeastern British Columbia. Of that total upstream watershed, about 191,000 square kilometers is located upstream of Grand Coulee Dam, with the immediate Rufus Woods Lake watershed only totaling about 4,000 square kilometers. The Columbia River watershed is a sparsely populated mountainous area. Major population centers are concentrated near Missoula and Butte in Montana, near Sandpoint and Coeur d'Alene in Idaho, near Spokane in Washington, and near Cranbrook and Castlegar in British Columbia. For the immediate Rufus Woods Lake watershed, there are only a few small towns and communities such as Coulee Dam, Elmer City, and Nespelum, located in Washington State along the reservoir (Corps 2009).

The economy of the Columbia River watershed relies heavily on forest products, mining, hydropower, recreation (tourism), technology, retail trade, and agriculture. The principal industries in the immediate Rufus Woods Lake watershed are fruit, wheat, cattle ranching, forest products, aquaculture, and service industries. Fruit orchards are located on side slopes immediately adjacent to the reservoir. Cattle ranching and dry-land wheat farming are important industries in the arid areas inland from the reservoir (Corps 2009).

1.4 CONTAMINANT SOURCES

Historical and current point and non-point source discharges of contaminants that may impact water and sediments in the Columbia River and Rufus Woods Lake exist in the watershed. Mining has been active in the watershed in both the United States and Canada since the late 1880s. In general, zinc and lead were the main metals mined in the watershed along with copper, gold, silver, tin, tungsten, and molybdenum (Mills 1977, EPA 2008). Mining in the watershed has declined, and actions have been taken to reduce the loading of contaminants from historic and active mines, including treatment and recycling of waste rock and tailings pile runoff, and restoration of abandoned mines.

Two major sources of contamination to the water and sediments upstream of Rufus Wood Lake are the Teck-Cominco Smelter in Trail, British Columbia, about 15 kilometers upstream of the international border, and the Zellstoff Celgar Ltd. bleached kraft pulp mill located in Castlegar, British Columbia, about 50 kilometers upstream of the border (EPA 2008). The Teck-Cominco facility is a lead and zinc smelter that has been in operation since 1896 (G3 Consulting 2001). The smelter was originally a copper smelter but was converted to lead and zinc in 1909 and is today one of the world's

largest metallurgical complexes. Historically, the Teck-Cominco facility discharged large quantities of slag material (the byproduct of the smelting furnaces) containing various quantities of trace and major metals to the Columbia River, as well as discharging processed wastewater containing arsenic, cadmium, lead, mercury, and zinc directly to the river. The facility also operated an ammonia phosphate fertilizer plant that discharged about 2.2 metric tons per day of phosphate into the river. The operation of the phosphate plant was discontinued in 1994 while the routine discharge of slag and smelter waste water to the river was discontinued in mid-1995 (EPA 2008).

The Zellstoff pulp mill used chlorine in the bleaching process from 1961 until mid-1993. Chlorine reacts with compounds in the wood resulting in discharged effluent containing organic compounds, including dioxins and furans (U.S. Geological Survey [USGS] 1994). Starting in 1991, the plant modernized its facilities, including the installation of a chlorine dioxide bleach plant and secondary treatment facility. Consequently, the discharge of chlorinated organic chemicals such as dioxins to the Columbia River has been greatly reduced (EPA 2008).

Rainbow trout (Oncorhynchus mykiss) fish farming began in Rufus Woods Lake in 1989 with a small operation located along the south shore of the lake in Douglas County. Currently, there are four aquaculture facilities located in Rufus Woods Lake along the north shore on the Confederated Tribes of the Colville Reservation (Colville Tribes). Pacific Aquaculture owns three of these facilities. Two were upgraded in 2008, and one was recently built and became operational in 2016. Faith Frontier Ministries owns the fourth facility, which has been in operation since 1995. The four farms have a combined production of about 7 million kilograms of trout per year in (EPA 2012a). The potential effects of aquaculture on fresh water and sediment quality are largely related to waste produced by the facilities via fish feed and feces (Environment Canada 2009). In addition, contaminants such as antibiotics, pesticides, herbicides, fungicides, and heavy metals are also of concern to surrounding waters and sediments (Department of Fisheries and Oceans Canada [DFO] 2006; Environment Canada 2009).

Numerous communities in British Columbia, Montana, Idaho, and Washington continue to discharge secondary treated water to the Columbia River and major tributaries such as the Pend Oreille River and Kootenai(y) River. In addition to these larger point sources, there are numerous small community wastewater systems and individual septic systems in the immediate Rufus Woods Lake watershed.

1.5 AQUACULTURE FACILITIES

Rainbow trout fish farming began in Rufus Woods Lake in 1989 with a small operation located along the south shore of the lake in Douglas County. These farms were acquired by Columbia River Fish Farms and moved in 1991 and 1997 to the north shore on the Colville Confederated Tribes Indian Reservation downstream of Grand Coulee Dam near the confluence of the Nespelem with the Columbia River. These two aquaculture facilities were acquired by Pacific Seafood in the fall of 2008 and renamed Pacific Aquaculture Inc. Site 1 and Site 2 (EPA 2012a). The facilities were initially in a state of disarray but have been upgraded by Pacific Aquaculture and have a combined

harvest of about 3.63 million kilograms of trout per year (EPA 2012a). Pacific Seafood constructed a third site in 2016 named Pacific Aquaculture Inc. Site 3. A smaller aquaculture facility called Chief Joseph Fish Farm is owned by Faith Frontier Ministries and located approximately 16 kilometers downstream of the Pacific Aquaculture facilities. Chief Joseph Fish Farm has been in operation since 1995 and harvests about 0.77 million kilograms of trout per year (EPA 2012a).

The three Pacific Aquaculture fish farm locations are shown in Figure 1-2. Site 1 is the farthest downstream, located at River Kilometer 932.6, about 27.4 km downstream of Grand Coulee Dam. The net pens at Site 1 consists of 20 steel net pens, each 25 meters by 25 meters in size, arranged in an array approximately 275 meters long and 55 meters wide (EPA 2012a). The site also contains on-shore fish production/waste facilities. Site 2 is upstream of Site 1 and is located at River Kilometer 936.3, about 23.7 kilometers downstream of Grand Coulee Dam. The net pens at Site 2 consists of 20 steel net pens, each 25 meters by 25 meters in size, arranged in an array approximately 275 meters long and 55 meters wide (EPA 2012a). Annual production was reported by the EPA (2012a) to be 2.27 million kilograms at Site 1, and 1.36 million kilograms at Site 2. Site 3 is located about 1.5 kilometers downstream of Site 1 and consists of 20 steel net pens, each 30 meters by 30 meters in size and arranged in an array approximately 335 meters long by 67 meters wide. Annual production estimated at Site 3 is 2.72 million kilograms (EPA 2012a).

In recent years, the environmental impacts of aquaculture on marine and freshwater ecosystems has received increasing attention (DFO 2006; Black 2008; Environment Canada 2009; Zivic et al. 2009). Waste produced by fish farms that can impact water and sediment quality includes nutrients, feces, feed pellets, and organic matter (Environment Canada 2009). In addition, contaminants such as antibiotics, pesticides, herbicides, fungicides, and heavy metals are also of concern to surrounding waters and sediments (DFO 2006; Environment Canada 2009). The influx of aquaculture waste products and contaminants into the surrounding waters and sediments has resulted in an overall concern regarding the environmental impact of aquaculture on water and sediment quality.

Phosphorus, nitrogen, carbon, copper, and zinc are the primary constituents of concern released to surface waters and sediments from aquaculture (Beveridge 2004; Podemski and Blanchfield 2006; Dean, Shimmield, and Black 2007; Mugg et al. 2007). The primary sources of many of these constituents are fecal material and uneaten feed. However, the primary source of copper to the surrounding waters and sediment is generally not feed (Dean, Shimmield, and Black 2007) and may be from anti-fouling agents if the aquaculture facility uses them on their net pens (Mugg et al. 2007). Dissolved carbon, phosphorus, nitrogen, and zinc may be released directly to the water column by the solubilization from feed and feces, and through gill and urinary excretion (Beveridge 2004; Mugg et al. 2007; Azevedo et al. 2011). Uneaten feed and fecal material are usually in the form of solid wastes that settle to the bottom. The greatest accumulation of wastes and corresponding sediment impact is generally either directly under the cages or immediately downstream near the cages (Cornel and Whoriskey 1993; Troell and Berg 1997). Settling velocities of fish feed and feces along with current

speed and water depth are important factors in determining how far downstream waste solids may be re-suspended and transported before they are deposited in the sediments (Black 2008). Sediments beneath freshwater aquaculture cages have shown enrichment in phosphorus, nitrogen, carbon, copper, and zinc (Troell and Berg 1997; Rooney and Podemski 2010).

1.6 PREVIOUS INVESTIGATIONS 1980s TO 2000s

The Washington State Department of Ecology (Ecology) maintains a long-term water quality monitoring station in the middle Columbia River immediately downstream of Grand Coulee Dam at the upstream boundary of Rufus Woods Lake. Parameters monitored at this station since about the 1980s include conventionals (temperature, oxygen, conductivity, pH, and turbidity) and nutrients (total phosphorus, orthophosphate, total nitrogen, nitrate nitrogen, and ammonia nitrogen). Additionally, chlorophyll a was added to this parameter list in 2009.

Richards, Rensel, and Siegrist (2011) summarized Ecology data collected at this station from the mid-1990s through 2009. The authors noted that up until the 1990s, biological productivity in the middle Columbia River was high due to the discharge of nutrients (ammonia and phosphorus) to the river from the Cominco Fertilizer Plant in Trail British Columbia. However, the closure of the fertilizer plant in 1994 resulted in a substantial decrease in phosphorus concentrations in the middle Columbia River (MacDonald Environmental Sciences Ltd. 1997). For example, the total phosphorus concentration at the Ecology middle Columbia River monitoring station was reduced from a mean concentration of 30.2 micrograms per liter (µg/L) from 1982 through 1988, to a mean concentration of 5.6 µg/L from 2000 through 2009 (Richards, Rensel, and Siegrist 2011). Concentrations of ammonia nitrogen in the middle Columbia River have decreased since the closure of the fertilizer plant while concentrations of nitrate nitrogen have remained stable. Consequently, total nitrogen to total phosphorus ratios increased from a mean growing season (April to October) value of 12-16:1 from 1976 to 1990, to about 29.8:1 from 2000 to 2009.

Water quality studies on the upper Columbia River immediately upstream of Rufus Woods Lake were conducted in Lake Roosevelt, the reservoir formed by Grand Coulee Dam, in 2000 and 2004 (Bonneville Power Administration [Bonneville] 2003, Bonneville 2006). In general, water quality in Lake Roosevelt was good with nutrient, transparency, and chlorophyll a concentrations in the oligotrophic to meso–oligotrophic range. Nutrient concentrations were generally low to moderate with a mean annual total phosphorus concentration of 16 µg/L in 2000 and 11 µg/L in 2004. Mean annual total nitrogen to total phosphorus ratios were large (range from 28:1 to 31:1), indicating phosphorus limitation in Lake Roosevelt. Lakewide chlorophyll a concentrations were low, ranging from a mean annual concentration of 1.1 µg/L in 2000 to 0.8 µg/L in 2004.

Water quality studies on the middle Columbia River immediately downstream of Rufus Woods Lake were conducted in Lake Pateros, the first reservoir downstream from Chief Joseph Dam formed by Wells Dam (EES Consulting 2006), and in Lake Entiat, the second reservoir downstream from Chief Joseph Dam formed by Rocky Reach Dam

(Parametrix 2001). For Lake Pateros, studies from 2005 to 2006 showed that the water quality was good with moderate water transparency, moderate chlorophyll a concentrations, and moderate total phosphorus concentrations. The trophic state of the reservoir was calculated to be mesotrophic showing moderate productivity. Total phosphorus concentrations ranged from below the detection limit of 2 to 30.8 µg/L. The annual mean total nitrogen to total phosphorus ratio was 14.8:1, just within the range of phosphorus limitation, suggesting slightly elevated total phosphorus concentrations. Phytoplankton samples were dominated by diatoms (EES Consulting 2006).

Water quality studies in Lake Entiat during 2000 showed that the water quality was generally good with high water transparency, high dissolved oxygen, moderate total phosphorus concentrations, and low to moderate chlorophyll a concentrations. The trophic state of the reservoir was calculated to be in the lower mesotrophic range showing moderate productivity. The summer average (June through September) total phosphorus concentrations (18.7 µg/L) was moderate while concentrations of dissolved inorganic nitrogen (ammonia, nitrate, and nitrite) ranged from about 50 µg/L to more than 200 µg/L. Total nitrogen to total phosphorus ratios were high, suggesting that phosphorus is scarce relative to nitrogen in Lake Entiat. Phytoplankton samples were dominated by diatoms with a prolonged spring phytoplankton bloom (Parametrix 2001).

1.7 CURRENT INVESTIGATION 2011 TO 2013

The Corps implemented an annual water quality monitoring program in 2011 to better establish the current state of the physical, chemical, and biological condition of Rufus Woods Lake and the Columbia River immediately downstream of Chief Joseph Dam (Corps 2011, Corps 2012, Corps 2013). Water quality data presented in this summary was derived from the Corps program from 2011 to 2013. The program consisted of eight permanent in-lake stations and one permanent downstream river station distributed throughout the reservoir (Figure 1-2). The in-lake stations consisted of two sites downstream of Grand Coulee Dam and upstream of the aquaculture facilities (CHJUP and CHJNSP), four sites immediately downstream of the aquaculture facilities (CHJNSP-1, CHJNSP-2, CHJNSP-3, and CHJNSP-4), one mid-reservoir site (CHJMID), and one site in the forebay of Chief Joseph Dam (CHJFB). In addition, a tailwater station (CHJTW) was located on the Columbia River and collected from the right bank about 2 kilometers downstream of Chief Joseph Dam. Water quality sampling station locations and details are summarized in Table 1-1, with general sampling locations shown in Figure 1-2. Water quality parameters of concern, analytical methods, detection limits, and sampling details are presented in Table 1-2.

Table 1-1. Water Quality Sampling Locations in Rufus Woods Lake from 2011 to 2013

Station Name	Station Location	Water Body	Latitude (NAD 83)	Longitude (NAD 83)
CHJUP	Downstream Buckley Bar	Rufus Woods Lake	48.071363	-119.018852
CHJNSP	Mouth Nespelem River	Rufus Woods Lake	48.131070	-119.046255
CHJNSP-1	30 m Downstream Aquaculture Site 2	Rufus Woods Lake	48.138527	-119.056363
CHJNSP-2	300 m Downstream Aquaculture Site 2	Rufus Woods Lake	48.139435	-119.059655
CHJNSP-3	30 m Downstream Aquaculture Site 1	Rufus Woods Lake	48.138411	-119.099771
CHJNSP-4	300 m Downstream Aquaculture Site 1	Rufus Woods Lake	48.139099	-119.102786
CHJMID	Mid Reservoir Location	Rufus Woods Lake	48.118595	-119.206056
CHJFB	Forebay	Rufus Woods Lake	47.997937	-119.620480
CHJTW	Tailwater	Rufus Woods Lake	48.004824	-119.658614

Table 1-2. Methods and Detection Limits for Water Quality Analyses

Type	Parameters	Method Number1/	Detection Limit/Unit	Container and Preservative	Holding Time	Analysis Key3/
Field	Temperature	Hydrolab	0.01°C	—	—	A
Field	pH	Hydrolab	0.01	—	—	A
Field	Conductivity	Hydrolab	0.1 mS/cm	—	—	A
Field	Dissolved oxygen	Hydrolab	0.01 mg/L	—	—	A
Chemical	Total phosphorus	SM18 4500PF	0.002 mg/L	P/G, 4° C, H2SO4 to pH<2	28 days	A
Chemical	Soluble phosphorus	SM18 4500PF	0.001 mg/L	P/G, 4°°C, filter immediately	48 hours	A
Chemical	Total nitrogen	SM20 4500NC	0.050 mg/L	P/G, 4°°C, H2SO4 to pH<2	28 days	A
Chemical	Nitrate+Nitrite -N	SM18 4500NO3F	0.010 mg/L	P/G, 4° C, H2SO4 to pH<2	28 days	A
Chemical	Ammonia - N	SM18 4500NH3H	0.005 mg/L	P/G, 4° C, H2SO4 to pH<2	28 days	A
Chemical	Alkalinity	SM18 2320B	1.00 mg/L	P/G, 4° C	14 days	A
Chemical	Hardness	SM18 2340B	1.00 mg/L	P/G, 4° C, HNO3 to pH<2	6 months	A
Chemical	Total organic carbon	EPA 415.1	0.25 mg/L	G, 4° C	28 days	A
Chemical	Total copper	EPA 200.8	0.0010 mg/L	P/G, 4° C2/	6 months	A
Chemical	Total zinc	EPA 200.7	0.005 mg/L	P/G, 4° C2/	6 months	A
Chemical	Calcium	EPA 200.7	0.100 mg/L	P/G, 4° C, HNO3 to pH<2	6 months	B
Chemical	Magnesium	EPA 200.7	0.100 mg/L	P/G, 4° C, HNO3 to pH<2	6 months	B
Chemical	Potassium	EPA 200.7	0.700 mg/L	P/G, 4° C, HNO3 to pH<2	6 months	B
Chemical	Sodium	EPA 200.7	0.500 mg/L	P/G, 4° C, HNO3 to pH<2	6 months	B
Chemical	Sulfate	SM18 4500SO4E	1.00 mg/L	P/G, 4° C	28 days	B
Chemical	Chloride	SM18 4500CLC	0.50 mg/L	P/G, 4° C	28 days	B
Chemical	Total aluminum	EPA 200.8	0.003 mg/L	P/G, 4° C2/	6 months	B
Chemical	Total arsenic	EPA 200.8	0.003 mg/L	P/G, 4° C2/	6 months	B
Chemical	Total cadmium	EPA 200.8	0.0002 mg/L	P/G, 4° C2/	6 months	B
Chemical	Total chromium	EPA 200.8	0.0020 mg/L	P/G, 4° C2/	6 months	B
Chemical	Total lead	EPA 200.8	0.0010 mg/L	P/G, 4° C2/	6 months	B
Chemical	Fats, oils, grease	EPA 1664	2.0 mg/L	G	6 months	C
Biological	Chlorophyll a	SM18 10200H	0.0001 mg/L	P, 4°C, filter, add MgCO3	28 days	D
Biological	Phytoplankton	–	–	P/G, 4°C, 1% Lugols or 3% Formaldehyde	12 months	D
Biological	Zooplankton	–	–	G, 4°C, 25% Isopropyl or 5% Formaldehyde	12 months	D
Biological	Anatoxin-a	KCEL SOP466	0.0185-0.02 µg/L	P/G, 4°C, 24 hours filter	28 days	E
Biological	Microcystin	KCEL SOP469	0.05-0.16 µg/L	P/G, 4°C	48 hours	E

Note: µS/cm = microsiemens per centimeter; mg/L = milligrams per liter.
1/ SM method numbers are from Greenberg, Eaton, and Clesceri (2000); EPA method numbers are from EPA (1983, 1984, and 1992), KCEL method numbers from Oehrle, Southwell, and Westrick 2010 and Mekebri, Blondina, and Crane 2009.
2/ Samples for analysis of total trace metals were preserved within 24 hours with HNO3 to pH<2.
3/ A = Stations CHJUP; CHJNSP; CHJNSP1,2,3,4; CHJMID; CHJFB; CHJTW for all months
B = Stations CHJUP; CHJMID; CHJFB for May, July, October
C = Stations CHJUP; CHJNSP; CHJNSP1,2,3,4; CHJMID; CHJFB as needed
D = Stations CHJUP, CHJNSP, CHJNSP1,2,3,4; CHJMID; CHJFB for all months
E = Stations shown in Tables 2-3 and 2-4

Phytoplankton samples intended for abundance, biovolume and composition data were collected from the photic zone at all water quality stations except CHJTW (Table 1-2). Zooplankton samples were collected by vertical tow from a depth of 10 meters to the surface using a 64-micrometer mesh net at all water quality stations except CHJTW (see Table 1-2). For harmful algae bloom sampling, sites were located throughout Rufus Woods Lake as well as upstream of Grand Coulee Dam in Lake Roosevelt and Banks Lake (Figure 1-3). Rufus Woods Lake sites were representative of locations where floating clumps of algae were most often observed, as well as public access locations where any harmful algae blooms would pose the greatest public risk. Priority was given to collecting floating mat samples located near boat ramps, docks, swimming beaches, and parks. Sampling sites upstream of Grand Coulee Dam were chosen to be representative of public access locations in the forebay of Lake Roosevelt and in Banks Lake. Harmful algae bloom site location details are shown in Table 1-3 to Table 1-5. Periphyton samples were collected in 2011 at 10 stations in Rufus Woods Lake (Table 1-6 and Figure 1-4).

Figure 1-3. Locations of Harmful Algae Bloom Monitoring Stations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake for 2011 to 2013

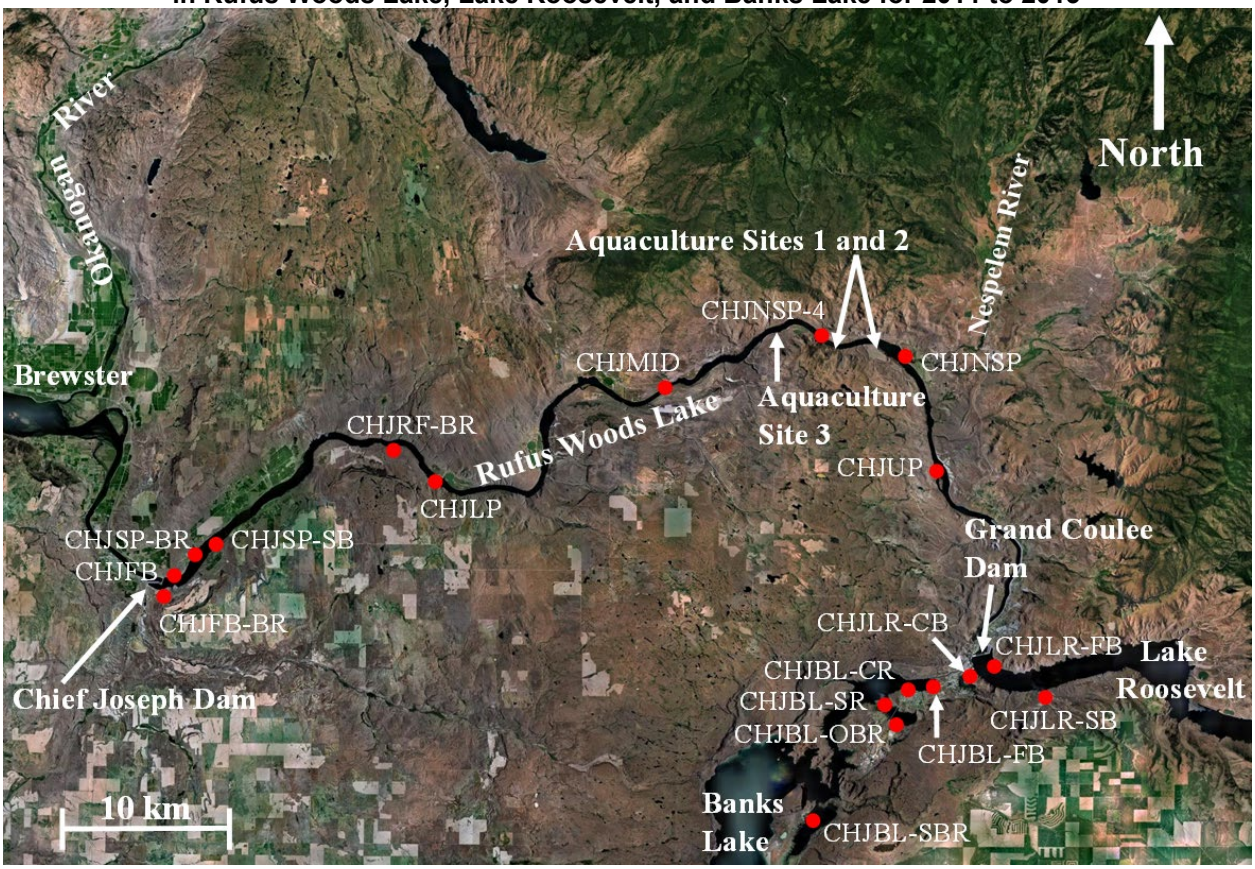


Figure 1-4. Locations of Periphyton Monitoring Stations in Rufus Woods Lake in 2011

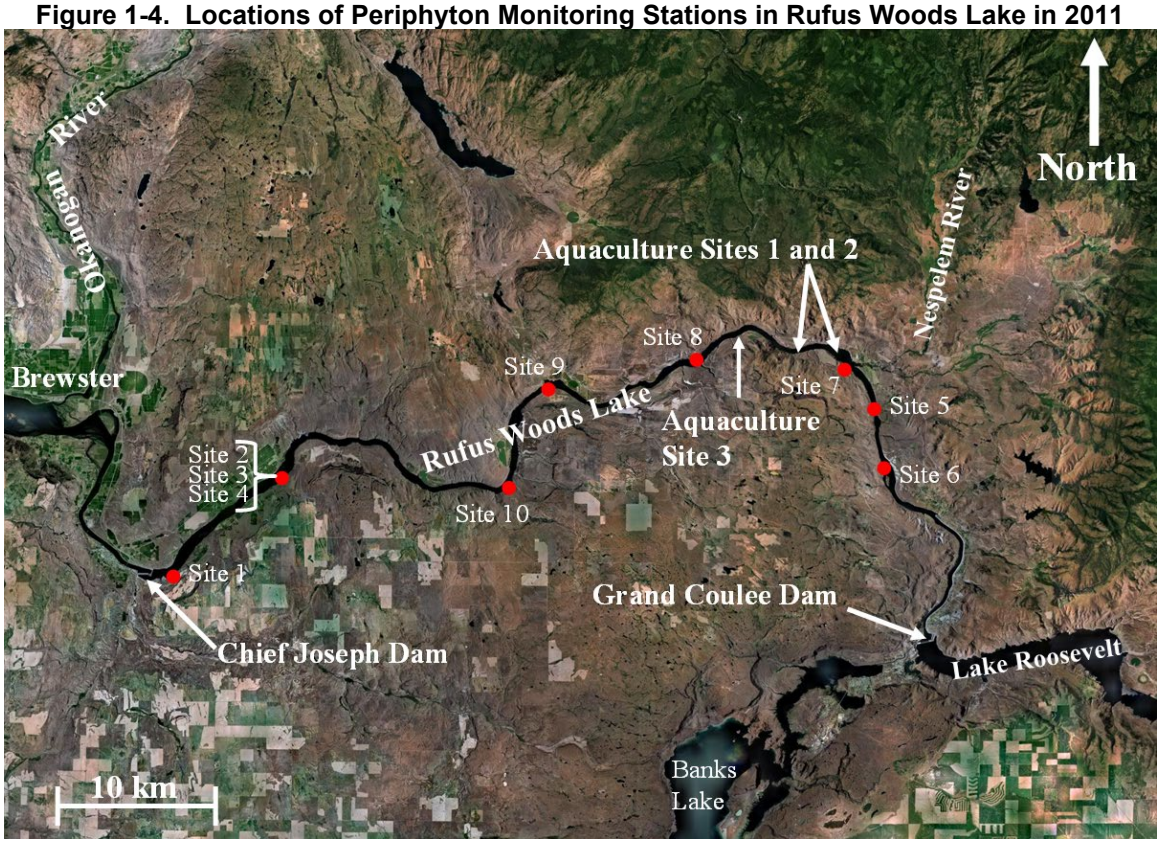


Table 1-3. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake 2011

Station Name	Station Location	Water Body	Latitude (NAD 83)	Longitude (NAD 83)	Sample Type
CHJFB	Forebay	Rufus Woods Lake	47.997937	-119.620480	1,2,3
CHJFB-BR	Forebay Boat Ramp	Rufus Woods Lake	47.992970	-119.621643	1,2,3
CHJLP	Lone Pine Island	Rufus Woods Lake	48.054002	-119.410701	2,3
CHJMID	Mid Reservoir Location	Rufus Woods Lake	48.118595	-119.206056	1,2,3
CHJNSP	Mouth Nespelem River	Rufus Woods Lake	48.131070	-119.046255	1,2,3
CHJNSP-4	Downstream Fish Farms	Rufus Woods Lake	48.139099	-119.102786	2,3
CHJRF-BR	Rocky Flats Boat Ramp	Rufus Woods Lake	48.066419	-119.430295	2,3
CHJSP-BR	State Park Boat Ramp	Rufus Woods Lake	48.014164	-119.607164	1,2,3
CHJSP-SB	State Park Swim Beach	Rufus Woods Lake	48.015525	-119.605246	2,3
CHJUP	Downstream Buckley Bar	Rufus Woods Lake	48.071363	-119.018852	1,2,3
CHJLR-FB	Roosevelt Forebay	Lake Roosevelt	47.947869	-118.986992	1
CHJLR-SC	Roosevelt Spring Canyon	Lake Roosevelt	47.935760	-118.934830	1
CHJBL-FB	Banks Lake Forebay	Banks Lake	47.938688	-119.018031	1
CHJBL-OBR	Osborne Boat Ramp	Banks Lake	47.923609	-119.060445	1

Sample Type 1: Phytoplankton ID, Biovolume, Density
Sample Type 2: Phytoplankton ID, Presence/Absence
Sample Type 3: Toxin Analysis

Table 1-4. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake, Lake Roosevelt, and Banks Lake 2012

Station Name	Station Location	Water Body	Latitude (NAD 83)	Longitude (NAD 83)	Sample Type
CHJFB	Forebay	Rufus Woods Lake	47.997937	-119.620480	1,2,3
CHJFB-BR	Forebay Boat Ramp	Rufus Woods Lake	47.992970	-119.621643	1,2,3
CHJLP	Lone Pine Island	Rufus Woods Lake	48.054002	-119.410701	2,3
CHJMID	Mid Reservoir Location	Rufus Woods Lake	48.118595	-119.206056	1,2,3
CHJNSP	Mouth Nespelem River	Rufus Woods Lake	48.131070	-119.046255	1,2,3
CHJNSP-4	Downstream Fish Farms	Rufus Woods Lake	48.139099	-119.102786	2,3
CHJRF-BR	Rocky Flats Boat Ramp	Rufus Woods Lake	48.066419	-119.430295	1,2,3
CHJSP-BR	State Park Boat Ramp	Rufus Woods Lake	48.014164	-119.607164	2,3
CHJSP-SB	State Park Swim Beach	Rufus Woods Lake	48.015525	-119.605246	1,2,3
CHJUP	Downstream Buckley Bar	Rufus Woods Lake	48.071363	-119.018852	1,2,3
CHJLR-CB	Roosevelt Crescent Bay	Lake Roosevelt	47.944041	-118.991357	1
CHJBL-CR	Coulee Resort	Banks Lake	47.934995	-119.029551	1
CHJBL-SR	Sun Resort	Banks Lake	47.927043	-119.057045	1
CHJBL-OBR	Osborne Boat Ramp	Banks Lake	47.923609	-119.060445	1
CHJBL-SBR	Steamboat Rock Boat Ramp	Banks Lake	47.863114	-119.117903	1

Sample Type 1: Phytoplankton ID, Biovolume, Density
Sample Type 2: Phytoplankton ID, Presence/Absence
Sample Type 3: Toxin Analysis

Table 1-5. Harmful Algae Bloom Sampling Locations in Rufus Woods Lake 2013

Station Name	Station Location	Water Body	Latitude (NAD 83)	Longitude (NAD 83)	Sample Type
CHJFB	Forebay	Rufus Woods Lake	47.997937	-119.620480	2,3
CHJFB-BR	Forebay Boat Ramp	Rufus Woods Lake	47.992970	-119.621643	2,3
CHJLP	Lone Pine Island	Rufus Woods Lake	48.054002	-119.410701	2,3
CHJMID	Mid Reservoir Location	Rufus Woods Lake	48.118595	-119.206056	2,3
CHJNSP	Mouth Nespelem River	Rufus Woods Lake	48.131070	-119.046255	2,3
CHJNSP-4	Downstream Fish Farms	Rufus Woods Lake	48.139099	-119.102786	2,3
CHJRF-BR	Rocky Flats Boat Ramp	Rufus Woods Lake	48.066419	-119.430295	2,3
CHJSP-BR	State Park Boat Ramp	Rufus Woods Lake	48.014164	-119.607164	1,2,3
CHJSP-SB	State Park Swim Beach	Rufus Woods Lake	48.015525	-119.605246	2,3
CHJUP	Downstream Buckley Bar	Rufus Woods Lake	48.071363	-119.018852	2,3

Sample Type 1: Phytoplankton ID, Biovolume, Density
Sample Type 2: Phytoplankton ID, Presence/Absence
Sample Type 3: Toxin Analysis

Table 1-6. Periphyton Sampling Locations in Rufus Woods Lake 2011

Periphyton Stations	Collection Date	Latitude	Longitude
Site 1	07-11-2011	47.995129°	-119.627259°
Site 2	07-11-2011	48.066496°	-119.430224°
Site 3	07-11-2011	48.066496°	-119.430224°
Site 4	07-11-2011	48.066496°	-119.430224°
Site 5	07-11-2011	48.093495°	-119.020256°
Site 6	07-11-2011	48.060505°	-119.015819°
Site 7	07-11-2011	48.128754°	-119.042744°
Site 8	07-11-2011	48.129105°	-119.177104°
Site 9	07-11-2011	48.115351°	-119.299882°
Site 10	07-11-2011	48.048128°	-119.339209°

1.8 WATER QUALITY CRITERIA

Ecology and the Colville Tribes determine water quality criteria for the Columbia River at Chief Joseph Dam in Washington. The Colville Tribes have classified the Columbia River as a Class I water body above Chief Joseph Dam and a Class II water body below the dam. Ecology has classified the Columbia River above and below Chief Joseph Dam as a salmonid spawning, rearing, and migration aquatic life use. General water quality standards for both the Colville Tribes and Ecology are presented in Table 1-7. At Chief Joseph Dam, the State of Washington and the Colville Tribe have a similar TDG standard of 110 percent. However, Washington allows exceedance of the 110 percent TDG criteria to facilitate fish passage spills as shown in Table 1-7. Chief Joseph Dam was granted a water quality criteria rule adjustment by Ecology for the 2011 to 2013 spill seasons for the purpose of managing system spill for improved fish conditions.

Table 1-7. Washington State Department of Ecology and Confederated Tribes of the Colville Reservation General Water Quality Standards

Parameter	Regulator	Standard
Total Dissolved Gas	Ecology	Salmonid spawning/rearing: Shall not exceed 110 percent TDG at any point of sample collection, except during spill season for fish passage in which TDG shall be measured as follows: (1) Must not exceed an average of 115 percent as measured in the forebay of the next downstream dam. (2) Must not exceed an average of 120 percent as measured in the tailrace of each dam; TDG is measured as an average of the 12 highest consecutive hourly readings in any one day, relative to atmospheric pressure. (3) A maximum TDG one-hour average of 125 percent as measured in the tailrace must not be exceeded during spillage for fish passage.
Total Dissolved Gas	Colville Tribes	Class I and II: Shall not exceed 110 percent TDG at any point of sample collection.
pH	Ecology	Salmonid spawning/rearing: pH shall be within the range of 6.5 to 8.5 with a human-caused variation within the above range of less than 0.5 units.
pH	Colville Tribes	Class I and II: Shall be within the range of 6.5 to 8.5 with a human-caused variation within a range of less than 0.5 units.
Dissolved Oxygen	Ecology	Salmonid spawning/rearing: Lowest 1-day minimum of 8.0 mg/L.
Dissolved Oxygen	Colville Tribes	Class I: Shall exceed 9.5 mg/L. Class II: Shall exceed 8.0 mg/L.
Temperature	Ecology	Salmonid spawning/rearing: Shall not exceed 17.5°C as measured by 7-day average of the daily maximum temperatures (7-DADMax) due to human activities. When natural conditions exceed 7-DADMax of 17.5°C, no temperature increase will be allowed which that will raise the receiving water 7-DADMax temperature by greater than 0.3°C.

Parameter	Regulator	Standard
Temperature	Colville Tribes	Class I: Shall not exceed 16.0°C due to human activities. When natural conditions exceed 16.0°C, no temperature increase will be allowed which that will raise the receiving water by greater than 0.3°C. Class II: Shall not exceed 18.0°C due to human activities. When natural conditions exceed 18.0°C, no temperature increase will be allowed which will raise the receiving water by greater than 0.3°C.

Criterion maximum concentrations (acute 1-hour average) and criterion chronic concentrations (chronic 4-day average) for metals sampled at Chief Joseph Dam are presented in Table 1-8. Total ammonia concentrations shown in Table 1-8 are based on the combined ionized (NH4+-N - ammonium) and unionized (NH3-N – ammonia) forms. However, only the unionized form of ammonia (NH3-N) is toxic to freshwater life. Equations can be used to estimate the concentration of unionized ammonia fraction from measured values of the pH and temperature of the water. In general, the unionized form of ammonia (NH3) represents an extremely small percentage of the total ammonia nitrogen concentration (Greenberg, Eaton, and Clesceri 1992).

Table 1-8. Washington State Department of Ecology and Colville Tribes Metals and Ammonia Water Quality Standards

Class	Parameters	Ecology Acute Water Quality Criteria[1] (µg/L)	Ecology Chronic Water Quality Criteria[1] (µg/L)	Colville Tribe Acute Water Quality Criteria[2] (µg/L)	Colville Tribe Chronic Water Quality Criteria[2] (µg/L)
Nutrients	Ammonia[3]	8100	2500	6700	1200
Dissolved Metals	Aluminum[4]	—	—	—	—
Dissolved Metals	Arsenic	360	190	360	190
Dissolved Metals	Cadmium	2.12*	0.71*	1.2*	0.172*
Dissolved Metals	Chromium	361.14*	117.14*	375*	48.8*
Dissolved Metals	Copper	10.52*	7.33*	8.3*	5.8*
Dissolved Metals	Lead	36.87*	1.43*	36.9*	1.4*
Dissolved Metals	Zinc	74.23*	67.79*	76*	76.6*
Total Metals	Aluminum[4]	750	87	750	87
Total Metals	Arsenic	360	190	360	190
Total Metals	Cadmium	2.2*	0.76*	1.27*	0.185*
Total Metals	Chromium	1142.84*	136.22*	1186.63*	56.72*
Total Metals	Copper	10.95*	7.64*	8.65*	6.03*
Total Metals	Lead	42.61*	1.66*	42.61*	1.66*
Total Metals	Zinc	75.91*	68.76*	77.72*	77.72*

Notes: 1. Source: Ecology (2011)
2. Source: EPA (2015)
3. Total ammonia concentration. Based on pH value of 7.8 and temperature of 18C.
4. EPA (1989)
* Hardness dependant. Value based on an average hardness in Rufus Woods Lake of 60 mg/L as $CaCO^3$.
— Not Available

1.9 EXISTING 303(D) AND TOTAL MAXIMUM DAILY LOADS

Rufus Woods Lake was identified by Ecology as water quality impaired and not fully supporting aquatic life in the Ecology 2016 Integrated Report (Ecology 2018). Consequently, Rufus Woods Lake was included in the 2016 Ecology Clean Water Act 303(d) list Category 5 for flow dissolved oxygen and temperature. The 303(d) list Category 5 is defined by the U.S. Environmental Protection Agency (EPA) as waters with one or more beneficial uses being impaired or threatened. A total maximum daily load (TMDL) is required to address the impairment or threat. For Rufus Woods Lake, a

TMDL is needed for dissolved oxygen and temperature. Rufus Woods Lake currently has an EPA-approved TMDL for total dissolved gas (TDG).

Rufus Woods Lake is located immediately downstream of Grand Coulee Dam and Lake Roosevelt, and nearly all the inflow to Rufus Woods Lake comes from Lake Roosevelt. As such, water or sediment quality impairments upstream of Grand Coulee Dam are of concern to Rufus Woods Lake. Lake Roosevelt and the Columbia River upstream of Grand Coulee Dam have been identified by Ecology as water and sediment quality impaired and not fully supporting aquatic life in the Ecology 2016 Integrated Report (Ecology 2018). This assessment listed Lake Roosevelt at Grand Coulee Dam as a Class II waterbody of concern due to sediment metal concentrations. Sediment contamination in Lake Roosevelt is of concern because Rufus Woods Lake is located immediately downstream, and transport of contaminated sediments from Lake Roosevelt may be impacting sediment quality in Rufus Woods Lake.

1.10 WASHINGTON DEPARTMENT OF HEALTH TOXIC CYANOBACTERIA GUIDANCE

The Washington State Department of Health (DOH) has developed recreational guidance for the toxins microcystins and anatoxin-a that are produced by certain genera of cyanobacteria (also known as blue-green algae). The DOH developed a three-tiered approach to manage lakes with cyanobacteria blooms, with special provisions for microcystin concentrations greater than 6 µg/L and/or anatoxin-a concentrations greater than 1 µg/L. A water body with a visible cyanobacteria bloom or scum is classified as Tier I, and samples should be collected and sent to a lab for microcystin and anatoxin-a analysis. If microcystin concentrations are greater than 6 µg/L and/or anatoxin-a concentrations are greater than 1 µg/L, the water body is classified as Tier II and a warning sign should be posted. If the water body has a history of toxic cyanobacteria blooms, if pet illnesses/death or human symptoms are reported, or if concentrations are high, the water body is classified as Tier III and a danger-closed sign is posted (DOH 2008).

1.11 DATA ANALYSIS

Data analysis in this study consisted of (1) comparing water quality parameters measured at all stations in Rufus Woods Lake from 2011 to 2013, (2) comparing water quality parameters measured at stations located upstream and downstream of aquaculture facilities to determine if longitudinal variations in water quality exist in Rufus Woods Lake, and (3) determining what, if any, relationships exist between water quality parameters and phytoplankton data. For this study, any data below the laboratory reporting limits was used in statistical tests and estimated at one-half the reporting limit. Water quality parameters used for these statistical analyses focused on nutrients and included total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate+nitrite-nitrogen, ammonia-nitrogen, chlorophyll a, and total organic carbon. Phytoplankton data used for these analyses focused on total phytoplankton density, total phytoplankton biovolume, and phytoplankton composition.

Boxplots were used to summarize water quality data measured at each station during the study. Boxplots display essential characteristics of a data set and are useful when comparing copious amounts of data between multiple datasets. Boxplots provide a visual summary of the center of the data (the median shown as a small box inside the larger box), the spread of the data (the interquartile range or larger box height representing 25 percent to 75 percent of the data), the skewness of the data (where the median box falls in relation to the larger box), and the range of outlier values (the whisker lines emanating from the box representing 10 to 90 percent of the data set).

A non-parametric Mann-Whitney test for independent samples was used at a significance level of $p < 0.05$ to evaluate whether significant differences in specific water quality parameters existed between sampling locations upstream and downstream of aquaculture facilities. The Mann-Whitney test is used to compare two independent groups of data that are not normally distributed to determine if one group tends to contain larger values than the other. Because water quality data is generally not normally distributed, the Mann-Whitney test has less problems when comparing two groups of data than the parametric t-test (Helsel and Hirsch 2002). To create a more robust dataset to compare, summer data (June to October) for the upstream and downstream stations from 2011, 2012, and 2013 was combined, and a significance level of $p < 0.05$ was used evaluate whether significant differences in a specific parameter existed.

Relationships between water quality parameters and phytoplankton data were conducted using the Kendall rank correlation analysis (Kendall's tau) (Helsel and Hirsch 2002). Kendall's tau is a non-parametric test used to identify relationships between variables. Tau measures the strength of all monotonic correlations including linear, non-linear, exponential, and power function relationships. A statistical significance level of $p < 0.05$ was used to identify relationships between two variables. To create a more robust data set to compare, summer data (June to October) from 2011, 2012, and 2013 was combined for all statistical tests.

SECTION 2 - WATER QUALITY

2.1 HYDROLOGICAL CHARACTERIZATION

2.1.1 Flow and Retention Time

Hydrographs of average daily discharge for the Columbia River at Bridgeport, Washington, for the monitoring periods 2011 to 2013 and for the historical period from 1975 to 2010 are presented in Figure 2-1. Columbia River flow volumes were high in 2011 and 2012 with peak May through July flows well above the 90th percentile of historical flows. Flows in 2013 were moderate and closer to the historical average than 2011 or 2012. Peak flows during 2011 were about 275,000 cfs in early June while peak flows in 2012 were slightly greater at about 280,000 cfs in early July. High flows during 2013 were about 200,000 cfs, with this maximum coming in late June. During all three years, flows were low during the September through November time period, generally in the 10th to 25th percentile of historical flow range.

Retention time, which is the inverse of the flushing rate, refers to the length of time water remains in a water body. Lake volume, inflow, and outflow are important factors in determining the overall retention time in a water body. One can calculate the retention time either by dividing the lake volume by the inflow (filling time) or by the outflow (residence time). In general, high flushing rates allow for the rapid exchange of chemical constituents through the lake. Longer retention times allow for the accumulation and transformations of chemical constituents in sediments and lake water, and their cycling through the ecosystem. Chief Joseph Dam is a run-of-river dam with little storage capacity, and a theoretical water retention time in Rufus Woods Lake is about 3 days. Average retention times in Rufus Woods Lake for 2011, 2012, and 2013 are presented in Figure 2-2. The flushing rate in Rufus Woods Lake is rapid, with retention times ranging from about 1 to 8 days depending on the time of year. Retention times are greatest during the lower flow late summer through winter time period and lowest during the higher flow spring and early summer time frame.

Figure 2-1. Comparison of the Historic Daily Flow for the Columbia River at Chief Joseph Dam from 1975 to 2010 with the Average Daily Flows for 2011, 2012, and 2013

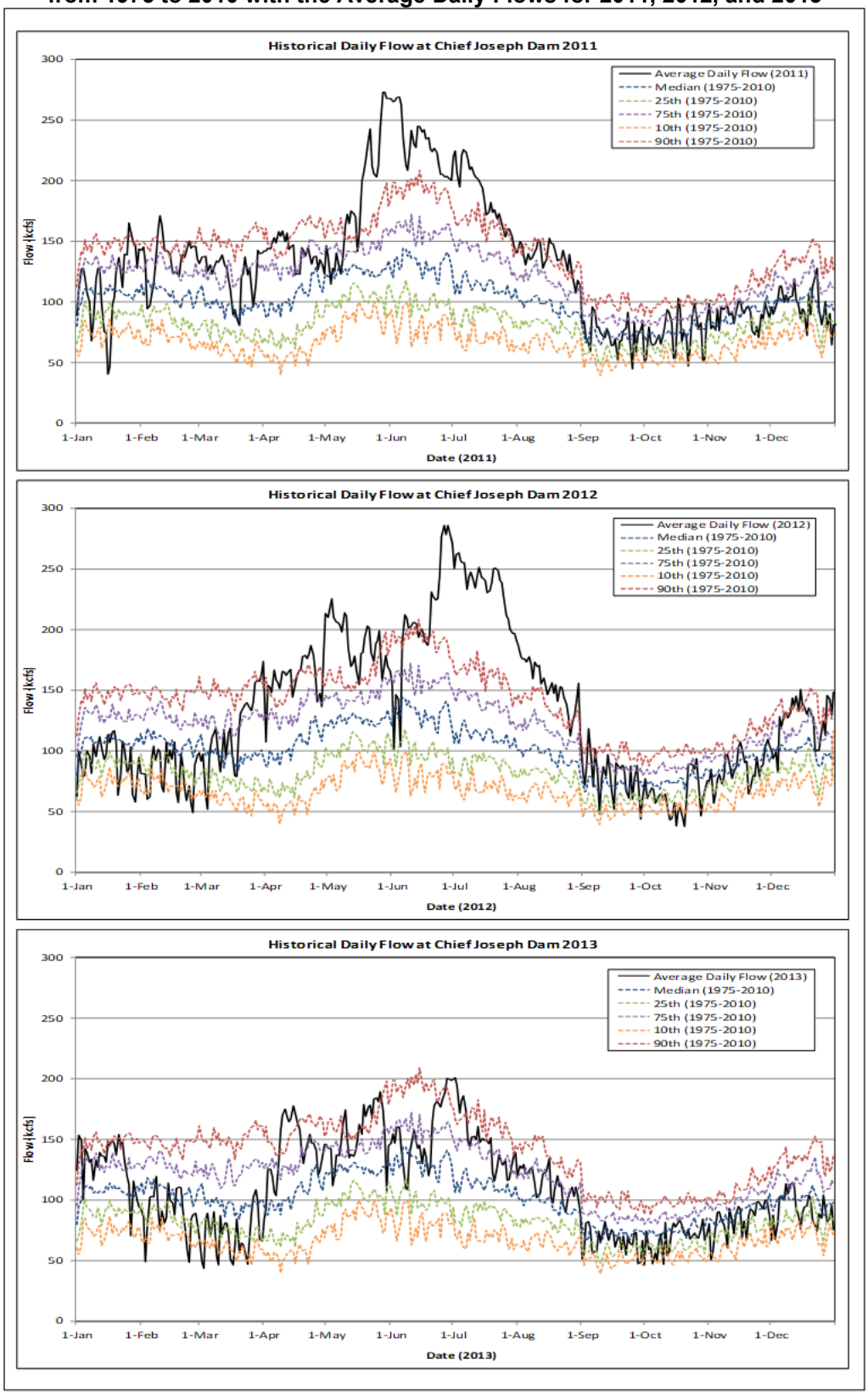
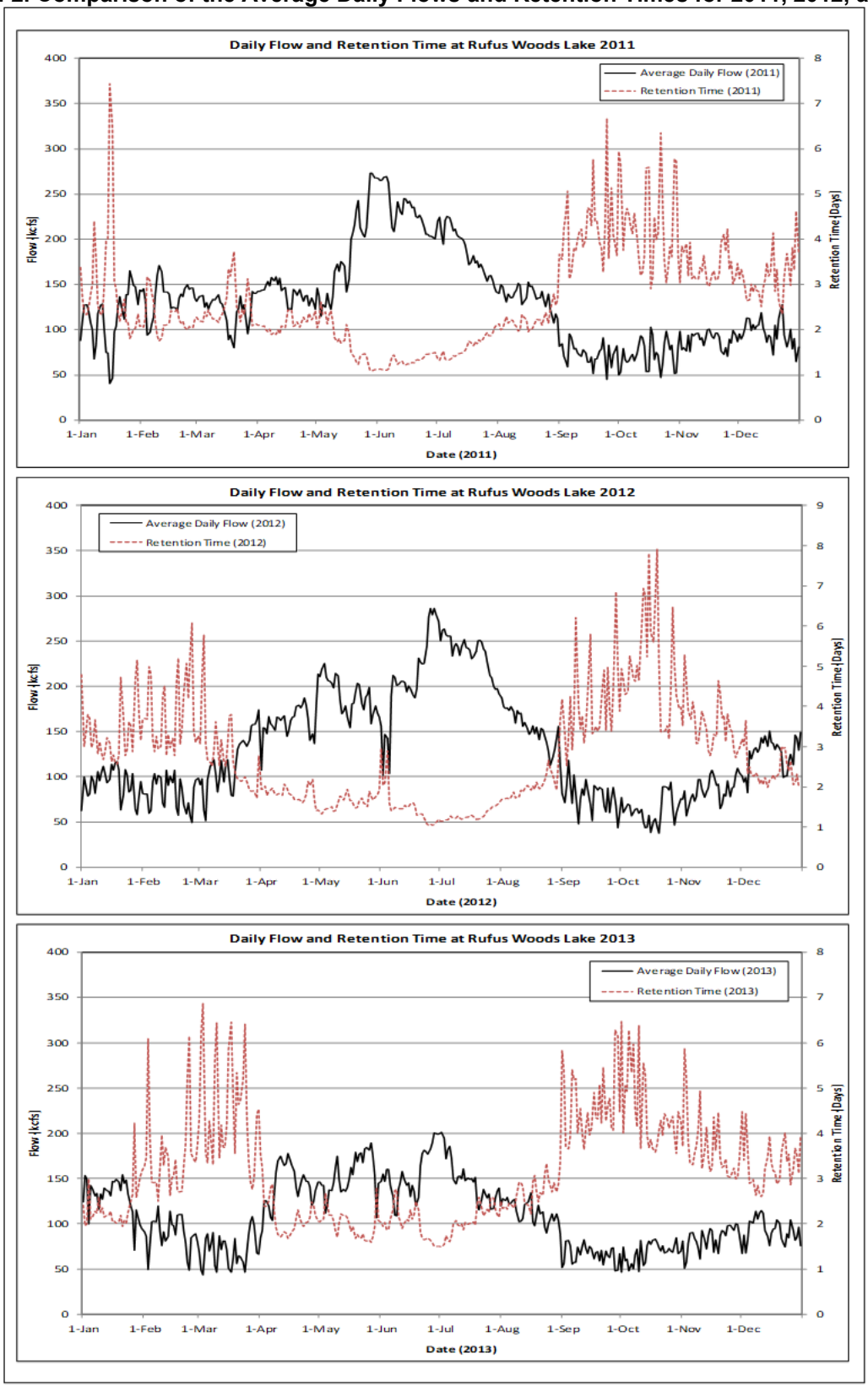


Figure 2-2. Comparison of the Average Daily Flows and Retention Times for 2011, 2012, and 2013

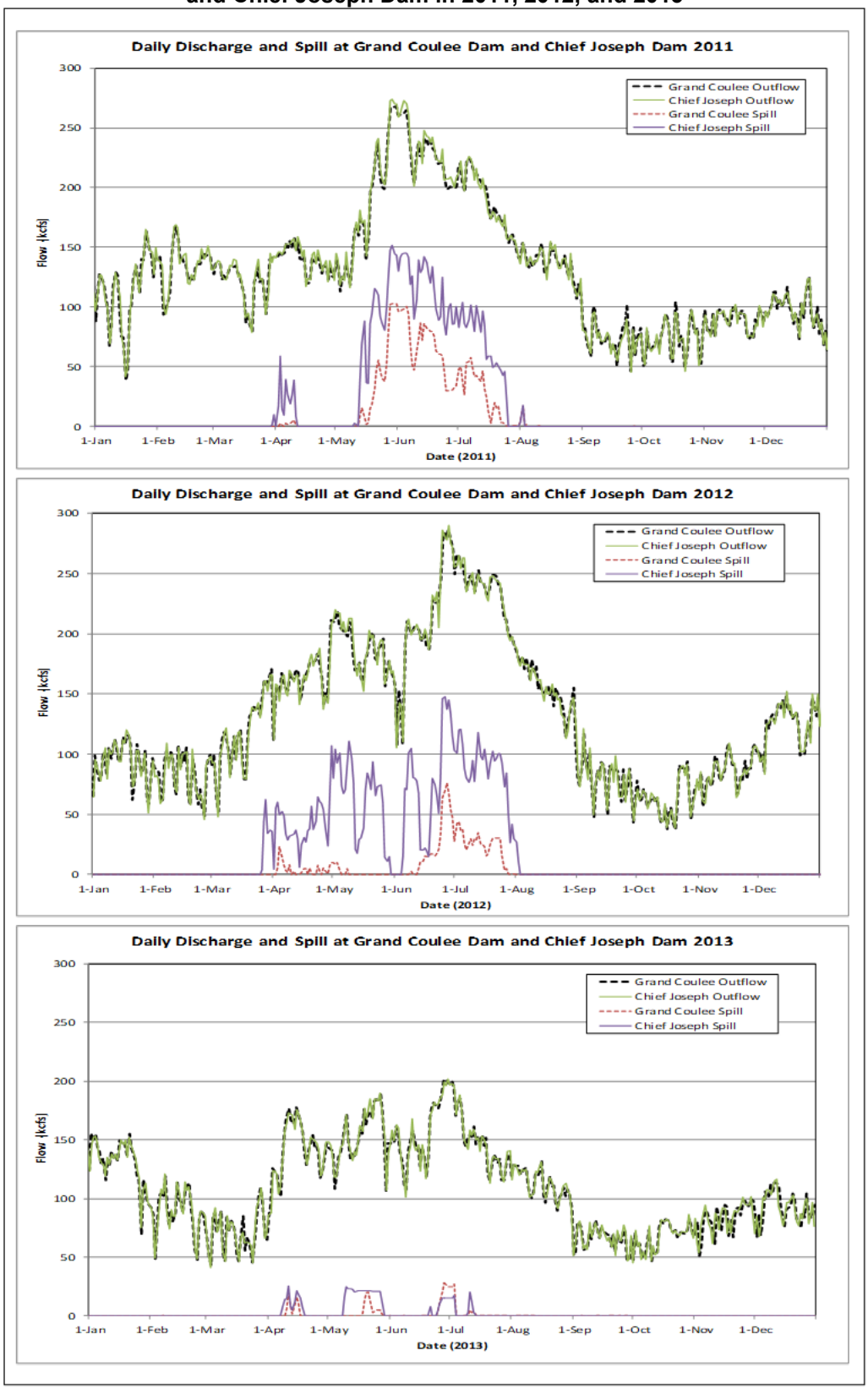


2.1.2 Spillway Flows

TDG saturations in rivers are increased when dams release water through the spillways. Spilling water at a dam results in increased TDG levels in downstream waters by plunging the aerated spill water to a depth where hydrostatic pressure increases the solubility of atmospheric gases. Elevated TDG saturations generated by spillway releases from dams are of concern because high saturations can promote the potential for gas bubble trauma in downstream aquatic biota (Weitkamp and Katz 1980; Weitkamp et al. 2002).

Spillway flows from Grand Coulee Dam impact TDG saturations in Rufus Woods Lake while spill from Chief Joseph Dam impacts TDG saturations downstream in the Columbia River. Spillway flows for both Grand Coulee Dam and Chief Joseph Dam for 2011, 2012, and 2013 are presented in Figure 2-3. Considerable spill occurred at both projects in 2011 and 2012 with little spill in 2013. For Grand Coulee Dam, spillway flows were greatest in 2011 with spill volumes up to 100,000 cfs measured in June. Grand Coulee spill was reduced in 2012 with little spill occurring in 2013. For Chief Joseph Dam, spillway flows were similar in 2011 and 2012 with spill volumes up to 150,000 cfs measured in June and July. Similar to Grand Coulee, little spill occurred at Chief Joseph Dam in 2013.

Figure 2-3. Average Daily Flow and Spill for Grand Coulee Dam and Chief Joseph Dam in 2011, 2012, and 2013



Grand Coulee Dam has the greatest power generation flow capacity (280,000 cfs) for dams on the Columbia River. Consequently, Grand Coulee generally only spills on average once every 6 years. However, maintenance work on several large powerhouse generating units from 2011 to 2013 resulted in a reduced powerhouse capacity for Grand Coulee and required considerable spill in 2011 and 2012. Grand Coulee spills water either via a series of outlet tubes (when forebay pool elevations are below 384 meters) or over the drum gates at times when forebay elevations are greater than 384 meters. TDG studies by Frizell (1997) show that spill from the outlet tubes increases TDG saturations in Rufus Woods Lake substantially more than spill over the drum gates. For 2011, the majority of spill was in late May and June via the outlet tubes, while in 2012, the majority of spill was in late June and July over the drum gates.

2.2 LAKE PHYSICAL AND CHEMICAL CONDITIONS

Selected physical and chemical water quality results for 2011 to 2013 are presented in Table 2-1 to Table 2-3.

Table 2-1. Rufus Woods Lake Water Quality Data for 2011

Location	Date	Total P (mg/L)	SRP (mg/L)	Ammonia (mg/L)	NO_3+NO_2 (mg/L)	Total N (mg/L)	Alkalinity (mgCaCO$_3$/L)	Hardness (mgCaCO$_3$/L)	TOC (mg/L)	Chl a (µg/L)	Phaeo a (µg/L)	Trans (meters)	Copper (mg/L)	Zinc (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Aluminum (mg/L)	Arsenic (mg/L)	Cadmium (mg/L)	Chromium (mg/L)	Lead (mg/L)
CHJUP	9-Mar-11	0.008	<0.001	<0.005	0.140	0.156	70.8	70.4	0.869	4.5	<0.1	4.88	<0.0010	<0.005	9.24	0.98	5.65	4.55	0.793	1.85	0.0044	<0.0030	<0.00020	<0.0020	<0.0010
CHJUP	14-Apr-11	0.015	0.001	0.013	0.226	0.281	72.2	65.7	1.18	4.0	0.3	2.44	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	5-May-11	0.012	<0.001	0.012	0.102	0.170	72.7	69.4	1.38	5.6	0.4	3.66	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	9-Jun-11	0.010	0.002	0.027	0.072	0.299	60.7	57.9	1.52	1.8	<0.1	3.96	0.0012	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJUP	13-Jul-11	0.008	0.002	0.011	0.040	0.177	62.4	60.0	1.62	2.1	0.6	4.88	0.0013	<0.005	7.27	0.88	15.2	3.99	0.692	1.41	0.0226	<0.0030	<0.00020	<0.0020	<0.0010
CHJUP	11-Aug-11	0.006	0.002	0.017	0.049	0.132	63.5	58.8	1.64	0.6	<0.1	7.92	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	15-Sep-11	0.005	0.005	<0.005	0.085	0.111	61.6	56.7	1.43	0.4	0.3	9.14	0.0014	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	20-Oct-11	0.009	0.004	<0.005	0.090	0.138	62.7	57.0	0.827	0.9	<0.1	8.23	<0.0010	<0.005	7.55	0.67	15.8	4.26	0.589	1.44	0.0076	<0.0030	<0.00020	<0.0020	<0.0010
CHJNSP	9-Mar-11	0.006	<0.001	<0.005	0.132	0.145	70.4	69.6	0.730	4.8	<0.1	5.79	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	14-Apr-11	0.015	0.002	0.006	0.226	0.342	67.5	67.4	1.22	4.0	0.7	2.74	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	5-May-11	0.012	<0.001	<0.005	0.106	0.154	73.2	69.8	1.34	5.1	0.9	3.05	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	9-Jun-11	0.011	0.002	0.017	0.072	0.253	60.4	57.5	1.60	2.3	<0.1	4.27	0.0012	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	13-Jul-11	0.009	0.001	0.011	0.039	0.137	62.4	60.2	1.60	2.7	0.6	4.27	0.0012	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	11-Aug-11	0.007	0.002	0.015	0.051	0.128	62.9	59.4	1.53	0.9	<0.1	8.23	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	15-Sep-11	0.005	0.003	<0.005	0.073	0.103	61.8	57.1	1.43	0.9	0.1	8.84	0.0014	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	20-Oct-11	0.008	0.004	<0.005	0.089	0.133	62.7	56.9	0.775	0.8	0.2	9.14	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	9-Mar-11	0.006	<0.001	<0.005	0.130	0.143	70.0	70.4	0.774	4.2	<0.1	4.88	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	14-Apr-11	0.015	0.001	0.005	0.225	0.352	70.8	66.4	1.27	4.3	0.6	2.74	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	5-May-11	0.014	<0.001	0.007	0.103	0.171	72.7	69.0	1.31	5.9	1.4	3.35	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	9-Jun-11	0.012	0.002	0.013	0.071	0.317	60.5	56.7	1.65	2.0	<0.1	3.96	0.0012	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	13-Jul-11	0.010	0.002	0.020	0.039	0.178	62.4	59.6	1.65	2.8	0.3	2.74	0.0011	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	11-Aug-11	0.008	0.003	0.028	0.050	0.150	64.1	59.4	1.48	1.1	<0.1	8.23	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	15-Sep-11	0.008	0.003	0.018	0.078	0.131	62.2	57.5	1.65	0.5	0.3	9.75	0.0017	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	20-Oct-11	0.010	0.006	0.028	0.089	0.168	62.8	57.4	0.794	0.7	<0.1	9.45	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	9-Mar-11	0.006	<0.001	<0.005	0.130	0.152	71.0	70.7	0.808	4.6	<0.1	5.18	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	14-Apr-11	0.016	0.001	0.007	0.226	0.298	69.5	65.9	1.23	3.7	0.6	2.74	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	5-May-11	0.012	<0.001	<0.005	0.102	0.162	73.2	68.8	1.33	5.6	1.1	3.35	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	9-Jun-11	0.010	0.002	0.015	0.071	0.308	61.4	56.9	1.62	2.0	<0.1	4.27	0.0011	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	13-Jul-11	0.009	0.001	0.017	0.040	0.138	62.5	59.6	1.61	2.7	0.4	3.05	0.0011	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	11-Aug-11	0.009	0.003	0.024	0.050	0.142	62.2	59.0	1.50	1.0	<0.1	8.53	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	15-Sep-11	0.006	0.004	0.006	0.079	0.124	62.3	57.3	1.44	0.7	0.2	10.06	0.0015	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	20-Oct-11	0.009	0.005	0.015	0.089	0.163	61.7	57.0	0.787	0.9	<0.1	9.14	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	9-Mar-11	0.008	<0.001	<0.005	0.133	0.149	70.4	71.1	0.879	4.8	<0.1	5.18	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	14-Apr-11	0.018	0.002	0.010	0.226	0.304	69.4	66.6	1.38	1.6	0.5	3.05	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	5-May-11	0.015	0.001	0.010	0.102	0.182	72.6	69.8	1.34	5.9	1.4	3.66	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	9-Jun-11	0.011	0.003	0.015	0.072	0.291	60.0	56.9	1.59	2.1	<0.1	3.66	0.0012	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	13-Jul-11	0.010	<0.001	0.015	0.039	0.132	62.0	59.0	1.77	2.7	0.6	3.35	0.0011	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	11-Aug-11	0.012	0.004	0.042	0.051	0.181	63.4	59.0	2.19	1.1	<0.1	8.23	0.0013	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	15-Sep-11	0.009	0.006	0.037	0.077	0.153	61.7	57.7	1.40	1.1	<0.1	10.97	0.0015	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	20-Oct-11	0.012	0.006	0.030	0.091	0.206	63.3	57.6	0.829	0.9	0.3	9.45	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	9-Mar-11	0.006	<0.001	<0.005	0.130	0.146	69.9	70.0	0.854	4.6	<0.1	5.18	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	14-Apr-11	0.017	0.002	0.008	0.226	0.356	69.1	66.8	1.25	4.3	0.4	3.05	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	5-May-11	0.016	0.001	0.007	0.103	0.173	72.9	70.2	1.31	6.1	1.0	3.66	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	9-Jun-11	0.011	0.002	0.012	0.072	0.297	61.0	56.9	1.64	1.9	<0.1	3.66	0.0012	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	13-Jul-11	0.009	<0.001	0.014	0.039	0.123	62.4	59.8	1.63	2.8	0.4	3.35	0.0013	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	11-Aug-11	0.008	0.003	0.025	0.051	0.144	62.3	59.2	1.65	1.1	<0.1	8.23	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	15-Sep-11	0.007	0.004	0.013	0.081	0.170	61.3	57.1	1.30	0.7	0.3	10.06	0.0014	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	20-Oct-11	0.007	0.005	0.016	0.089	0.153	61.9	57.0	0.850	1.0	<0.1	8.84	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	9-Mar-11	0.007	<0.001	<0.005	0.131	0.142	68.9	69.6	0.791	5.0	<0.1	4.88	<0.0010	<0.005	9.24	0.98	5.28	4.42	0.767	1.81	0.0046	<0.0030	<0.00020	<0.0020	<0.0010
CHJMID	14-Apr-11	0.018	0.003	0.006	0.226	0.321	70.5	66.8	1.19	4.3	0.4	2.74	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	5-May-11	0.013	<0.001	<0.005	0.101	0.168	71.8	69.2	1.34	5.9	0.5	3.96	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	9-Jun-11	0.011	0.002	0.010	0.071	0.326	60.6	56.7	1.63	2.4	<0.1	3.66	0.0012	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJMID	13-Jul-11	0.009	<0.001	0.012	0.041	0.145	62.0	59.6	1.87	3.0	<0.1	4.27	0.0011	<0.005	7.40	0.88	15.1	3.82	0.704	1.42	0.0240	<0.0030	<0.00020	<0.0020	<0.0010
CHJMID	11-Aug-11	0.008	0.002	0.016	0.051	0.135	61.9	59.8	1.44	1.1	<0.1	8.53	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	15-Sep-11	0.007	0.002	0.009	0.068	0.111	58.0	57.1	1.37	0.7	0.3	10.97	0.0012	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	20-Oct-11	0.007	0.004	0.012	0.091	0.212	62.5	56.8	0.744	0.7	<0.1	8.53	<0.0010	<0.005	8.65	0.60	15.8	4.21	0.593	1.47	0.0102	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	9-Mar-11	0.008	<0.001	<0.005	0.130	0.147	69.5	69.2	0.841	5.3	<0.1	4.88	<0.0010	<0.005	9.68	0.88	5.39	4.43	0.777	1.81	0.0054	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	14-Apr-11	0.015	0.002	<0.005	0.227	0.285	71.8	68.0	1.16	5.2	<0.1	2.44	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	5-May-11	0.013	<0.001	<0.005	0.096	0.164	73.0	69.0	1.35	6.4	0.9	3.35	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	9-Jun-11	0.010	0.002	0.010	0.072	0.295	59.5	57.1	1.64	2.3	<0.1	3.96	0.0013	0.008	—	—	—	—	—	—	—	—	—	—	—
CHJFB	13-Jul-11	0.010	<0.001	0.010	0.041	0.131	62.5	59.2	1.62	3.0	0.3	4.27	0.0015	<0.005	7.35	0.78	15.1	3.82	0.713	1.44	0.0277	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	11-Aug-11	0.007	0.002	0.016	0.053	0.142	62.9	59.6	1.51	1.4	<0.1	8.23	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	15-Sep-11	0.006	0.003	0.009	0.077	0.128	62.0	56.9	1.26	1.2	0.1	8.53	0.0013	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	20-Oct-11	0.006	0.004	<0.005	0.096	0.193	62.3	56.3	0.803	1.1	0.3	8.53	<0.0010	<0.005	7.80	0.59	15.7	4.2	0.593	1.46	0.0120	<0.0030	<0.00020	<0.0020	<0.0010
CHJTW	9-Mar-11	0.007	<0.001	<0.005	0.132	0.141	69.4	69.4	0.804	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	14-Apr-11	0.015	0.001	<0.005	0.223	0.355	69.8	67.8	1.14	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	5-May-11	0.013	0.001	<0.005	0.097	0.171	73.0	70.4	1.29	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	9-Jun-11	0.012	0.002	0.010	0.075	0.295	60.8	56.3	1.68	—	—	—	0.0013	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJTW	13-Jul-11	0.010	<0.001	0.011	0.044	0.140	61.4	59.6	—	—	—	—	0.0012	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	11-Aug-11	0.006	0.002	0.012	0.055	0.141	63.9	59.4	1.51	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	15-Sep-11	0.006	0.004	<0.005	0.078	0.141	60.8	57.9	1.48	—	—	—	0.0012	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	20-Oct-11	0.008	0.004	<0.005	0.095	0.178	62.5	54.8	0.775	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—

Note: Total P = total phosphorus; SRP = ; TOC = ; Chl a = Phaeo a = ; Trans = .

Table 2-2. Rufus Woods Lake Water Quality Data for 2012

Location	Date	Total P (mg/L)	SRP (mg/L)	Ammonia (mg/L)	NO_3+NO_2 (mg/L)	Total N (mg/L)	Alkalinity (mgCaCO$_3$/L)	Hardness (mgCaCO$_3$/L)	TOC (mg/L)	Chl a (µg/L)	Phaeo a (µg/L)	Trans (meters)	Copper (mg/L)	Zinc (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Aluminum (mg/L)	Arsenic (mg/L)	Cadmium (mg/L)	Chromium (mg/L)	Lead (mg/L)
CHJUP	13-Mar-12	0.007	<0.001	0.007	0.182	0.206	69.6	65.1	0.571	2.8	<0.1	6.4	<0.0010	<0.005	10.7	0.88	17.8	5.02	0.668	1.77	0.0082	<0.0030	<0.00020	<0.0020	<0.0010
CHJUP	11-Apr-12	0.010	<0.001	0.008	0.212	0.312	67.9	67.6	1.05	3.5	0.8	3.1	<0.0010	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJUP	10-May-12	0.014	<0.001	0.020	0.078	0.215	60.5	56.8	2.23	2.5	<0.1	3.5	0.0019	0.010	8.55	1.25	16.2	3.98	0.941	2.21	0.0838	<0.0030	<0.00020	<0.0020	<0.0010
CHJUP	6-Jun-12	0.007	0.001	0.016	0.058	0.118	62.6	57.7	1.23	2.9	0.6	3	0.00	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJUP	11-Jul-12	0.007	0.002	0.010	0.047	0.160	59.2	58.0	1.37	1.6	0.39	4.5	0.001	<0.005	6.5	1.0	16.7	3.99	0.515	1.59	0.0098	<0.0030	<0.00020	<0.0020	<0.0010
CHJUP	8-Aug-12	0.006	0.002	0.009	0.076	0.216	57.9	58.0	1.22	1.2	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	19-Sep-12	0.008	0.003	0.014	0.128	0.198	60.6	55.8	0.84	<0.1	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJUP	17-Oct-12	0.006	0.002	<0.005	0.114	0.148	59.2	—	1.1	1.2	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	13-Mar-12	0.008	<0.001	0.006	0.175	0.188	70.4	66.1	0.591	3.2	<0.1	6.1	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	11-Apr-12	0.012	<0.001	0.005	0.212	0.322	69.2	68.0	0.872	4.3	<0.1	4	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	10-May-12	0.016	<0.001	0.013	0.086	0.219	60.8	56.7	2.07	2.4	<0.1	3.1	0.0012	0.009	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	6-Jun-12	0.008	<0.001	0.020	0.059	0.141	61.5	58.3	1.23	2.4	0.8	3.5	0.00	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	11-Jul-12	0.008	0.001	0.007	0.051	0.173	58.8	—	1.34	2.3	<0.1	4.75	0.002	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	8-Aug-12	0.006	0.002	0.007	0.080	0.152	58.6	59.9	1.14	1.3	<0.1	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	19-Sep-12	0.007	0.003	0.028	0.130	0.185	61.0	57.9	0.88	1.0	<0.1	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	17-Oct-12	0.006	0.003	0.006	0.109	0.144	59.0	—	0.9	1.6	<0.1	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	13-Mar-12	0.010	0.002	0.010	0.181	0.205	70.0	66.0	0.576	3.1	<0.1	6.8	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	11-Apr-12	0.014	<0.001	0.011	0.216	0.279	69.2	67.3	0.869	3.7	0.4	3.5	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	10-May-12	0.016	<0.001	0.025	0.081	0.272	60.5	58.0	2.13	2.4	<0.1	3.1	0.0012	0.009	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	6-Jun-12	0.008	<0.001	0.031	0.058	0.131	62.6	57.1	1.26	3.2	0.2	3.25	0.00	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	11-Jul-12	0.008	0.003	0.021	0.050	0.183	60.2	—	1.44	2.3	<0.1	4	0.002	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	8-Aug-12	0.007	0.002	0.021	0.078	0.151	58.5	61.8	1.14	1.2	<0.1	8	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	19-Sep-12	0.011	0.005	0.034	0.130	0.256	58.8	57.1	0.88	0.6	<0.1	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	17-Oct-12	0.010	0.005	0.014	0.114	0.167	58.3	—	0.9	0.8	<0.1	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	13-Mar-12	0.009	<0.001	0.006	0.172	0.206	68.5	67.4	0.632	3.0	<0.1	6.4	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	11-Apr-12	0.011	<0.001	0.008	0.211	0.313	68.8	66.5	0.862	4.0	<0.1	3.6	<0.0010	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	10-May-12	0.015	<0.001	0.014	0.081	0.210	60.3	57.4	2.07	2.4	<0.1	3.2	0.0012	0.009	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	6-Jun-12	0.008	<0.001	0.023	0.058	0.112	61.9	57.1	1.22	2.9	<0.1	3.25	0.00	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	11-Jul-12	0.006	0.002	0.010	0.051	0.191	58.2	—	1.30	2.0	<0.1	4.25	0.002	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	8-Aug-12	0.006	0.001	0.011	0.079	0.172	58.7	60.5	1.11	1.2	<0.1	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	19-Sep-12	0.008	0.004	0.010	0.131	0.198	60.2	59.4	0.95	0.8	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	17-Oct-12	0.007	0.003	<0.005	0.115	0.152	59.3	—	0.9	0.8	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	13-Mar-12	0.009	<0.001	0.015	0.197	0.245	69.4	67.4	0.562	2.6	<0.1	6.1	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	11-Apr-12	0.012	<0.001	0.013	0.210	0.327	68.8	66.5	0.897	3.7	0.4	3.6	<0.0010	0.007	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	10-May-12	0.017	<0.001	0.021	0.083	0.252	60.0	57.2	1.98	2.4	<0.1	3.1	0.0015	0.015	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	6-Jun-12	0.010	0.002	0.025	0.055	0.135	62.3	56.8	1.22	2.9	0.6	3.5	<0.0010	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	11-Jul-12	0.006	<0.001	0.014	0.050	0.172	58.5	—	1.39	2.0	<0.1	4	0.002	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	8-Aug-12	0.008	0.003	0.026	0.079	0.159	59.2	60.2	1.15	1.1	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	19-Sep-12	0.011	0.005	0.035	0.127	0.224	61.8	59.4	0.93	0.8	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	17-Oct-12	0.010	0.005	0.026	0.117	0.158	56.3	—	1.0	0.8	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	13-Mar-12	0.008	<0.001	<0.005	0.174	0.187	68.3	66.2	0.604	2.8	<0.1	6.4	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	11-Apr-12	0.012	<0.001	0.009	0.211	0.320	69.2	67.6	0.841	4.0	0.3	3.5	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	10-May-12	0.018	<0.001	0.019	0.082	0.271	61.0	57.0	2.07	2.6	<0.1	3	0.0013	0.009	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	6-Jun-12	0.009	<0.001	0.025	0.057	0.141	59.3	57.7	1.23	2.7	0.9	3.5	<0.0010	0.0	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	11-Jul-12	0.006	<0.001	0.008	0.047	0.202	58.0	—	1.45	2.0	<0.1	4	0.002	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	8-Aug-12	0.007	0.002	0.016	0.082	0.180	57.4	60.2	1.12	1.4	<0.1	9.25	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	19-Sep-12	0.009	0.004	0.015	0.132	0.177	59.6	57.5	0.92	0.8	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	17-Oct-12	0.009	0.005	0.017	0.115	0.153	58.6	—	0.9	0.9	<0.1	9.5	0.01	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJMID	13-Mar-12	0.007	<0.001	<0.005	0.174	0.341	70.8	75.9	0.623	2.6	<0.1	6.1	<0.0010	<0.005	10.3	0.85	21.1	5.64	0.686	1.79	0.0096	<0.0030	<0.00020	<0.0020	<0.0010
CHJMID	11-Apr-12	0.012	<0.001	0.006	0.211	0.320	70.0	68.0	0.984	4.1	<0.1	3.5	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJMID	10-May-12	0.017	<0.001	0.014	0.082	0.238	59.8	56.8	2.04	2.5	<0.1	3	0.0013	0.008	8.38	1.25	16.2	3.99	0.941	2.16	0.0800	<0.0030	<0.00020	<0.0020	<0.0010
CHJMID	6-Jun-12	0.008	<0.001	0.020	0.057	0.155	61.3	59.3	1.24	2.9	0.6	3.5	<0.0010	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJMID	11-Jul-12	0.006	0.001	0.006	0.050	0.169	59.2	57.7	1.36	2.1	<0.1	4.5	0.001	<0.005	13.8	1.1	16.6	3.96	0.520	1.54	0.0121	<0.0030	<0.00020	<0.0020	<0.0010
CHJMID	8-Aug-12	0.007	0.002	0.006	0.080	0.265	58.8	59.4	1.13	1.1	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	19-Sep-12	0.007	0.003	0.009	0.128	0.185	61.6	56.4	0.95	1.0	<0.1	10	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJMID	17-Oct-12	0.007	0.002	0.010	0.116	0.144	58.3	—	0.8	1.2	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	13-Mar-12	0.010	<0.001	<0.005	0.175	0.184	72.0	66.3	0.662	2.8	<0.1	6.4	<0.0010	<0.005	10.3	0.96	18.0	5.21	0.712	1.80	0.0071	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	11-Apr-12	0.011	<0.001	<0.005	0.207	0.300	70.0	68.4	0.790	3.5	0.3	3.6	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—
CHJFB	10-May-12	0.015	<0.001	0.012	0.085	0.220	61.0	58.2	1.94	2.0	<0.1	3	0.0020	0.010	8.08	1.34	16.5	4.10	0.956	2.24	0.0813	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	6-Jun-12	0.008	<0.001	0.019	0.062	0.170	61.9	57.4	1.27	2.9	0.6	3	<0.0010	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJFB	11-Jul-12	0.006	<0.001	0.006	0.048	0.190	60.6	57.6	1.36	2.4	<0.1	4	0.001	<0.005	8.3	1.0	16.6	3.93	0.525	1.58	0.0119	<0.0030	<0.00020	<0.0020	<0.0010
CHJFB	8-Aug-12	0.007	0.002	<0.005	0.080	0.128	56.8	59.4	1.14	1.4	<0.1	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	19-Sep-12	0.008	0.003	<0.005	0.130	0.178	60.4	57.9	0.97	2.2	<0.1	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJFB	17-Oct-12	0.007	0.002	<0.005	0.124	0.154	60.5	—	0.9	1.5	<0.1	9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	13-Mar-12	0.008	<0.001	<0.005	0.175	0.203	71.5	66.1	0.651	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	11-Apr-12	0.010	<0.001	<0.005	0.202	0.328	70.6	67.0		—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	10-May-12	0.016	<0.001	0.013	0.074	0.228	62.2	58.4	1.94	—	—	—	0.0012	0.010	—	—	—	—	—	—	—	—	—	—	—
CHJTW	6-Jun-12	0.011	<0.001	0.015	0.061	0.162	61.9	58.6	1.30	—	—	—	<0.0010	0.01	—	—	—	—	—	—	—	—	—	—	—
CHJTW	11-Jul-12	0.007	<0.001	0.009	0.050	0.186	59.2	—	1.38	—	—	—	0.001	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	8-Aug-12	0.007	0.002	<0.005	0.084	0.154	58.5	59.4	1.13	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	19-Sep-12	0.009	0.003	0.006	0.136	0.175	60.2	58.6	0.95	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—
CHJTW	17-Oct-12	0.007	0.002	<0.005	0.129	0.160	58.2	—	0.8	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—

Table 2-3. Rufus Woods Lake Water Quality Data for 2013

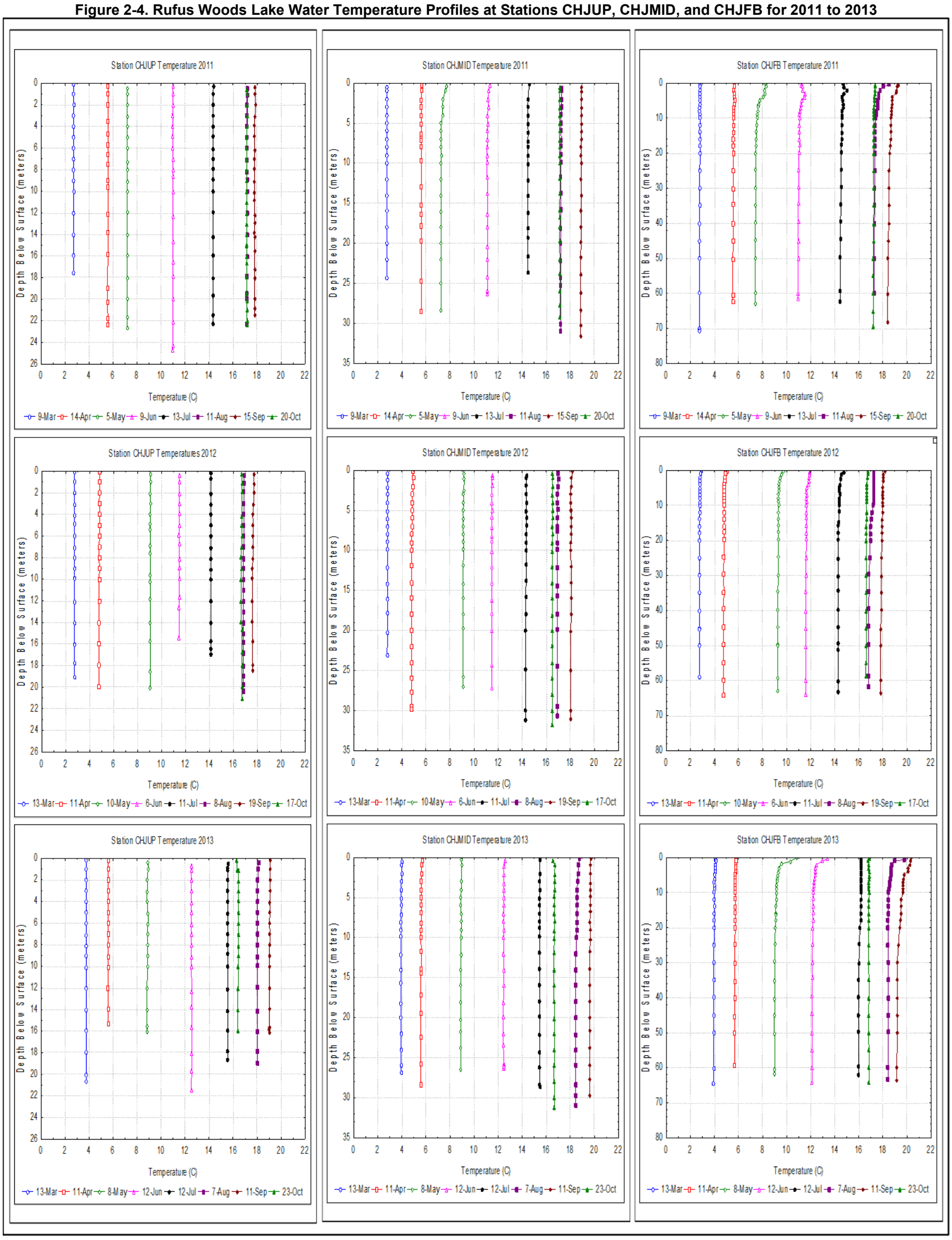
Location	Date	Total P (mg/L)	SRP (mg/L)	Ammonia (mg/L)	NO_3+NO_2 (mg/L)	Total N (mg/L)	Alkalinity (mgCaCO$_3$/L)	Hardness (mgCaCO$_3$/L)	TOC (mg/L)	Chl a (µg/L)	Phaeo a (µg/L)	Trans (meters)	Copper (mg/L)	Zinc (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Aluminum (mg/L)	Arsenic (mg/L)	Cadmium (mg/L)	Chromium (mg/L)	Lead (mg/L)	FOG (mg/L)
CHJUP	13-Mar-13	0.008	0.001	0.007	0.182	0.216	71.5	71.1	0.609	2.4	<0.1	8.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	11-Apr-13	0.006	0.001	0.017	0.242	0.281	72.1	71.4	0.965	2.3	<0.1	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	8-May-13	0.011	<0.001	0.011	0.092	0.179	66.6	63.1	1.57	2.4	<0.1	6.5	0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	12-Jun-13	0.006	0.002	0.024	0.060	0.200	64.2	—	1.56	1.4	<0.1	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	12-Jul-13	0.007	0.002	0.016	0.062	0.155	63.3	—	1.26	1.1	<0.1	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	7-Aug-13	0.006	0.001	<0.005	0.086	0.116	64.0	—	0.930	1.1	0.2	11.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	11-Sep-13	0.006	0.004	<0.005	0.102	0.122	64.4	66.8	0.759	0.5	0.4	13.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJUP	23-Oct-13	0.007	0.003	<0.005	0.106	0.130	64.4	59.4	0.749	0.5	0.8	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	13-Mar-13	0.006	<0.001	<0.005	0.180	0.190	72.2	69.6	0.623	2.5	<0.1	7.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP	11-Apr-13	0.007	0.001	0.011	0.242	0.302	73.3	71.1	1.06	2.0	<0.1	5.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	8-May-13	0.008	0.001	0.011	0.077	0.164	67.3	63.7	1.68	2.3	<0.1	3.0	<0.0010	0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	12-Jun-13	0.007	<0.001	0.023	0.061	0.115	64.2	—	1.49	1.4	0.3	5.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	12-Jul-13	0.006	0.001	0.008	0.061	0.148	63.7	—	1.25	1.3	0.2	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	7-Aug-13	0.007	0.002	0.011	0.071	0.114	65.0	—	0.939	0.5	1.3	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	11-Sep-13	0.006	0.002	<0.005	0.088	0.115	63.6	63.1	0.682	0.8	0.7	10.2	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP	23-Oct-13	0.006	0.003	0.008	0.101	0.127	64.6	60.2	0.659	1.1	0.8	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-1	13-Mar-13	0.007	<0.001	0.007	0.173	0.207	71.3	69.2	0.637	2.1	<0.1	8.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	11-Apr-13	0.008	0.002	0.035	0.256	0.305	72.8	71.1	1.02	2.0	<0.1	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-1	8-May-13	0.012	0.001	0.035	0.083	0.174	68.2	62.3	1.69	2.3	<0.1	5.5	0.0013	0.006	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-1	12-Jun-13	0.008	0.003	0.037	0.060	0.126	63.8	—	1.54	1.4	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	2.80
CHJNSP-1	12-Jul-13	0.008	0.003	0.046	0.063	0.188	63.6	—	1.32	1.3	0.2	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	5.19
CHJNSP-1	7-Aug-13	0.007	0.003	0.027	0.083	0.143	63.5	—	0.930	1.1	0.2	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	4.02
CHJNSP-1	11-Sep-13	0.006	0.003	0.025	0.098	0.145	63.8	62.3	0.754	0.8	0.5	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-1	23-Oct-13	0.008	0.004	0.022	0.105	0.157	62.2	61.0	0.986	1.1	0.6	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	13-Mar-13	0.007	<0.001	<0.005	0.171	0.175	71.1	68.8	0.576	2.0	<0.1	7.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	11-Apr-13	0.009	0.001	0.024	0.244	0.297	71.4	72.2	0.976	2.1	<0.1	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	8-May-13	0.011	0.001	0.015	0.073	0.174	66.0	62.7	1.65	2.7	<0.1	5.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	12-Jun-13	0.006	<0.001	0.026	0.062	0.116	62.8	—	1.43	1.4	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-2	12-Jul-13	0.007	0.002	0.020	0.060	0.143	63.6	—	1.31	1.3	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	5.57
CHJNSP-2	7-Aug-13	0.005	0.002	0.012	0.071	0.136	64.4	—	0.956	0.5	1.0	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-2	11-Sep-13	0.007	0.003	0.010	0.100	0.129	63.8	63.3	0.772	0.8	0.5	9.8	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	2.73
CHJNSP-2	23-Oct-13	0.007	0.003	0.010	0.112	0.152	62.6	61.0	0.734	1.3	0.3	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	13-Mar-13	0.007	<0.001	0.008	0.172	0.191	70.0	69.2	0.625	2.2	<0.1	8.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	11-Apr-13	0.009	0.002	0.028	0.243	0.298	74.0	70.4	0.963	2.4	<0.1	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	6.35
CHJNSP-3	8-May-13	0.011	<0.001	0.016	0.079	0.158	67.2	63.1	1.59	2.3	<0.1	5.5	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-3	12-Jun-13	0.007	0.002	0.028	0.065	0.123	64.8	—	1.40	1.2	0.4	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-3	12-Jul-13	0.007	0.002	0.023	0.059	0.181	63.8	—	1.32	1.3	0.3	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	7-Aug-13	0.008	0.002	0.024	0.070	0.126	63.3	—	0.957	0.8	0.7	10.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-3	11-Sep-13	0.008	0.003	0.020	0.098	0.143	62.4	63.5	0.684	1.1	0.4	10.9	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-3	23-Oct-13	0.009	0.004	0.028	0.102	0.158	63.7	59.8	0.807	1.1	0.8	8.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-4	13-Mar-13	0.008	0.001	0.007	0.172	0.212	69.8	69.6	0.659	2.4	<0.1	7.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	11-Apr-13	0.007	0.001	0.017	0.241	0.287	71.2	71.9	0.920	2.3	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	8-May-13	0.012	<0.001	0.011	0.071	0.152	67.6	63.7	1.61	2.5	0.6	6.0	<0.0010	0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	12-Jun-13	0.008	0.002	0.025	0.068	0.114	64.0	—	1.53	1.4	0.2	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJNSP-4	12-Jul-13	0.007	0.002	0.017	0.059	0.131	63.5	—	1.26	1.1	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	7-Aug-13	0.010	0.002	0.021	0.073	0.131	65.2	—	0.969	0.8	0.7	10.0	0.0073	0.012	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	11-Sep-13	0.006	0.002	0.010	0.106	0.130	62.7	63.7	0.621	0.5	1.0	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJNSP-4	23-Oct-13	0.008	0.004	0.015	0.105	0.153	66.1	60.8	0.688	1.1	0.6	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJMID	13-Mar-13	0.007	<0.001	<0.005	0.179	0.188	70.4	68.4	0.618	2.4	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	11-Apr-13	0.007	0.001	0.020	0.261	0.293	72.4	70.7	0.917	2.1	0.5	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	8-May-13	0.011	<0.001	0.011	0.088	0.167	67.4	63.7	1.67	2.1	0.2	6.0	<0.0010	0.006	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	12-Jun-13	0.008	<0.001	0.023	0.079	0.106	63.5	—	1.43	1.2	0.4	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	12-Jul-13	0.007	0.001	0.011	0.059	0.167	61.6	—	1.22	1.3	<0.1	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	7-Aug-13	0.005	0.001	0.013	0.066	0.114	64.4	—	0.918	1.1	0.4	9.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	11-Sep-13	0.006	0.002	0.007	0.099	0.118	64.0	63.5	0.774	1.1	0.8	10.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJMID	23-Oct-13	0.007	0.003	0.012	0.103	0.141	64.8	60.8	0.948	1.5	<.1	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	13-Mar-13	0.007	<0.001	<0.005	0.164	0.189	70.2	69.6	0.638	2.4	<0.1	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	11-Apr-13	0.007	<0.001	0.017	0.252	0.312	71.2	70.4	0.930	2.5	0.2	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	8-May-13	0.010	<0.001	0.009	0.065	0.148	68.2	65.3	1.68	3.0	0.5	6.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	12-Jun-13	0.007	0.005	0.021	0.074	0.117	64.8	—	1.38	0.8	0.3	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	12-Jul-13	0.006	0.001	0.012	0.058	0.177	62.5	—	1.24	1.3	0.2	7.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	<2.00
CHJFB	7-Aug-13	0.006	0.003	0.012	0.070	0.121	64.2	—	0.915	1.1	0.4	9.0	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	
CHJFB	11-Sep-13	0.007	0.001	<0.005	0.101	0.141	64.0	63.3	0.991	4.8	0.6	6.5	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJFB	23-Oct-13	0.007	0.002	0.010	0.110	0.131	63.7	60.8	0.827	2.1	0.5	9.5	<0.0010	0.007	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	13-Mar-13	0.006	<0.001	<0.005	0.162	0.189	70.4	69.2	0.643	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	11-Apr-13	0.007	0.001	0.012	0.252	0.295	71.6	67.7	0.911	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	8-May-13	0.012	<0.001	0.014	0.076	0.182	67.6	62.5	1.59	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	12-Jun-13	0.007	<0.001	0.019	0.073	0.109	64.4	—	1.38	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	12-Jul-13	0.006	0.001	0.01	0.061	0.155	62.7	—	1.23	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	7-Aug-13	0.007	0.002	0.012	0.068	0.112	63.0	—	1.05	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	11-Sep-13	0.007	0.002	0.005	0.091	0.116	62.0	63.7	0.691	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—
CHJTW	23-Oct-13	0.008	0.003	0.008	0.110	0.125	64.6	62.0	0.594	—	—	—	<0.0010	<0.005	—	—	—	—	—	—	—	—	—	—	—	—

2.2.1 Water Temperature

The temperature-related characteristics of water have a large effect on water quality and the ecology of lakes. As lake water warms in the spring and summer, it becomes less dense and floats on top of colder water. In the absence of sufficient energy (e.g., wind or high inflows) to mix the water and equilibrate the temperature, a lake will thermally stratify and form two separate temperature layers. Thermal stratification produces a warm water upper layer, called the epilimnion, and a cold water bottom layer, called the hypolimnion. The transition zone between these two layers is called the metalimnion or thermocline and is marked by rapid changes in water temperatures from top to bottom. Because of the temperature difference in a stratified lake, there is little mixing of water between the epilimnion and hypolimnion until the lake de-stratifies in the fall and winter, resulting in a uniform temperature throughout the water column.

Little to no stratification was observed in Rufus Woods Lake during 2011, 2012, and 2013 largely due to the high flows and short retention times in the lake. Temperature profiles collected in Rufus Woods Lake at the upstream (CHJUP) middle (CHJMID) and forebay (CHJFB) water quality stations are presented in Figure 2-4. Water temperatures during all three years followed a similar pattern of warming from March through September and cooling in October, with the warmest temperatures experienced during August and September. For the 2011 to 2013 period, temperatures at the upstream, aquaculture, and middle stations peaked at about 18 to 19°C, while temperatures at the forebay station were slightly warmer and peaked at about 19 to 20°C.

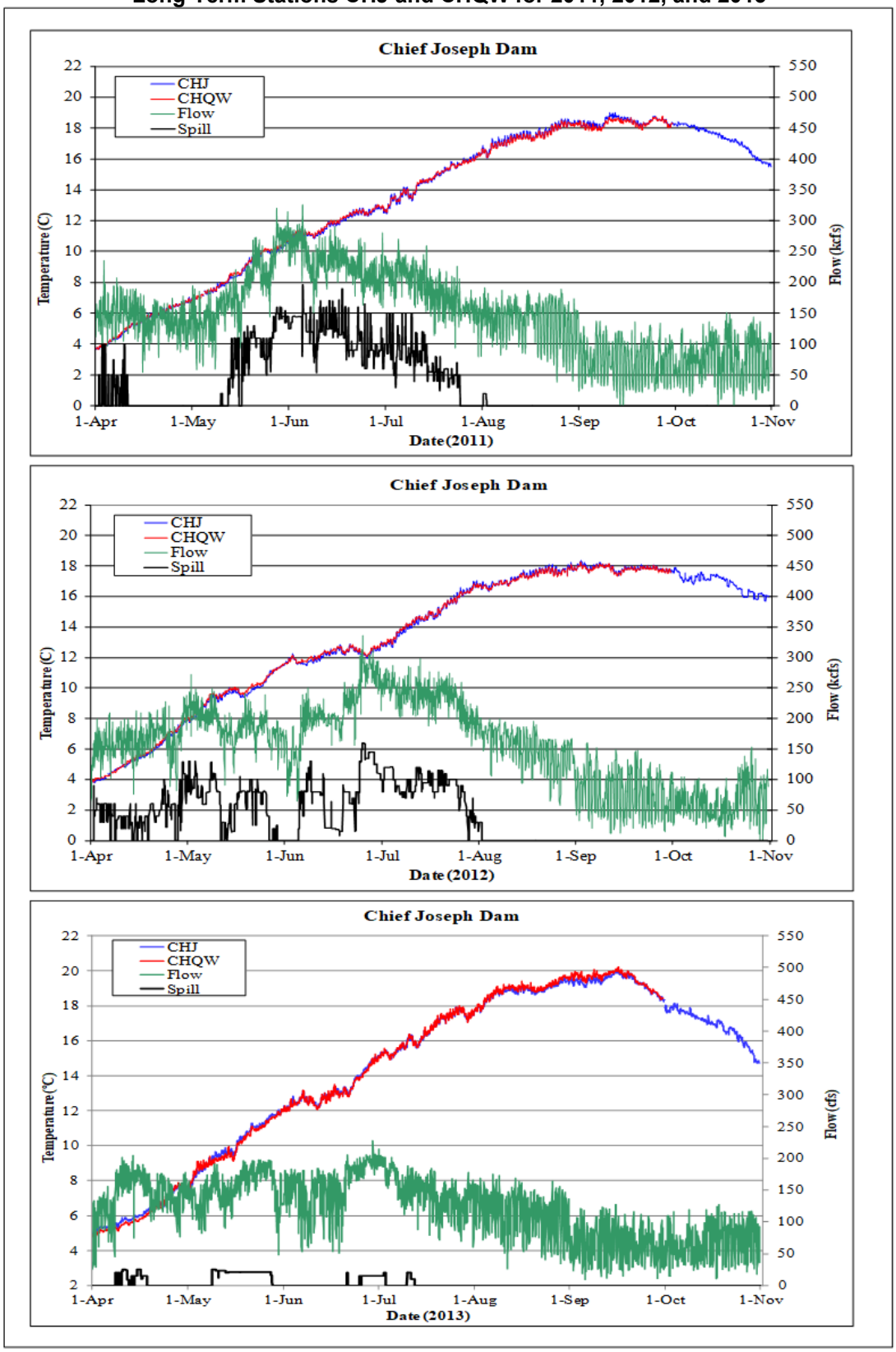
Figure 2-4. Rufus Woods Lake Water Temperature Profiles at Stations CHJUP, CHJMID, and CHJFB for 2011 to 2013



Vertical thermal gradients were apparent only during August and September at the forebay station (CHJFB) as indicated by the temperature profile time histories presented in Figure 2-4. The forebay stratification during these two months was very weak with surface temperatures about 1 to 2 degrees Celsius warmer in the top few meters. The forebay of Rufus Woods Lake represents the deepest and widest area in the lake with the lowest water velocities, which allowed for the development of the small thermal gradient in August and September. Vertical temperature profiles at the upstream (CHJUP) and middle (CHJMID) stations show that Rufus Woods Lake is completely mixed at these locations due to the high flows.

Real-time hourly temperatures are collected in the Chief Joseph Dam forebay and tailwater from April through October.The Chief Joseph Dam forebay station (CHJ) is located at a depth of 6 meters in Rufus Woods Lake near the left bank by the powerhouse. The Chief Joseph Dam tailwater station (CHQW) is located next to water quality station CHJTW at a depth of about 3 meters along the right bank of the river, 2 kilometers downstream from the spillway. Continuous near-surface water temperatures collected at long-term fixed monitoring stations CHJ and CHQW are shown in Figure 2-5. In general, hourly temperatures were greater than 16°C from about the middle of July through late October, and greater than 17.5°C from about the beginning of August through the end of September.

Figure 2-5. Continuous Hourly Temperature, Flow and Spill at Long-Term Stations CHJ and CHQW for 2011, 2012, and 2013



2.2.2 Transparency

Water transparency was measured in Rufus Woods Lake using a Secchi disk, which is an 8-inch disk with alternating black and white quadrants. The depth at which the disk can no longer be seen in the water is called the Secchi disk depth. This depth is a relative measure of water transparency that can be used to look at changes in water clarity over time and between sampling stations. Water clarity is an important parameter when determining the trophic status of a lake because the number of phytoplankton suspended in the water column directly impacts transparency. However, transparency alone cannot be used to predict the trophic state because many other factors can affect transparency including suspended matter, soil particles, and natural water color.

Monthly changes in transparency at water quality stations in Rufus Woods Lake for 2011, 2012, and 2013 are presented in Figure 2-6. Transparency depths and seasonal trends were similar between 2011 and 2012 for all stations with generally moderate transparencies in March (range of 5 to 7 meters), lower transparencies from April through July (range of 3 to 5 meters), and greater transparencies from August through October (range of 8 to 11 meters). The reduced April through July transparencies in 2011 and 2012 may be partly due to the greater Columbia River flows passing through Rufus Woods Lake during these years, bringing in greater loads of suspended solids and turbidity. A moderately strong negative relationship between transparency and chlorophyll a is apparent in 2011 and 2012, suggesting that in addition to flow, the reduced water clarity measured in 2011 and 2012 may also be due to the amount of algae suspended in the water column (Figure 2-7).

Figure 2-6. Rufus Woods Lake Transparencies for 2011, 2012, and 2013

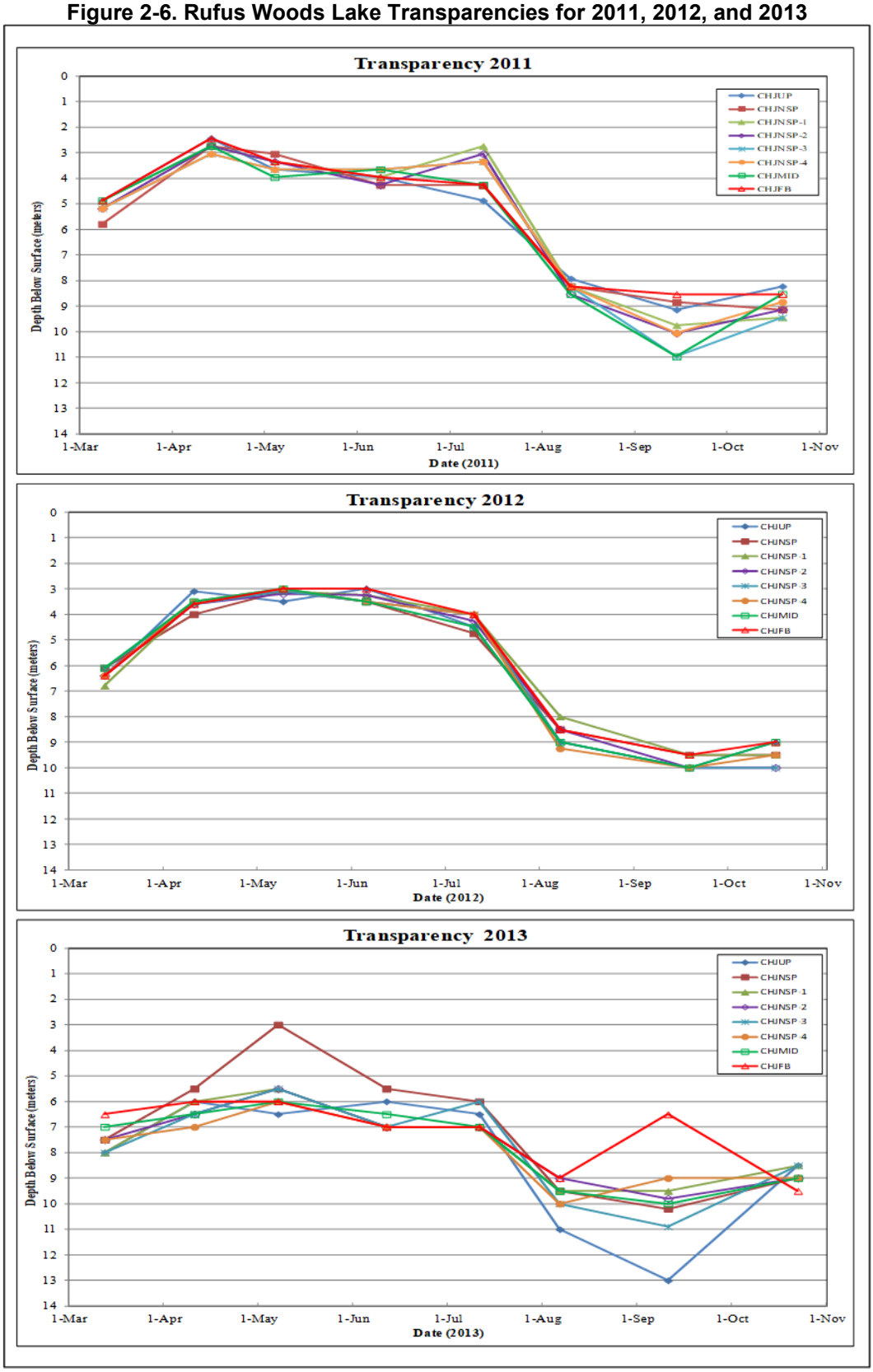
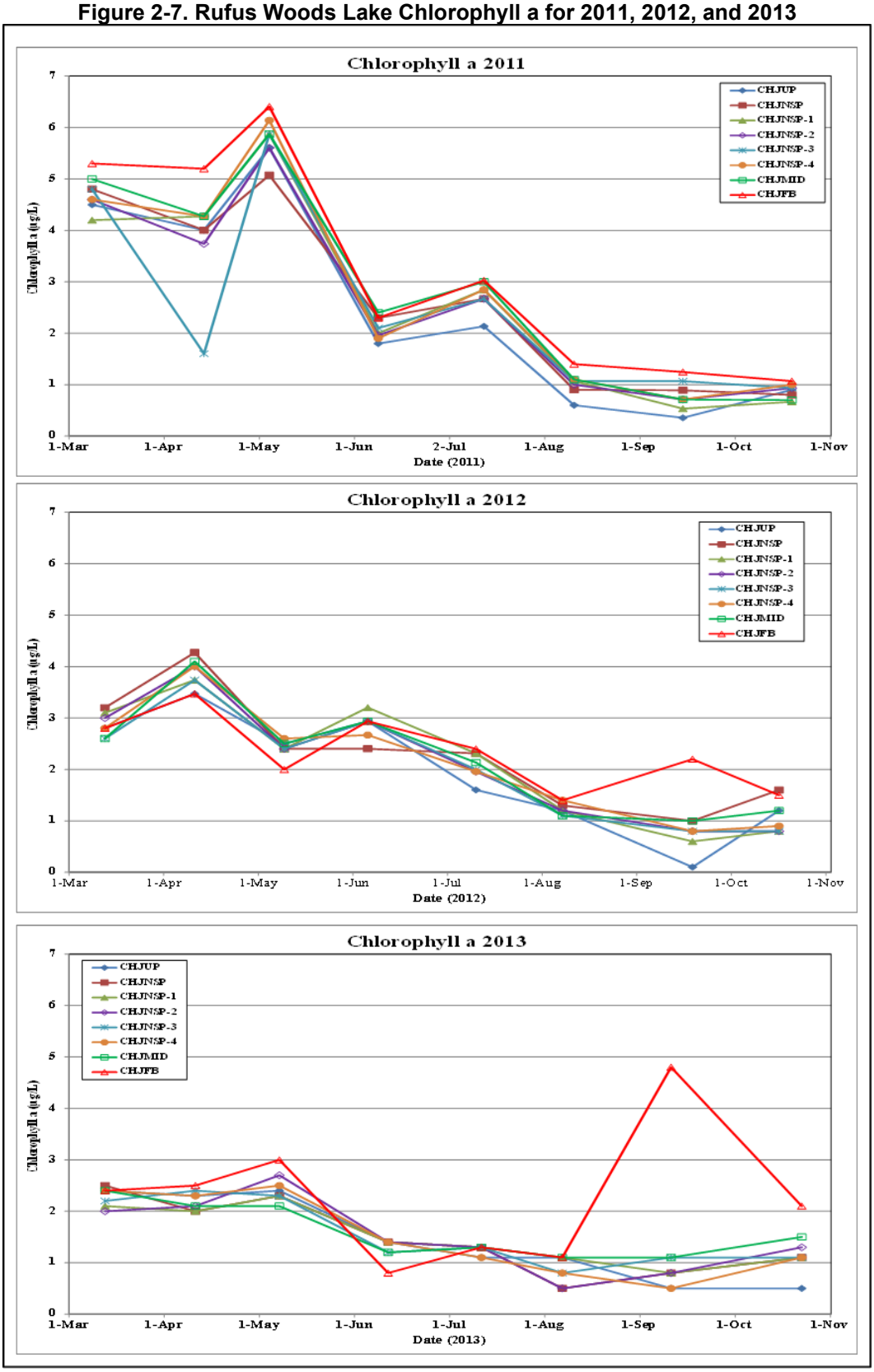


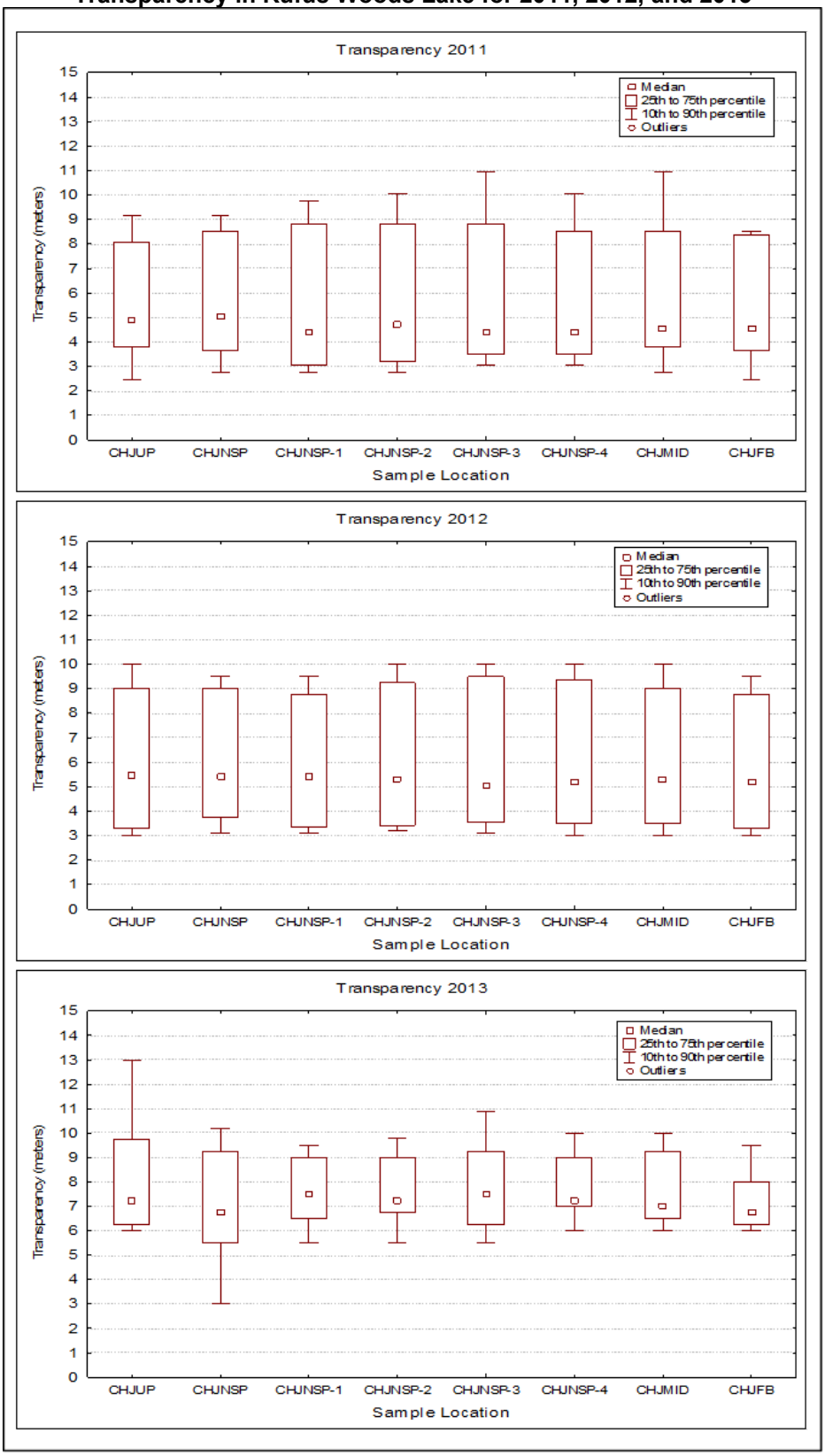
Figure 2-7. Rufus Woods Lake Chlorophyll a for 2011, 2012, and 2013



Transparencies were greater in 2013 with a slightly different seasonal pattern (Figure 2-6). At all stations except CHJNSP, transparencies were moderate from March to July (range of 6 to 8 meters) with no decrease in water clarity during the spring runoff period of April through July. Lower Columbia River flows and reduced chlorophyll a concentrations in 2013 are likely responsible for the increased transparency in Rufus Woods Lake (Figure 2-6 and Figure 2-7). At CHJNSP, transparencies decreased from about 6 meters in April to 3 meters in May before increasing back to 6 meters in June. The decreased water clarity in May at Station CHJNSP was due to turbid runoff from the Nespelem River that impacted the station, which is located near the mouth of the river. Transparencies increased from July through October for all stations except CHJFB, which experienced a sharp decrease in water clarity in September. This September decrease appears related to increased algal growth measured at the forebay as seen from the relationship between chlorophyll a and transparency at Station CHJFB (Figure 2-7). Similar to 2011 and 2012, a moderately strong negative relationship between transparency and chlorophyll a is apparent for the entire 2013 sampling season.

A summary of annual (March to October) water transparencies at each station from 2011 to 2013 is presented in Figure 2-8. Annual transparency data was similar between stations for each year but exhibited year-to-year variations. The median annual transparency ranged from 4 to 5 meters in 2011, to 5 to 6 meters in 2012, and 7 to 8 meters in 2013. The overall range of data was substantially greater in 2011 and 2012 compared to 2013 likely due to the lower transparencies measured those years during the April through July time period.

Figure 2-8. Statistical Summary of Annual (March to October) Transparency in Rufus Woods Lake for 2011, 2012, and 2013



2.2.3 Dissolved Oxygen

The concentration of dissolved oxygen in the water is important for determining the types of organisms that can survive and for regulating chemical processes, such as nutrients released from the sediments. For example, anoxic (no oxygen) conditions at the sediment water interface can result in the release of phosphorus from the sediments into the overlying water. Oxygen is supplied to the water from the atmosphere and from aquatic plants through photosynthesis. Oxygen can be removed from water by the respiration of aquatic organisms and plants, as well as the decomposition of organic matter in the water and sediments by bacteria.

The solubility of oxygen in water is affected by temperature and air pressure. Oxygen solubility increases in cold water and with higher atmospheric partial pressure. Washington State water quality standards for dissolved oxygen in the Columbia River at Rufus Woods Lake are to exceed 8 mg/L (see Table 2-7). Monthly dissolved oxygen profiles collected in Rufus Woods Lake at the upstream (CHJUP) middle (CHJMID) and forebay (CHJFB) water quality stations are presented in Figure 2-9. Downstream Columbia River dissolved oxygen concentrations measured at the tailwater station CHJTW are shown in Figure 2-10.

Figure 2-9. Rufus Woods Lake Dissolved Oxygen Profiles at Stations CHJUP, CHJMID, and CHJFB for 2011 to 2013

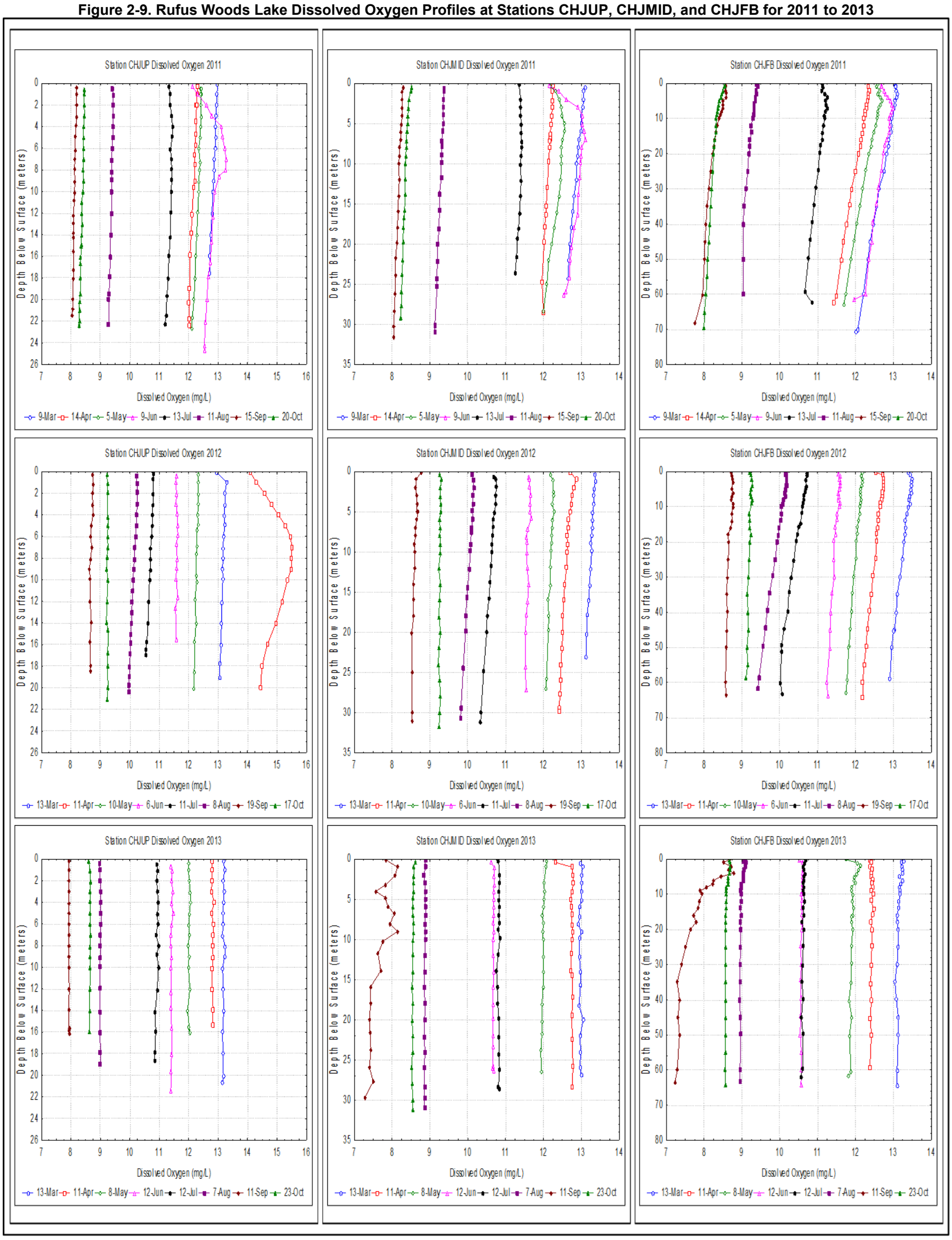
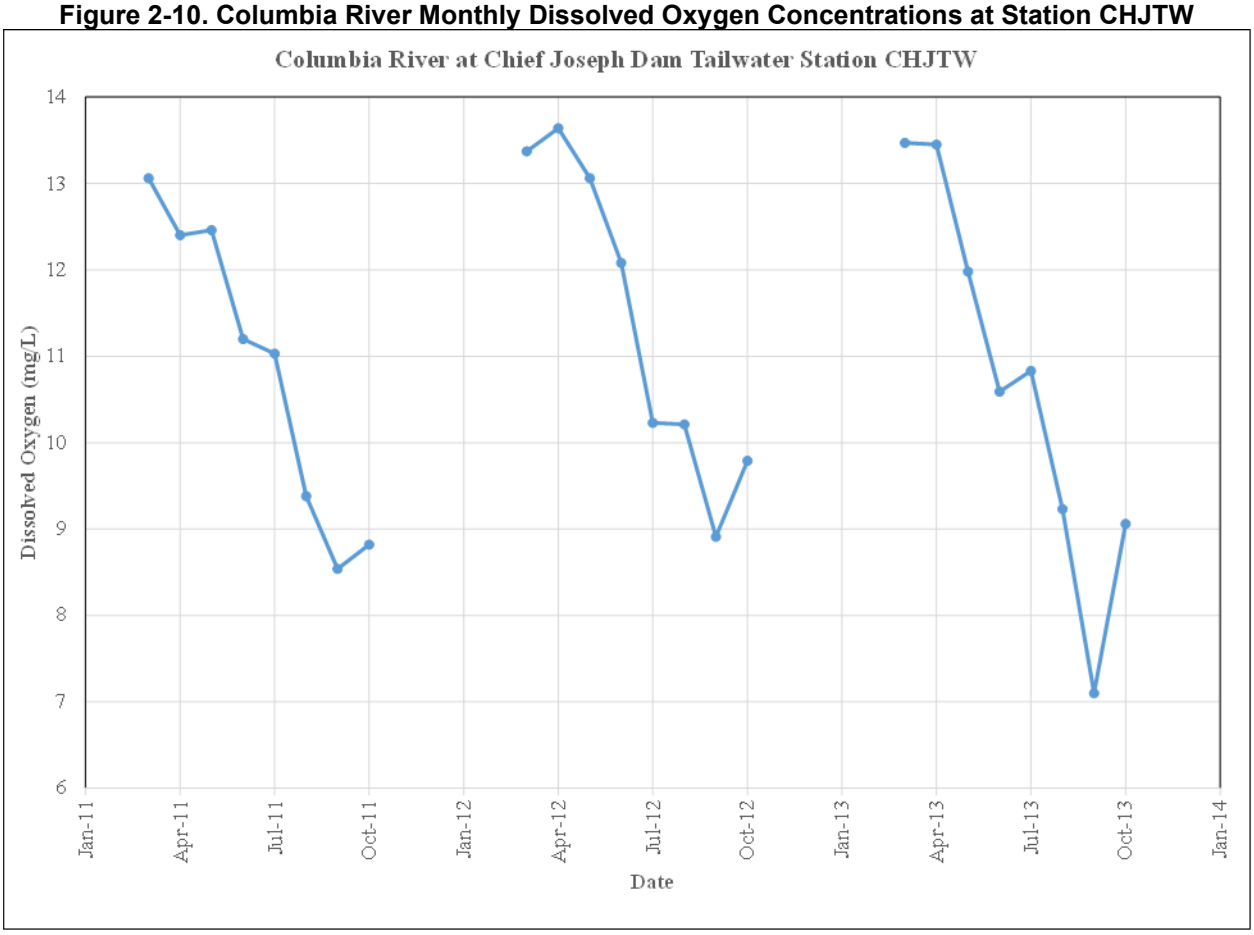


Figure 2-10. Columbia River Monthly Dissolved Oxygen Concentrations at Station CHJTW



In general, dissolved oxygen concentrations in Rufus Woods Lake followed a similar pattern at each station for all 3 years. Concentrations were greatest in March and April, decreased through the year to a low in September, and then increased in October. This temporal pattern in dissolved oxygen is related to the natural warming and cooling of water in Rufus Woods Lake from spring through fall. Small exceptions to this general trend were seen in 2011 when dissolved oxygen concentrations at some stations increased and peaked in June. This late spring oxygen maxima was related to both increased phytoplankton concentrations in Rufus Woods Lake and to spillway releases from Grand Coulee Dam. Phytoplankton growth increases dissolved oxygen in the water column through photosynthesis while spillway releases increase the TDG saturation (including oxygen) of the water.

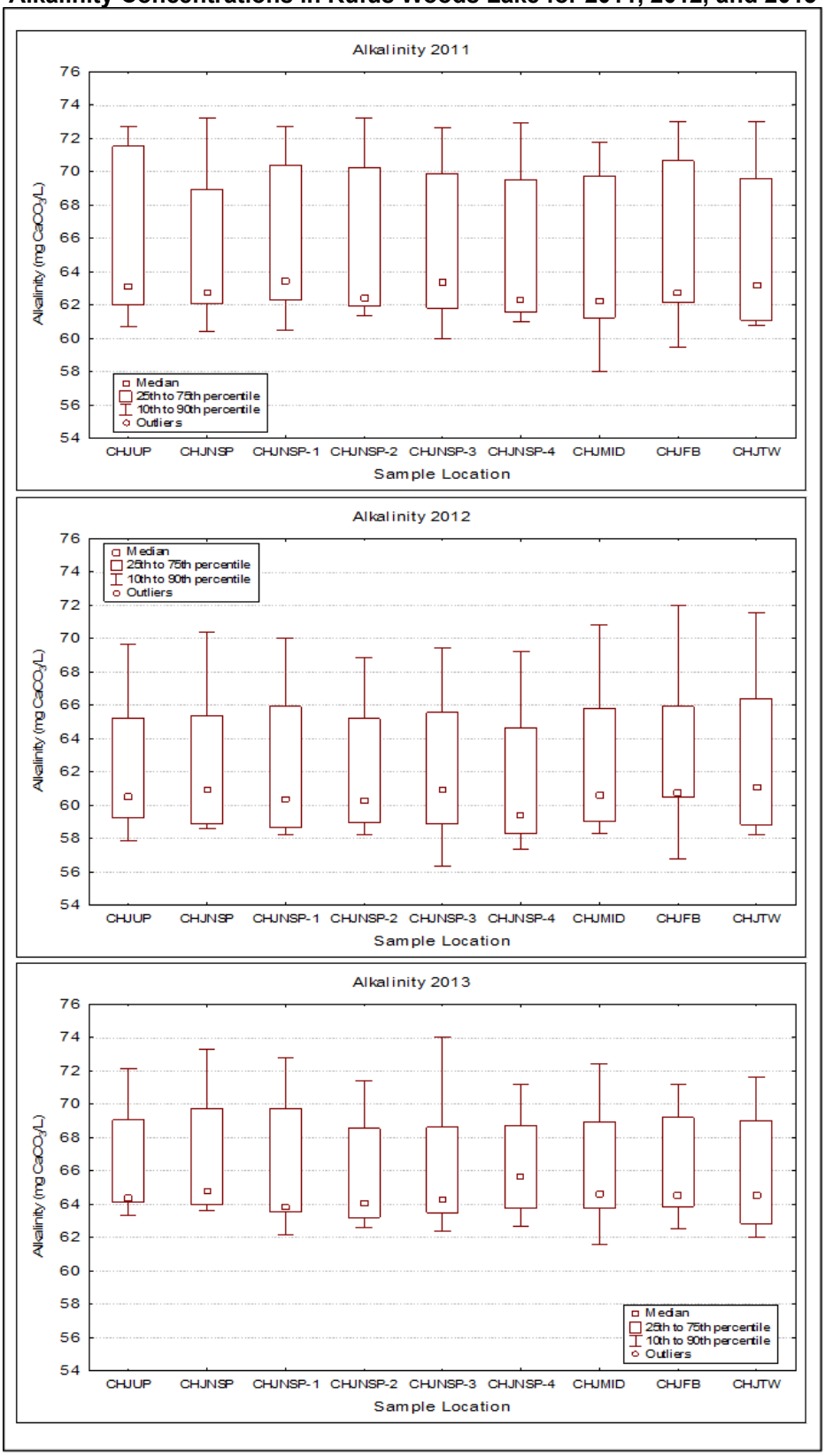
Vertical profile data shows that Rufus Woods Lake is well oxygenated from the surface to the bottom at all stations. Only small decreases (about 1 mg/L) in dissolved oxygen were apparent between the surface and bottom. As previously noted, dissolved oxygen concentrations were greatest in Rufus Woods Lake during months when water temperatures were coolest or when Grand Coulee Dam was spilling water. Dissolved oxygen in Rufus Woods Lake exceeded 8 mg/L at all stations for all months and years except for September 2013 when concentrations in the lake averaged about 7 to 8 mg/L and were about 7.1 mg/L downstream in the Columbia River at station CHJTW (Figure

2-9 and Figure 2-10). The lower oxygen concentrations in September 2013 in Rufus Woods Lake and the downstream Columbia River were likely a direct function of the warmer water temperatures measured in the lake during 2013 (see Figure 2-4). However, the greater oxygen concentrations measured near the surface at CHJFB in September 2013 are likely due to increased algae concentrations measured in the forebay (see Figure 2-7).

2.2.4 Alkalinity, Hardness and pH

Alkalinity is a measure of the buffering capacity of the water to changes in pH. In many freshwater ecosystems, alkalinity is a function of the concentration of bicarbonates, carbonates, and hydroxides (Wetzel 1975). It is likely that the alkalinity of Rufus Woods Lake is dominated by the carbonate system (HCO_3 and CO_3). Over the duration of the study, alkalinity concentrations in Rufus Woods Lake were similar between stations and years and ranged from 56 to 74 mg as calcium carbonate per liter ($CaCO_3$/L), with a median concentration of 63 mg $CaCO_3$/L (Figure 2-11 and Table 2-1 to Table 2-3). Based on this data, Rufus Woods Lake would be classified as having moderate alkalinity with an average buffering capacity to pH changes.

Figure 2-11. Data Summary of Annual (March to October) Alkalinity Concentrations in Rufus Woods Lake for 2011, 2012, and 2013



Hardness is a measure of the amount of calcium and magnesium salts in water that are often combined with either bicarbonate or carbonate, or with anions such as sulfate or chloride (Wetzel 1975). Harder waters have greater concentrations of calcium and magnesium salts. In freshwater, hardness can be important in determining the toxicity of many metals, such as copper and zinc. Toxicity decreases with an increase in hardness. Therefore, hardness measurements are necessary to calculate water quality criteria for various metals. For Rufus Woods Lake, hardness was similar between stations and ranged from 55 to 76 mg $CaCO_3$/L, with a median concentration of 61 mg $CaCO_3$/L (see Table 2-1 to Table 2-3). These concentrations represent moderately hard water that is typical of freshwater ecosystems in the Columbia Basin of Eastern Washington (Briggs and Ficke 1977).

The parameter pH is a measure of the hydrogen ion activity in the water and is measured on a base-10 logarithmic scale from 0 to 14 with values less than 7 being acidic, values greater than 7 being basic, and a value of 7 being neutral. Washington State water quality standards for pH in the Columbia River at Rufus Woods Lake are 6.5 to 8.5 (see Table 2-7). In general, pH values were similar between stations and years and ranged from about 6.8 to 8.4, with a median pH of about 7.7. This data indicates that Rufus Woods Lake is a near neutral to slightly basic lake. Except for a few outliers during the 3-year study, the higher pH values were largely associated with near surface waters and were likely due to photosynthetic activity of algae removing carbon dioxide from the water, thereby increasing pH.

2.2.5 Specific Conductivity

Conductivity is a measurement of a solutions ability to conduct electricity and is often used as an indicator of the amount of dissolved ions present because conductivity increases with an increase in dissolved ions. Specific conductivity is the conductivity, normalized to a standard temperature (25°C), and is reported in (µS/cm). During the study, Rufus Woods Lake specific conductivity was similar between stations and years and ranged from about 93 µS/cm to 153 µS/cm, with a median conductivity of 127 µS/cm. Monthly vertical profiles show little difference in specific conductivity with depth. In general, specific conductivity measured at all stations was greatest during March and April, decreased during the May and June spring freshet time period, and remained relatively stable during the July through October time period.

2.2.6 Nutrients

Phosphorus and nitrogen are the major nutrients required for the growth and productivity of phytoplankton and aquatic plants. The vast majority of lake water quality problems are associated with an overabundance of these nutrients resulting in excessive phytoplankton growth, causing nuisance blooms and resulting decay. The decay of large amounts of phytoplankton can reduce oxygen concentrations to levels that are harmful to many organisms. In freshwater ecosystems, phosphorus is generally the nutrient with the smallest supply-to-demand ratio for phytoplankton growth. Consequently, phosphorus is often the nutrient that limits productivity in freshwater ecosystems and has relatively limited sources, so it is frequently focused on for control

of eutrophication. However, in some circumstances, nitrogen can be limiting instead of phosphorus, although nitrogen cycling and control of nitrogen sources is more complex. Increased phosphorus and nitrogen inputs to freshwater ecosystems from human activities can be attributed to numerous sources including: the discharge of detergents, runoff containing fertilizers, seepage from failing septic systems, urban runoff and sewage discharges, as well as farm animal and aquaculture waste discharges.

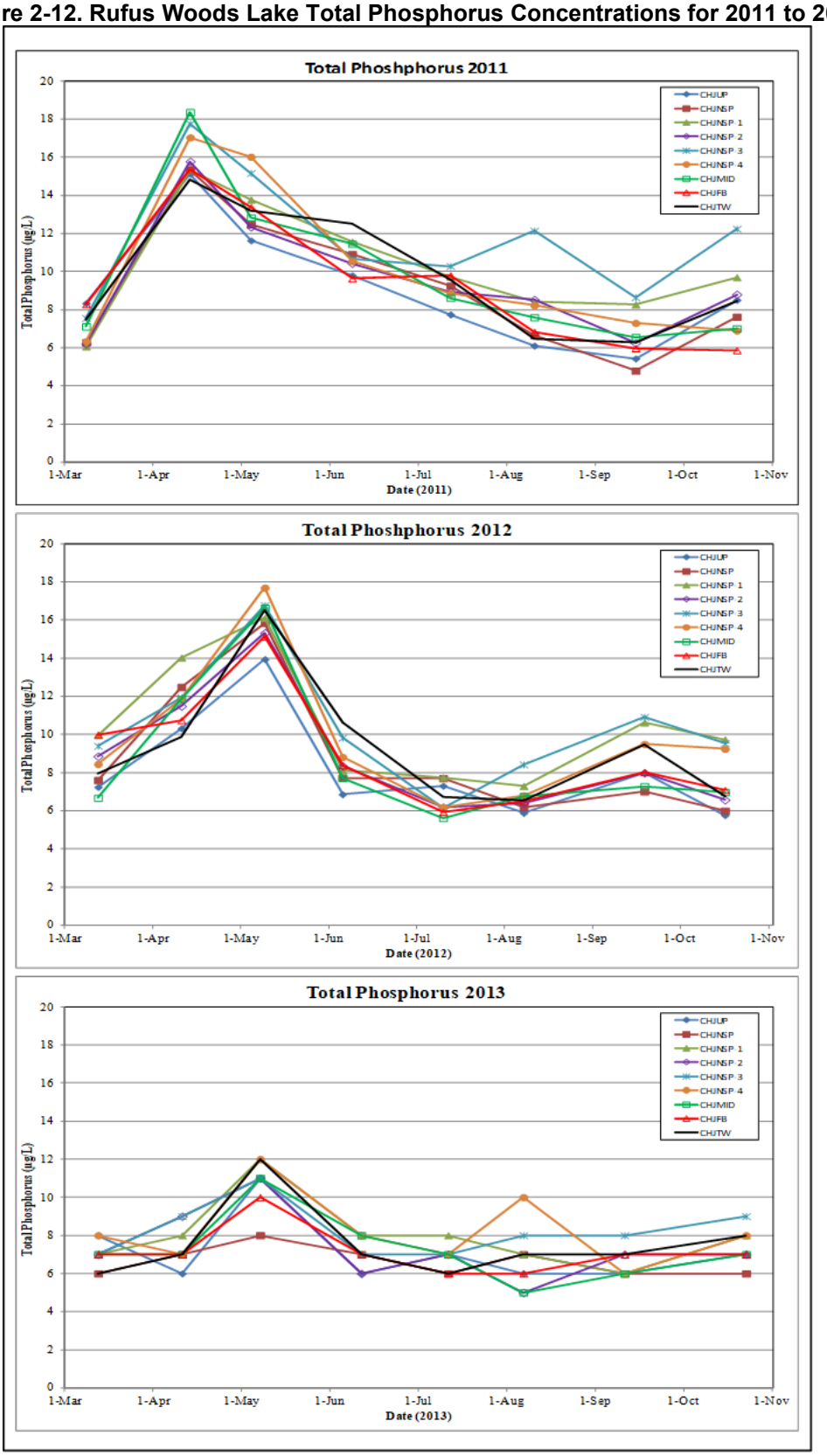
Ecology established ecoregional and trophic state total phosphorus concentration action values for establishing nutrient criteria in lakes and reservoirs with a mean detention time greater than 15 days (Ecology 2011). Although Rufus Woods Lake has a mean detention time less than 15 days (see Figure 2-2), it is still of value to compare Rufus Woods nutrient concentrations to the Ecology ecoregional action values in order to better understand the water quality conditions in the reservoir. For the Columbia Basin ecoregion, which contains Rufus Woods Lake, a total phosphorus criterion of 10 µg/L or less is set for oligotrophic, 10 to 20 µg/L for lower mesotrophic, 20 to 35 µg/L for upper mesotrophic, and eutrophic with an action value of greater than 35 µg/L. Currently, Ecology has not set forth any action values for establishing nitrogen criteria in lakes and reservoirs.

2.2.6.1 *Phosphorus*

Phosphorus concentrations in Rufus Woods Lake were reported as total phosphorus and soluble reactive phosphorus. Total phosphorus represents all forms of phosphorus in water, both dissolved and particulate, including all organically combined phosphorus and all phosphate. Soluble reactive phosphorus represents the dissolved form of phosphorus that is readily available for aquatic plant uptake.

Monthly concentrations of total phosphorus in Rufus Woods Lake for 2011 to 2013 are presented in Figure 2-12 and Table 2-1 to Table 2-3. Total phosphorus concentrations measured during the study ranged from 5 µg/L to 18 µg/L and followed similar seasonal patterns with low concentrations in March, increasing concentrations during high runoff spring conditions in April and May, and decreasing concentrations during the summer and fall. Concentrations of total phosphorus were greatest at all stations in Rufus Woods Lake during 2011 and 2012, likely due to the higher runoff conditions and greater flow in the Columbia River during those 2 years. A similar increase in total phosphorus concentrations during the high-flow April and May time period was previously noted in the middle Columbia River at Rocky Reach Reservoir (Parametrix 2001).

Figure 2-12. Rufus Woods Lake Total Phosphorus Concentrations for 2011 to 2013



Boxplots of total phosphorus concentrations for each station for the 2011 to 2013 study are shown in Figure 2-13. Median total phosphorus concentrations ranged from about 8 µg/L to 11 µg/L in 2011 and 2012, and from about 7 µg/L to 8 µg/L in 2013. The range of concentrations measured at all stations in 2011 and 2012 was greater than in 2013 likely due to the differences in runoff volumes in the Columbia River between years. Small differences in total phosphorus median concentrations and range of data existed between stations with the greatest concentrations measured downstream of the aquaculture facilities at stations CHJNSP-1 and CHJNSP-3. These small differences in total phosphorus concentrations between stations are seen more clearly when looking at summer (June to October) data for the entire 2011 to 2013 sampling period (Figure 2-14). Summer total phosphorus concentrations were greater immediately downstream of the aquaculture sites (CHJNSP-1 and CHJNSP-3) than at other stations. This data suggests that the aquaculture facilities may be a source of phosphorus to Rufus Woods Lake.

Figure 2-13. Rufus Woods Lake Data Summary of Annual (March to October) Total Phosphorus Concentrations for 2011 to 2013

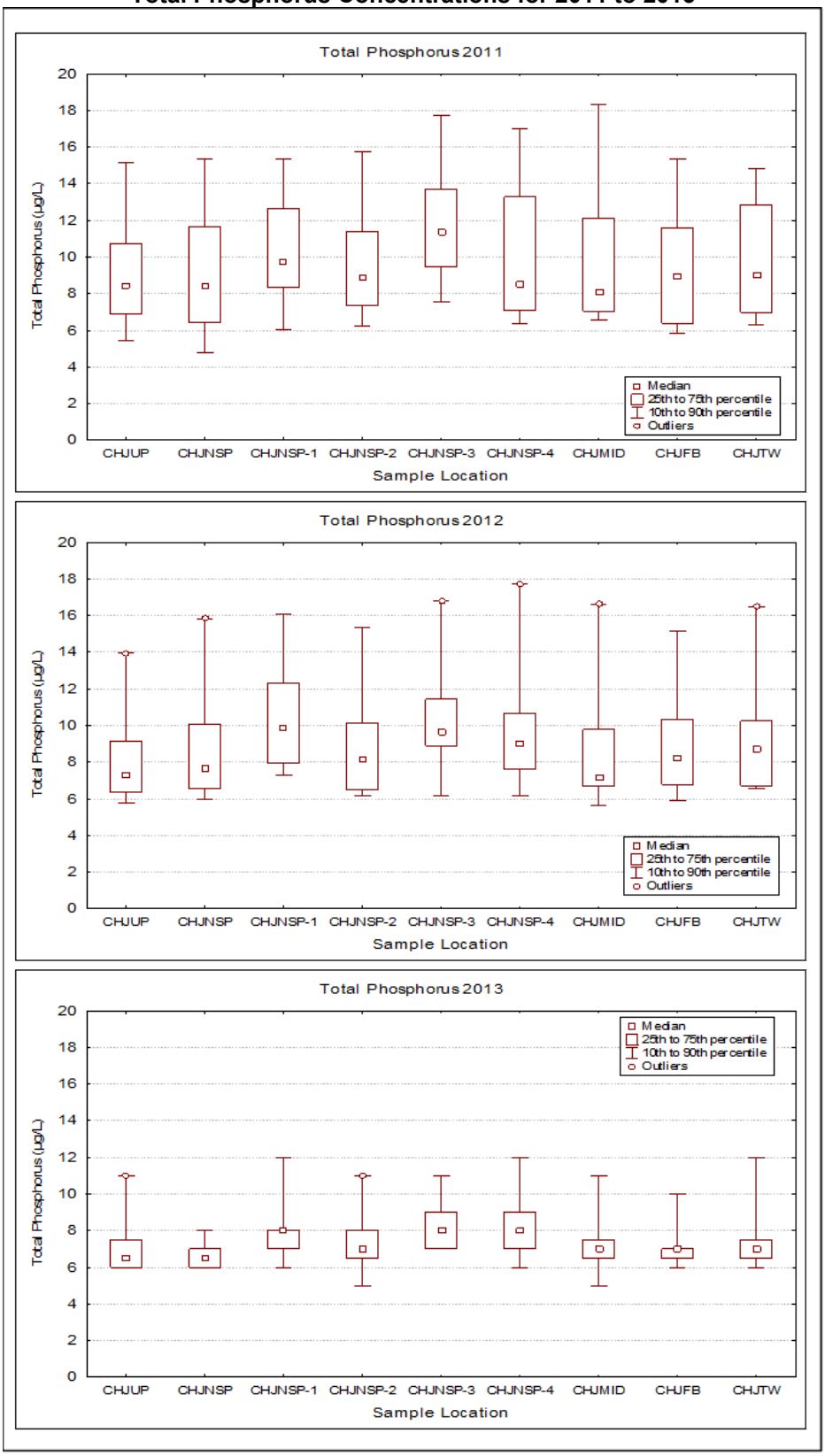
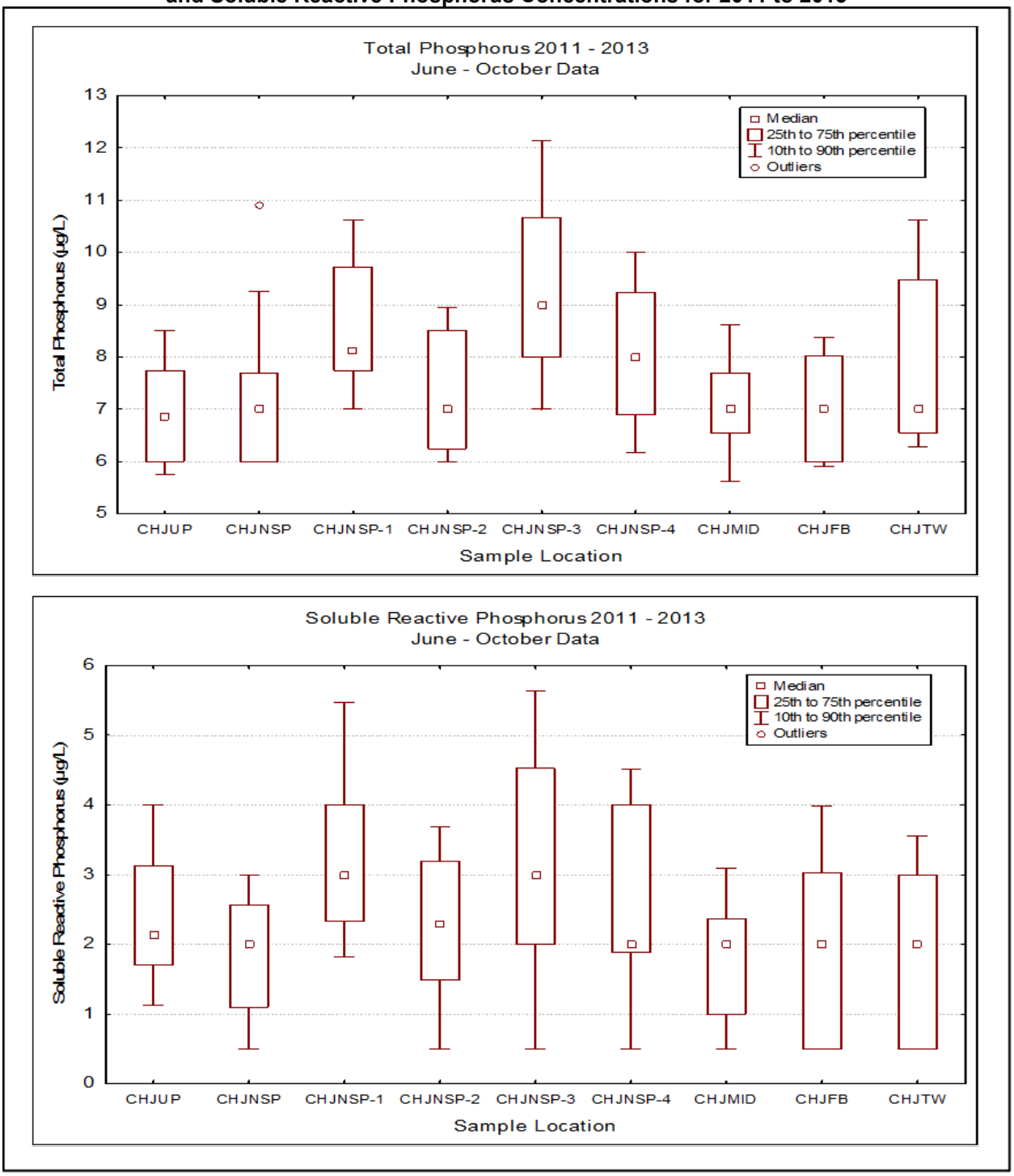


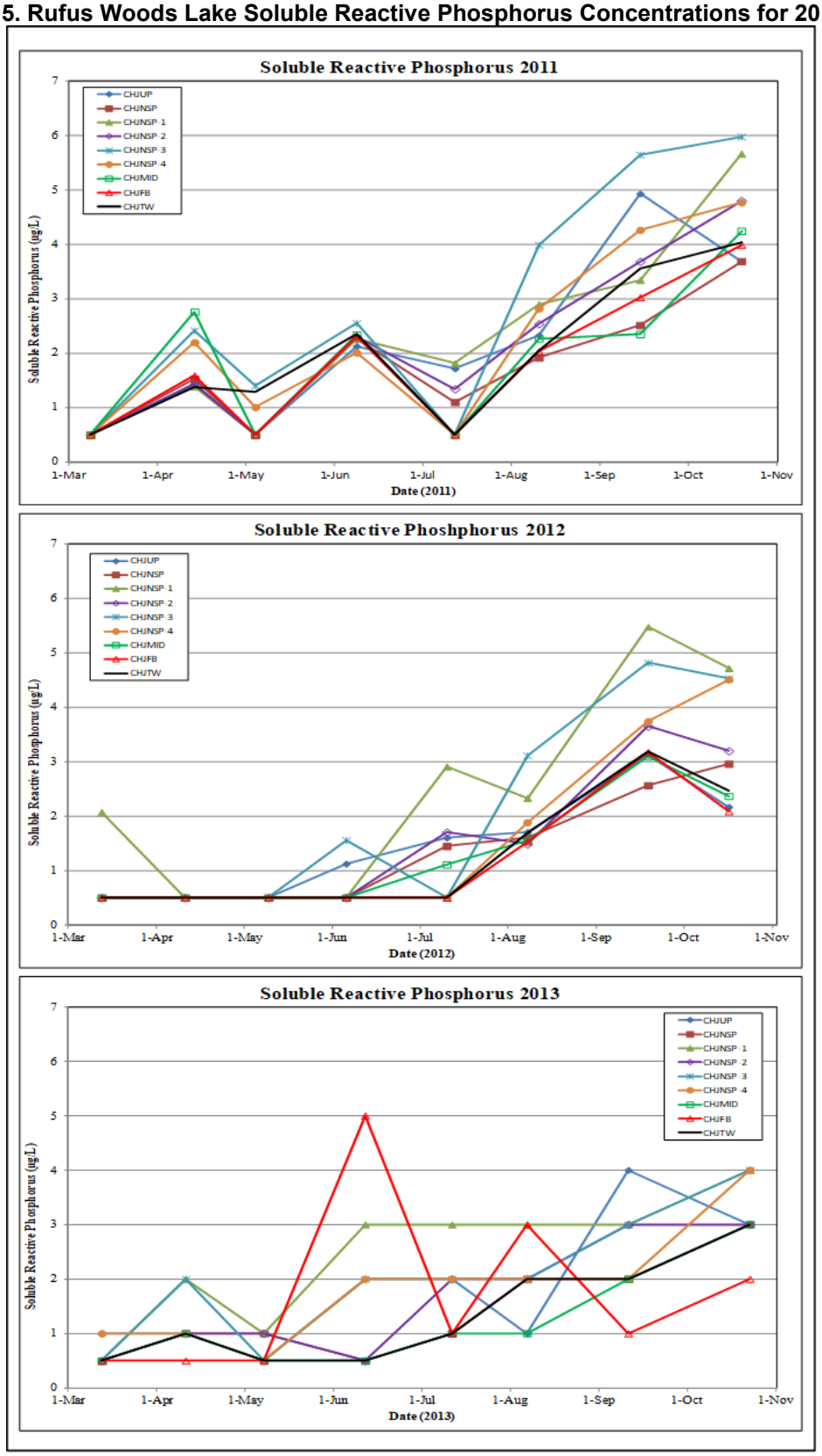
Figure 2-14. Rufus Woods Lake Data Summary of Summer (June to October) Total Phosphorus and Soluble Reactive Phosphorus Concentrations for 2011 to 2013



Soluble reactive phosphorus concentrations were low in Rufus Woods Lake, ranging from less than the detection limit of 1 µg/L to a maximum concentration of 6 µg/L (Figure 2-15 and Table 2-1 to Table 2-3). In general, soluble reactive phosphorus concentrations at all stations during the 2011 to 2013 study were lowest during the spring high flow (March through June) and increased during the summer and fall (July

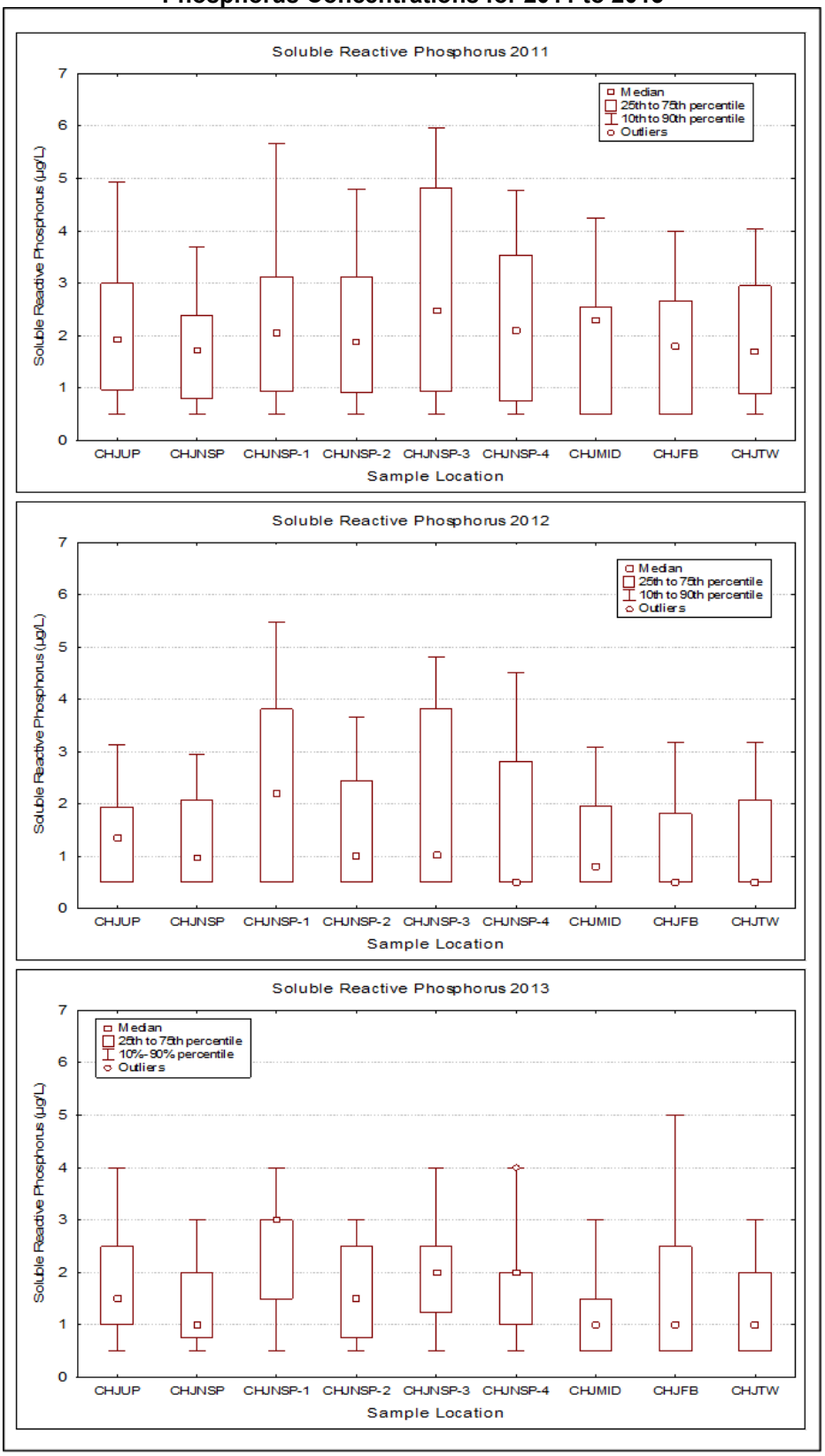
through October). Similar to total phosphorus concentrations, soluble reactive phosphorus concentrations were greatest during 2011 and 2012 with slightly lower concentrations measured in 2013. Because soluble reactive phosphorus stimulates algal growth in fresh waters, it is typically lowest during periods of algal uptake or growth. For Rufus Woods Lake, the seasonal progression of soluble reactive phosphorus suggests that algal growth is largely occurring during the March through June time period with a decrease in algal growth during the summer and fall. This seasonality correlates well to chlorophyll a concentrations measured in Rufus Woods Lake (see Figure 2-7) during the study, affirming the relationship between soluble reactive phosphorus uptake and algal growth.

Figure 2-15. Rufus Woods Lake Soluble Reactive Phosphorus Concentrations for 2011 to 2013



Median soluble reactive phosphorus concentrations in Rufus Woods Lake were low and ranged from about 1 to 2 µg/L at most stations (Figure 2-16). The overall range in concentrations was greatest in 2011 and 2012. There were only small differences in annual soluble reactive phosphorus concentrations measured between stations for 2011, 2012, and 2013. However, these differences in concentrations between stations are seen more clearly when looking at summer (June to October) data for the entire 2011 to 2013 sampling period (Figure 2-14). Similar to summer total phosphorus concentrations, summer soluble reactive phosphorus concentrations were slightly greater at stations CHJNSP-1 and CHJNSP-3, which are located immediately downstream of the aquaculture facilities.

Figure 2-16. Rufus Woods Lake Data Summary of Annual (March to October) Soluble Reactive Phosphorus Concentrations for 2011 to 2013



2.2.6.2 *Nitrogen*

Nitrogen, like phosphorus, is essential for the growth and production of phytoplankton in fresh waters. In freshwater ecosystems, nitrogen exists in many forms including dissolved molecular nitrogen, organic nitrogen, nitrite, nitrate, and ammonia. Sources of nitrogen to freshwaters are varied and include atmospheric inputs via precipitation, nitrogen fixation in the water and sediments, and via surface and groundwater inputs. Losses of nitrogen in the freshwater ecosystem include outflow from the system; reduction of nitrate to nitrogen via denitrification and the subsequent release of nitrogen from the water to the atmosphere; and sedimentation of inorganic and organic forms of nitrogen (Wetzel 1975). The most common forms of nitrogen used by freshwater plants for growth are the dissolved forms that include ammonia-nitrogen and nitrate-nitrogen.

Three forms of nitrogen were measured, total nitrogen, nitrate + nitrite-nitrogen (NO_3 + NO_2-N), and ammonia-nitrogen (NH_4+-N + NH_3-N). The dissolved inorganic forms of nitrogen, ammonia and nitrate + nitrite are all readily available for plant growth. Total nitrogen was measured by the persulfate digestion method (see Table 2-2) and includes all inorganic plus organic forms of nitrogen, in both dissolved and particulate fractions. Nitrate + nitrite- nitrogen represents dissolved oxidized nitrogen, with nitrite being an intermediate state between ammonia and nitrate. Nitrate is an essential plant nutrient, while nitrite can be a plant nutrient but is generally unstable and is rapidly oxidized to ammonia in oxygenated waters. Ammonia nitrogen is an essential plant nutrient that is often utilized before nitrate. Ammonia is formed in the natural environment through the fixation of nitrogen gas, excretion by animals, and the decomposition of organic material (plant and animal tissues). In the aquatic environment, ammonia is produced and excreted by fish. Ammonia is reported as the combined ionized (NH_4^+-N - ammonium) and unionized (NH_3-N - ammonia) forms of ammonia. The unionized form of ammonia (NH_3-N) is toxic to freshwater life and is most prevalent at high pH (greater than about 9.3 pH units). Equations can be used to estimate the concentration of unionized ammonia fraction from measured values of the pH and temperature of the water (see Table 2-8). In general, for pH and temperature values measured in Rufus Woods Lake, the unionized form of ammonia (NH_3-N) represents an extremely small percentage of the total ammonia nitrogen concentration (Greenberg, Eaton, and Clesceri 1992).

Total nitrogen concentrations in Rufus Woods Lake ranged from 103 to 352 µg/L in 2011, from 112 to 341 µg/L in 2012, and from 106 to 312 µg/L in 2013 (Figure 2-17 and Table 2-1 to Table 2-3). As seen in Figure 2-18, median total nitrogen concentrations and the range of data were similar between stations for each sampling season. These similarities are also seen when looking at summer (June to October) data for the entire 2011 to 2013 sampling study (Figure 2-19). In general, total nitrogen followed similar seasonal patterns for each year with moderate concentrations in March, a sharp increase in April, a decline in May and June, and relatively stable low concentrations from July through October. A noticeable exception is a second peak in total nitrogen that occurred in June 2011. This second peak was measured at all stations and is interesting because a similar increase in nitrate and ammonia was not measured (see discussion below). It is likely that this second peak in total nitrogen was dominated by organic nitrogen in the water and may be the result of the high spring flows in the

Columbia River during 2011 (see Figure 2-1). The spill volumes from Grand Coulee Dam were very high during June 2011 with the majority of this spill via the outlet tubes on the face of the dam. It is possible that the increased spill during June 2011 stirred up organic materials from the river bottom downstream of Grand Coulee Dam, resulting in an increase in organically bound nitrogen.

Figure 2-17. Rufus Woods Lake Total Nitrogen Concentrations for 2011, 2012, and 2013

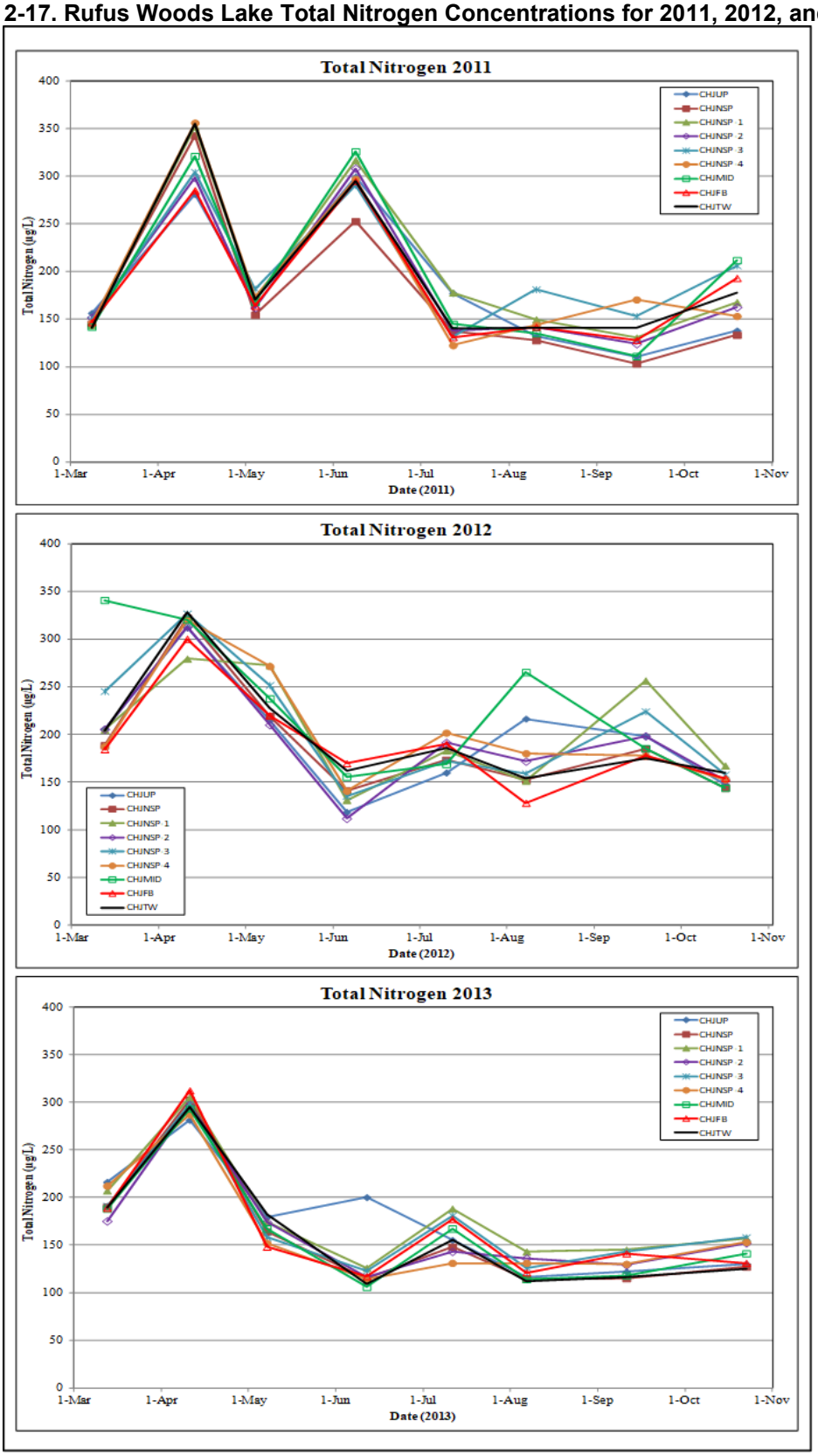
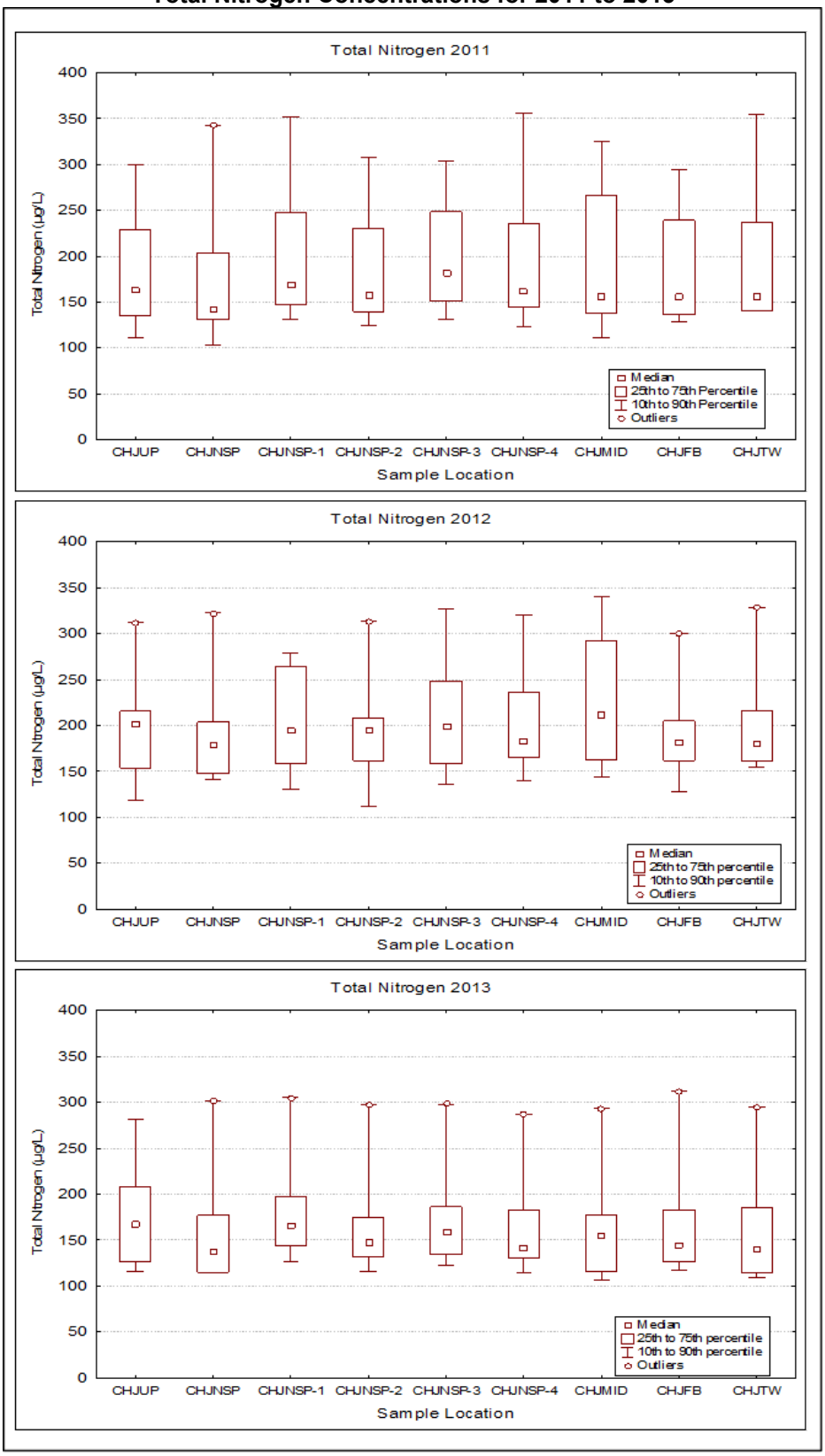


Figure 2-18. Rufus Woods Lake Data Summary of Annual (March to October) Total Nitrogen Concentrations for 2011 to 2013



Nitrate+nitrite-nitrogen concentrations at all stations followed similar seasonal patterns with moderate concentrations in March, peak concentrations in April, decreasing concentrations from May through July, and slightly increasing concentrations from August through October (Figure 2-20). Nitrate concentrations at all stations ranged from 39 to 227 µg/L in 2011, from 47 to 216 µg/L in 2012, and from 58 to 261 µg/L in 2013 (see Table 2-1 to Table 2-3). Median nitrate + nitrite concentrations ranged from about 80 to 100 µg/L at most stations between 2011 and 2013 with little to no station to station differences in nitrate + nitrite (Figure 2-21). These similarities are clearly seen when looking at summer (June to October) data for the entire 2011 to 2013 sampling study (see Figure 2-19).

Figure 2-19. Rufus Woods Lake Data Summary of Summer (June to October) Total Nitrogen, Nitrate+Nitrite, and Ammonia Concentrations for 2011 to 2013

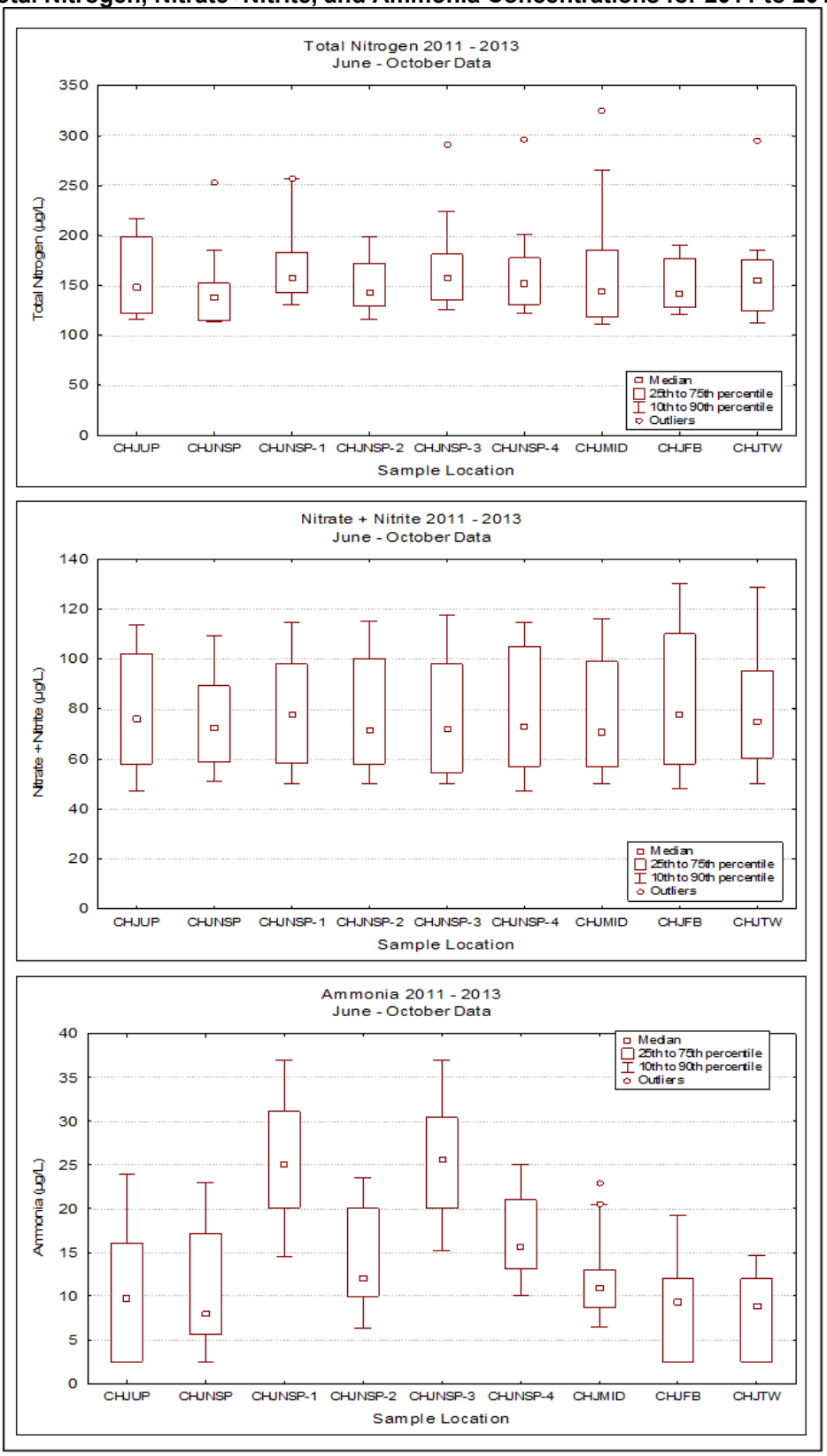
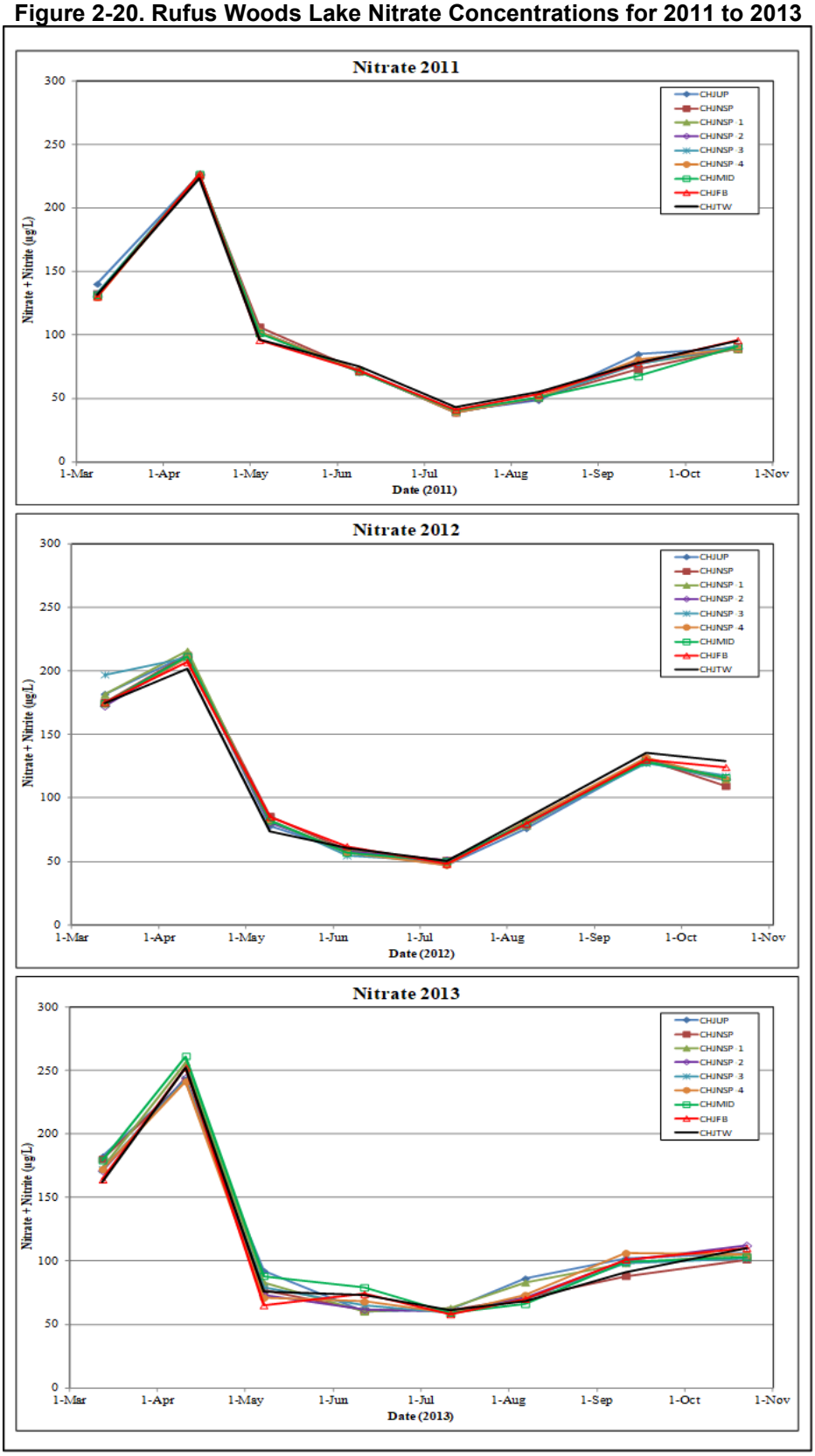


Figure 2-20. Rufus Woods Lake Nitrate Concentrations for 2011 to 2013



Ammonia concentrations varied between stations in Rufus Woods Lake during the 2011 to 2013 sampling study (Figure 2-22). Concentrations ranged from less than the detection limit of 5 µg/L to 42 µg/L in 2011, from less than detection to 35 µg/L in 2012, and from less than detection to 46 µg/L in 2013 (see Table 2-1 to Table 2-3). In general, ammonia concentrations were greatest during the June to October time period, with the highest concentrations measured downstream of the aquaculture facilities at stations CHJNSP-1 and CHJNSP-3, as well as slightly greater concentrations at CHJNSP-2 and CHJNSP-4. Median ammonia concentrations in Rufus Woods Lake ranged from about 5 to 15 µg/L at most stations except CHJNSP-1 and CHJNSP-3, which ranged from about 15 to 30 µg/L (Figure 2-23). These differences in ammonia concentrations between stations are seen more clearly when looking at summer (June to October) data for the entire 2011 to 2013 sampling period (see Figure 2-19). The overall range in summer ammonia concentrations at all stations in Rufus Woods Lake were substantially greater at stations CHJNSP-1, CHJNSP-3, and CHJNSP-4 than other stations. The increased ammonia concentrations immediately downstream of the aquaculture facilities are likely due to this nutrient being released directly to the water column by fish excretion as well as the decomposition of feed and feces (Beveridge 2004; Mugg et al. 2007; Azevedo et al. 2011). These greater summer ammonia concentrations at stations downstream of the aquaculture facilities correspond to increased total phosphorus and soluble reactive phosphorus concentrations measured downstream of the aquaculture sites.

Figure 2-21. Rufus Woods Lake Data Summary of Annual (March to October) Nitrate+Nitrite Concentrations for 2011 to 2013

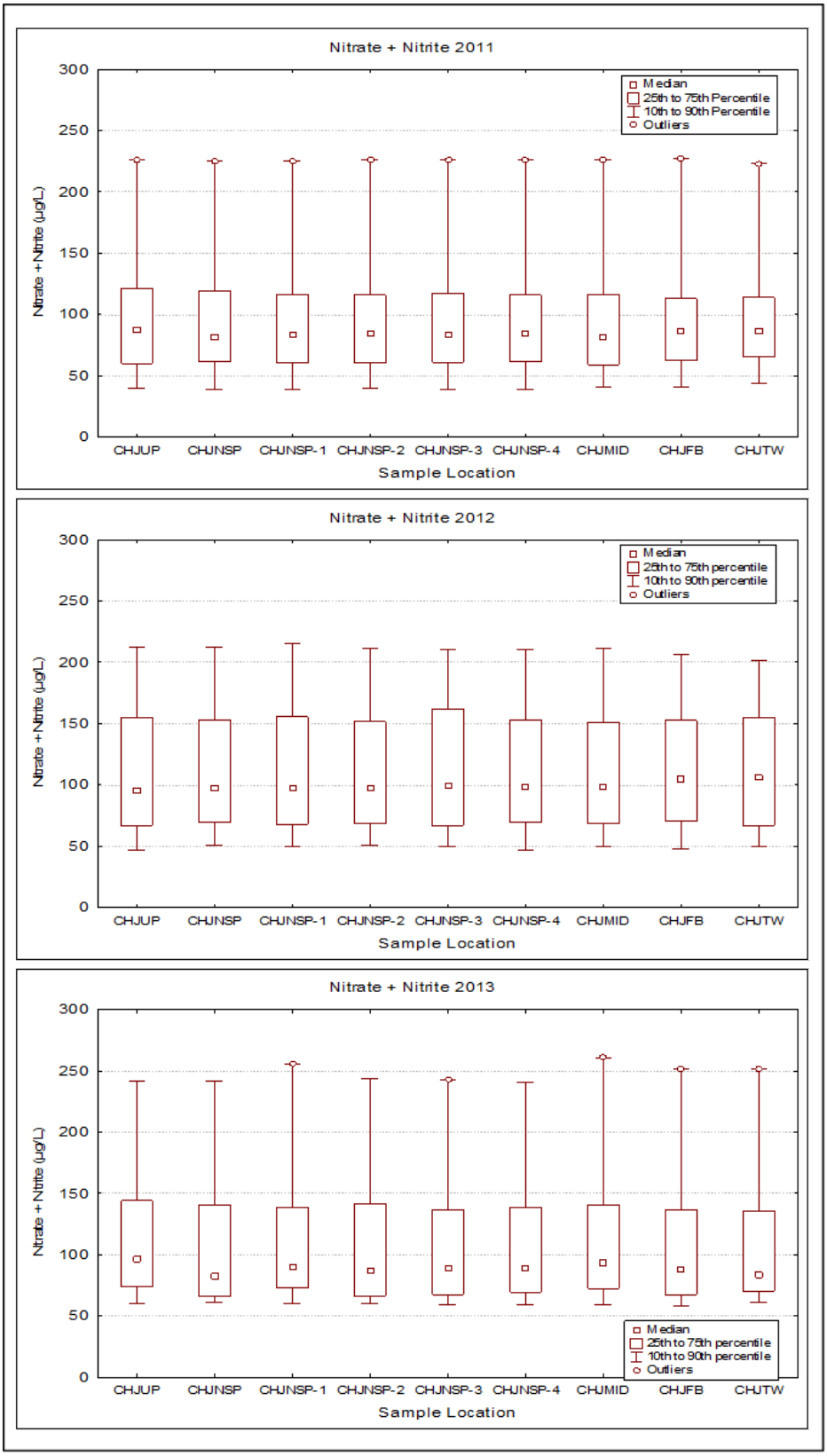


Figure 2-22. Rufus Woods Lake Ammonia Concentrations for 2011 to 2013

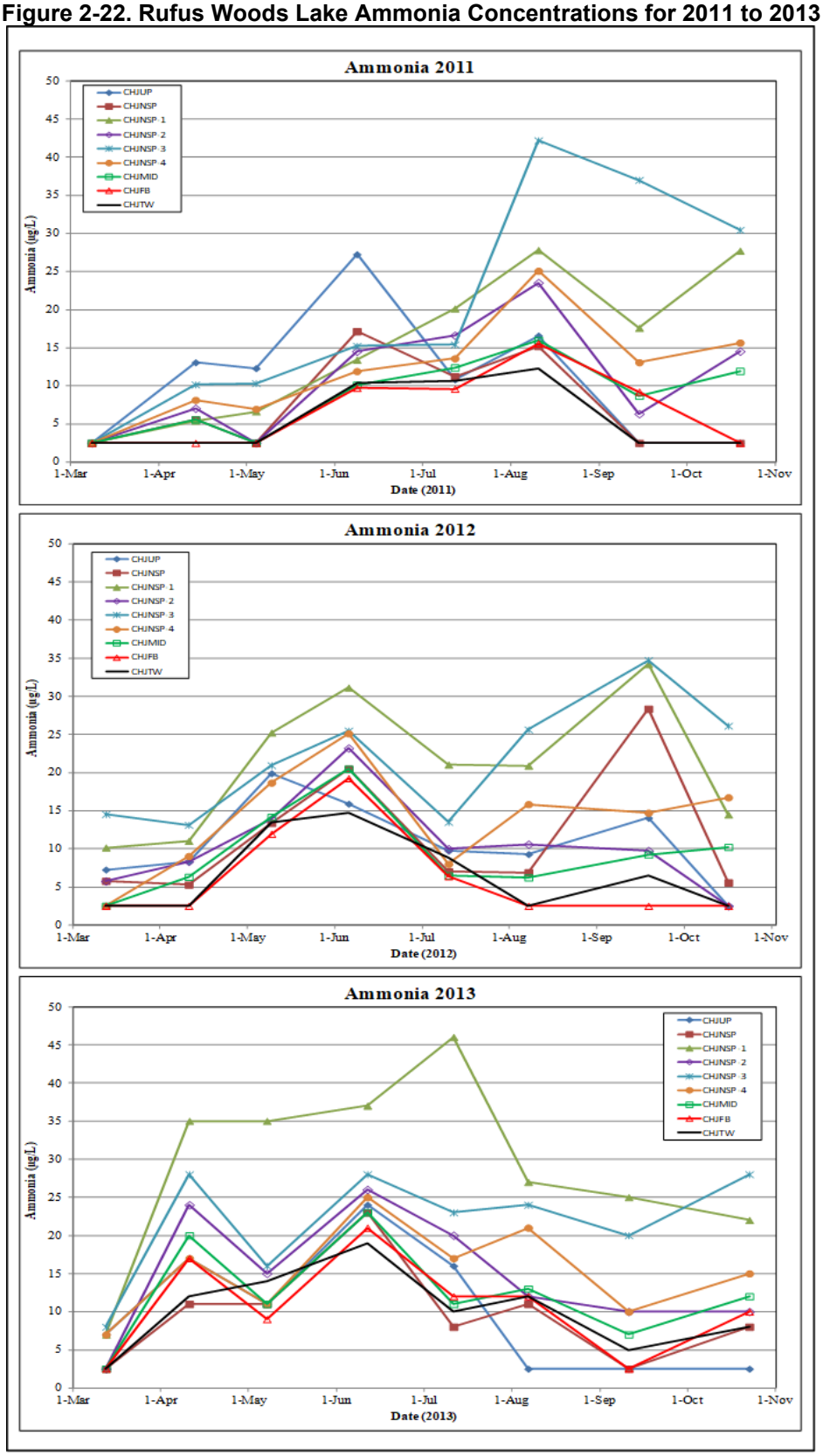
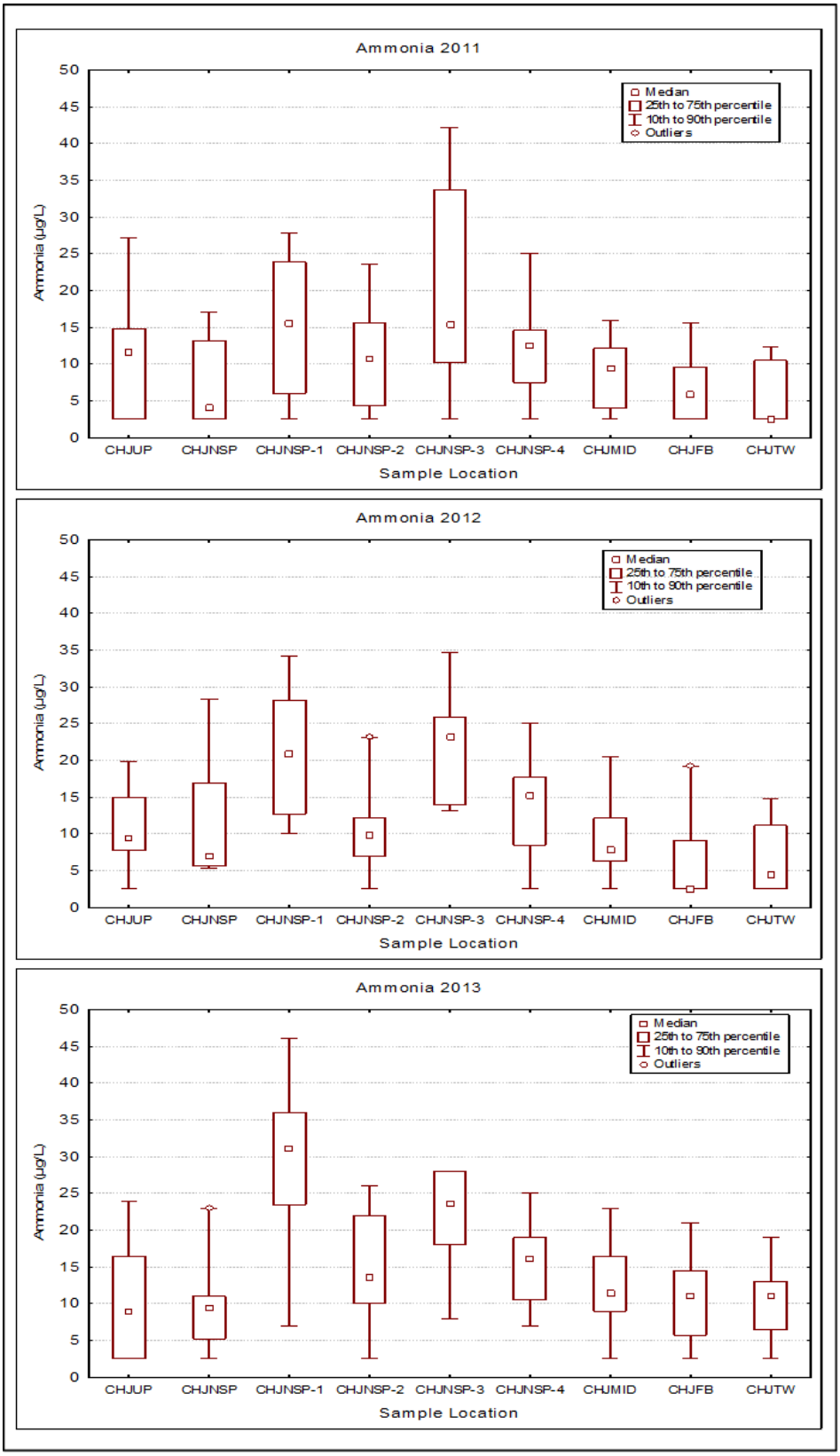


Figure 2-23. Rufus Woods Lake Data Summary of Annual (March to October) Ammonia Concentrations from 2011 to 2013



2.2.6.3 *Nutrient Limitation*

Phosphorus and nitrogen are the two major essential nutrients that limit phytoplankton growth in freshwater ecosystems. The limiting nutrient concept maintains that the growth of a plant crop will be limited by the essential nutrient in shortest supply (Ryding and Rast 1989). Total nitrogen to total phosphorus ratios (TN:TP) are often used to determine whether nitrogen or phosphorus is most likely to limit phytoplankton growth. Typically, TN:TP ratios, by weight, that are greater than 17:1 suggest phosphorus limitation while ratios less than 10:1 suggest nitrogen limitation (Forsberg and Ryding 1980). Temporal variations in the TN:TP ratios at all stations in Rufus Woods Lake are seen in Figure 2-24. The seasonal progression of TN:TP suggests that phosphorus concentrations likely limit algal growth in Rufus Woods Lake. Although no station had a TN:TP ratio that was less than 10, indicating nitrogen limitation, several stations were between 10 and 17, suggesting that either nitrogen or phosphorus could be limiting or that both nitrogen and phosphorus were limiting (co-limitation). Summer (June to October) TN:TP medians and range of data for each station were slightly greater than the 17:1 ratio, suggesting phosphorus consistently limits phytoplankton growth in Rufus Woods Lake during the summer months (Figure 2-25).

Figure 2-24. Rufus Woods Lake Total Nitrogen to Total Phosphorus Ratios for 2011 to 2013

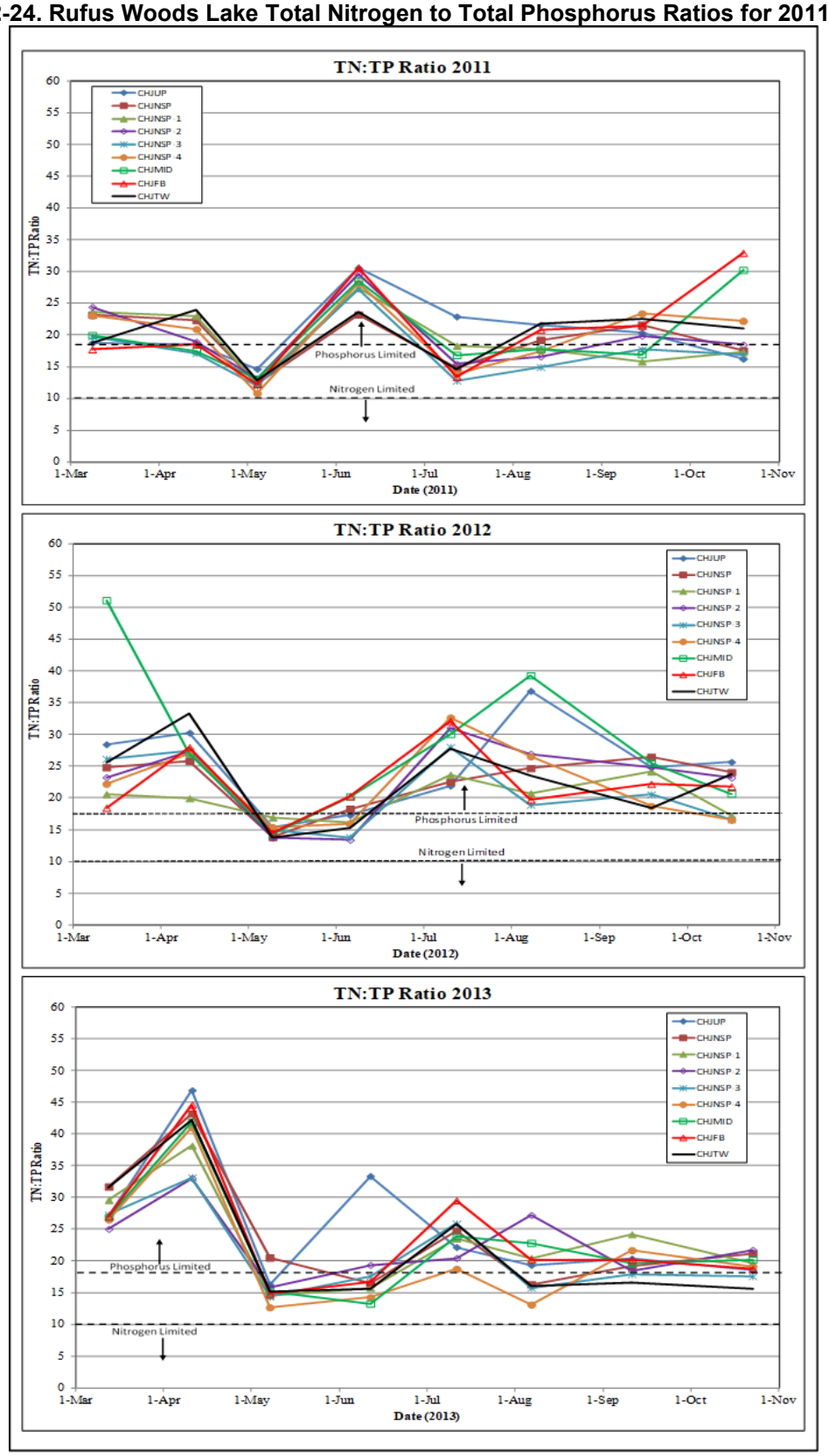
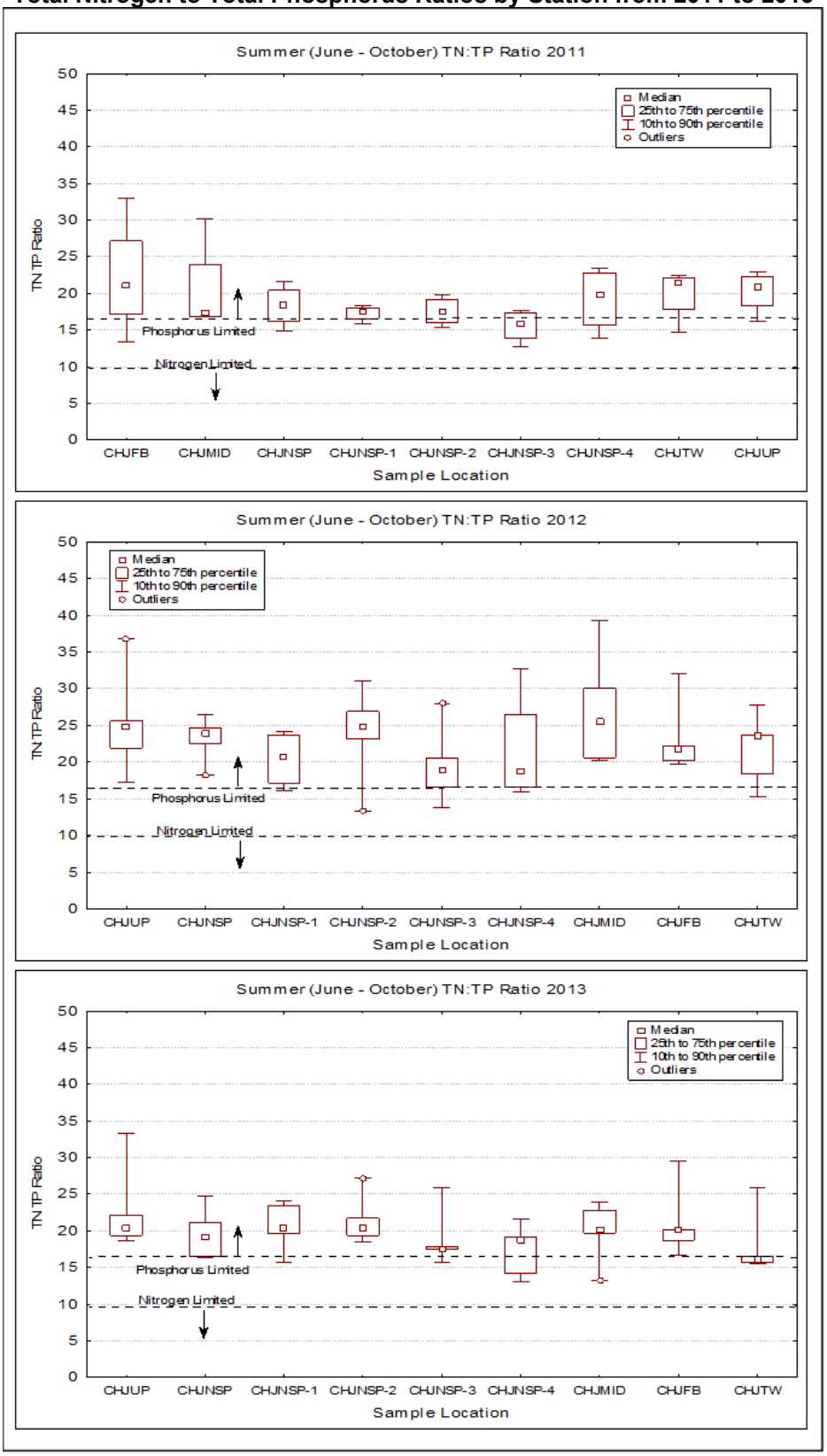


Figure 2-25. Rufus Woods Lake Data Summary of Summer (June to October) Total Nitrogen to Total Phosphorus Ratios by Station from 2011 to 2013

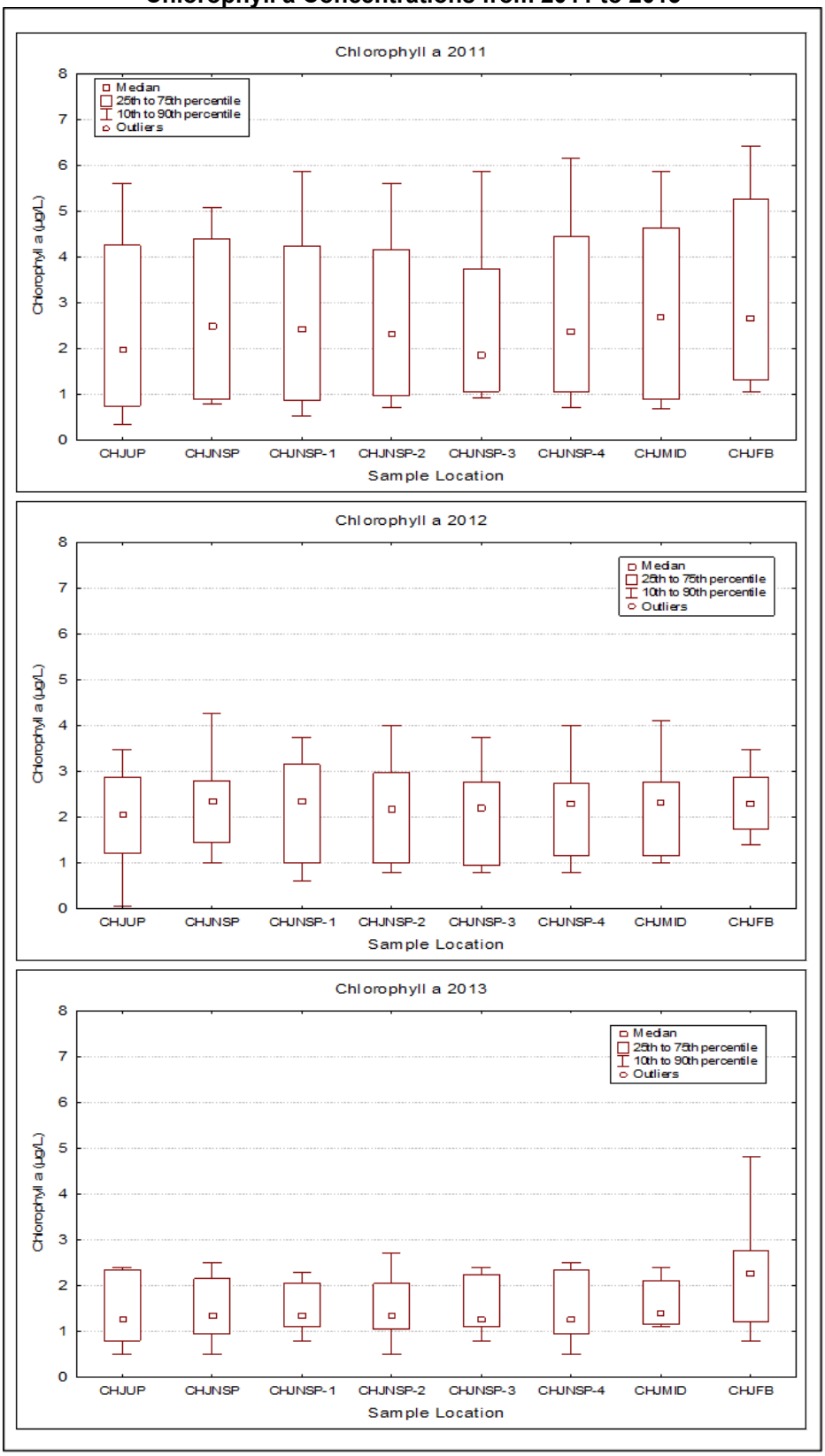


2.2.7 Chlorophyll a

Chlorophyll a is the primary photosynthetic pigment in all photosynthetic organisms that require oxygen and is found in all freshwater phytoplankton species. Consequently, measurements of chlorophyll a in the water column are an indirect estimate of the amount of phytoplankton present. Although there are several different forms of chlorophyll present in plants, chlorophyll a is the dominant form and is generally considered an indicator of phytoplankton biomass in freshwater ecosystems (Wetzel 1975).

Temporal variations in chlorophyll a occurred at all stations during 2011, 2012, and 2013 (see Figure 2-7). Chlorophyll a concentrations ranged from less than 0.1 µg/L to 6.4 µg/L, with the highest concentrations measured at all stations in May 2011 (see Table 2-1 to Table 2-3). The overall range of chlorophyll a concentrations were greatest in 2011 with lower concentrations measured in 2012 and 2013. In general, chlorophyll a concentrations varied seasonally, with peak concentrations occurring during the March to June time period and reduced concentrations during the July to October period, although this seasonality in concentrations was muted in 2013. One exception to the seasonal trend was seen in September 2013 when a spike in chlorophyll a (4.8 µg/L) was measured at station CHJFB. Median chlorophyll a concentrations ranged from about 2 to 3 µg/L in 2011 and 2012, and from about 1 to 2 µg/L in 2013 (Figure 2-26). The overall range of data was substantially greater in 2011 than in 2012 and 2013 largely due to the higher peak concentrations measured from March to June in 2011 (see Figure 2-7).

Figure 2-26. Rufus Woods Lake Data Summary of Annual (March to October) Chlorophyll a Concentrations from 2011 to 2013



2.2.8 Trophic State

The biological productivity, or trophic state, can be classified into three general categories: oligotrophic (low productivity), mesotrophic (moderate productivity), and eutrophic (high productivity). Lakes with low nutrient concentrations and low rates of phytoplankton productivity are classified as oligotrophic. Lakes with high nutrient concentrations and high rates of phytoplankton productivity are classified as eutrophic. Mesotrophic lakes have nutrient concentrations and phytoplankton productivity between eutrophic and oligotrophic lakes.

The water quality parameters most often used to assess the trophic state of a lake are total phosphorus, chlorophyll a, and transparency. These three variables have been used by Carlson (1977) and the Organization for Economic Co-Operation and Development (OECD 1982) to develop a trophic state classification system. The general relationship between these three variables and tropic state based on summer mean values and annual mean values are summarized in Table 2-4. Another useful way to group lakes by trophic classification is with the trophic state index (TSI), which is based on linear regression relationships developed for total phosphorus, chlorophyll a, and transparency in lakes (Carlson 1977). Trophic state indices were computed using equations developed by Carlson (1977) that classify a lake as oligotrophic with a TSI value less than 40, as mesotrophic with a TSI value between 40 and 50, and as eutrophic with a TSI value greater than 50 (Table 2-4). Carlson (1977) recommended using summer TSI values to classify lakes while the OECD (1982) recommends annual values. For this study, both summer TSI values and annual OECD values are presented to provide additional insight on the trophic state of Rufus Woods Lake.

Table 2-4. Trophic Classification Values for Rufus Woods Lake from 2011 to 2013

Trophic State Classification	Total Phosphorus (µg/L)	Chlorophyll a (µg/L)	Transparency (meters)	Carlson Trophic State Index[3]
Oligotrophic				<40
Annual Mean Values Threshold[1]	<10	<2.6	>6	
Summer Mean Values Threshold[2]	<12	<2.6	>4	
Mesotrophic				40-50
Annual Mean Values Threshold[1]	10-35	2.6-8.0	3-6	
Summer Mean Values Threshold[2]	12-24	2.6-6.4	2-4	
Eutrophic				>50
Annual Mean Values Threshold[1]	>35	>8	<3	
Summer Mean Values Threshold[2]	>24	>6.4	<2	

Notes:
1. Based on OECD (1982)
2. Based on Carlson (1977)
3. Carlson (1977)
   Transparency TSI= 60-14.41*ln mean secchi disk (m)
   Chlorphyll a TSI= 9.81*ln mean chl a (µg/L)+30.6
   Total Phosphorus TSI= 14.42*ln mean TP + 4.15

Rufus Woods Lake would be classified as oligotrophic on the basis of both summer TSI values (Table 2-5) and annual OECD values (Table 2-6). Even though the annual OECD values in 2011 would classify the lake as mesotrophic, annual values in 2012 and 2013 were strongly oligotrophic. It is likely that the very high runoff experienced in the Columbia River in 2011 resulted in moderately productive mesotrophic water quality conditions.

Table 2-5. Carlson Trophic State Index Values for Rufus Woods Lake from 2011 to 2013

	Total Phosphorus (TSI)			Chlorophyll a (TSI)			Transparency (TSI)		
STATION	2011	2012	2013	2011	2012	2013	2011	2012	2013
Summer (June - October)									
CHJUP	32.1	31.6	30.9	30.6	30.8	29.8	30.9	29.8	28.4
CHJNSP	32.4	31.6	30.9	33.3	34.9	30.8	30.7	29.9	30.0
CHJNSP-1	35.9	35.6	33.0	33.0	32.6	31.9	30.9	30.5	29.5
CHJNSP-2	34.4	31.7	30.9	33.4	32.3	31.2	30.6	29.7	29.4
CHJNSP-3	38.5	35.4	33.8	34.1	32.2	31.5	30.0	29.6	29.2
CHJNSP-4	33.8	34.0	33.8	34.0	32.9	30.4	30.7	29.7	29.4
CHJMID	33.1	31.5	31.4	33.7	33.6	32.7	29.9	29.8	29.4
CHJFB	32.4	32.0	31.4	35.7	36.8	37.5	31.2	30.5	30.4
Whole Lake Mean	34.1	32.9	32.0	33.5	33.3	32.0	30.6	29.9	29.5

Notes: Concentrations in regular type indicate oligotrophic conditions, **bold** type indicate mesotrophic condtions and **bold underline** type indicate eutrophic conditions.

Table 2-6. OECD Trophic State Classification Total Phosphorus, Chlorophyll a, and Transparency Values for Rufus Woods Lake from 2011 to 2013

OECD (1982) Closed Boundary Annual Mean Values (µg/L)

	2011			2012			2013		
Station	**TP**	**Trans**	**Chl a**	**TP**	**Trans**	**Chl a**	**TP**	**Trans**	**Chl a**
CHJUP	9.1	5.6	2.5	8.2	6.1	2.0	6.5	8.2	1.5
CHJNSP	9.2	5.8	2.7	8.8	6.1	2.3	6.3	7.0	1.5
CHJNSP-1	10.4	5.6	2.7	10.4	6.0	2.2	7.3	7.6	1.5
CHJNSP-2	9.7	5.8	2.7	8.9	6.2	2.1	6.5	7.7	1.5
CHJNSP-3	11.8	5.9	2.5	10.4	6.2	2.0	8.0	7.8	1.6
CHJNSP-4	10.1	5.8	2.8	9.8	6.1	2.1	7.8	7.8	1.5
CHJMID	9.9	5.9	2.9	8.7	6.1	2.2	6.3	7.7	1.6
CHJFB	9.4	5.5	3.2	9.0	5.9	2.3	6.5	7.2	2.3
Whole Lake Mean	9.9	5.8	2.7	9.3	6.1	2.2	6.9	7.6	1.6

	TP	Trans	Chl a
Oligotrophic	<10	>6	<2.5
Mesotrophic	10 - 35	3 - 6	2.5 - 8
Eutrophic	>35	<3	>8

2.2.9 Major Anions (SO_4, Cl) and Cations (Ca, Mg, Na, K)

The chemical composition of the major ions of many freshwater lakes is largely derived from the weathering of soils and rocks in the drainage basin, atmospheric precipitation, and evaporation (Wetzel 1975). The ion balance of most freshwaters are dominated by the major cations calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K), and the major anions carbonate (CO_3), bicarbonate (HCO_3), sulfate (SO_4), and chloride (Cl). Other elements, such as phosphorus and nitrogen, are important biologically but are typically only a minor part of the overall chemical composition of freshwater ecosystems.

The major anions and cations were collected at quarterly intervals during 2011 and 2012 at stations CHJUP, CHJMID, and CHJFB (see Table 2-1 to Table 2-3). Over the course of the study, calcium and magnesium were the dominant cations in Rufus Woods Lake and ranged from about 15 to 21 mg/L and 4 to 5 mg/L, respectively. Sodium and potassium concentrations were less, ranging from about 1.4 to 1.9 mg/L and 0.7 to 0.9 mg/L, respectively. In general, magnesium, sodium, and potassium were relatively stable showing little spatial or temporal variation in concentrations, while calcium concentrations varied slightly between stations and dates. Rufus Woods Lake concentrations of calcium, magnesium, and potassium were similar to the mean composition for river waters in North America of 21, 5, and 1.4 mg/L, respectively, with lower concentrations of sodium than the mean for North American rivers of 9 mg/L (Wetzel 1975).

The importance and role of the carbonate system in Rufus Woods Lake was previously described for alkalinity and hardness. After carbonate/bicarbonate, sulfate was the dominant anion with concentrations ranging from about 7 to 10 mg/L. During the study,

chloride concentrations were low and typically in the less than 1 mg/L range. Similar to calcium, sulfate plays an important role in influencing growth and population dynamics of freshwater biota. Consequently, minor shifts in sulfate concentrations were seen between sampling dates and station locations. Conversely, chloride concentrations remained relatively stable in Rufus Woods Lake, indicating the minor role this ion plays in freshwater ecosystems. Rufus Woods Lake concentrations of sulfate and chloride were lower than the mean composition for river waters in North America of 20 and 8 mg/L, respectively (Wetzel 1975).

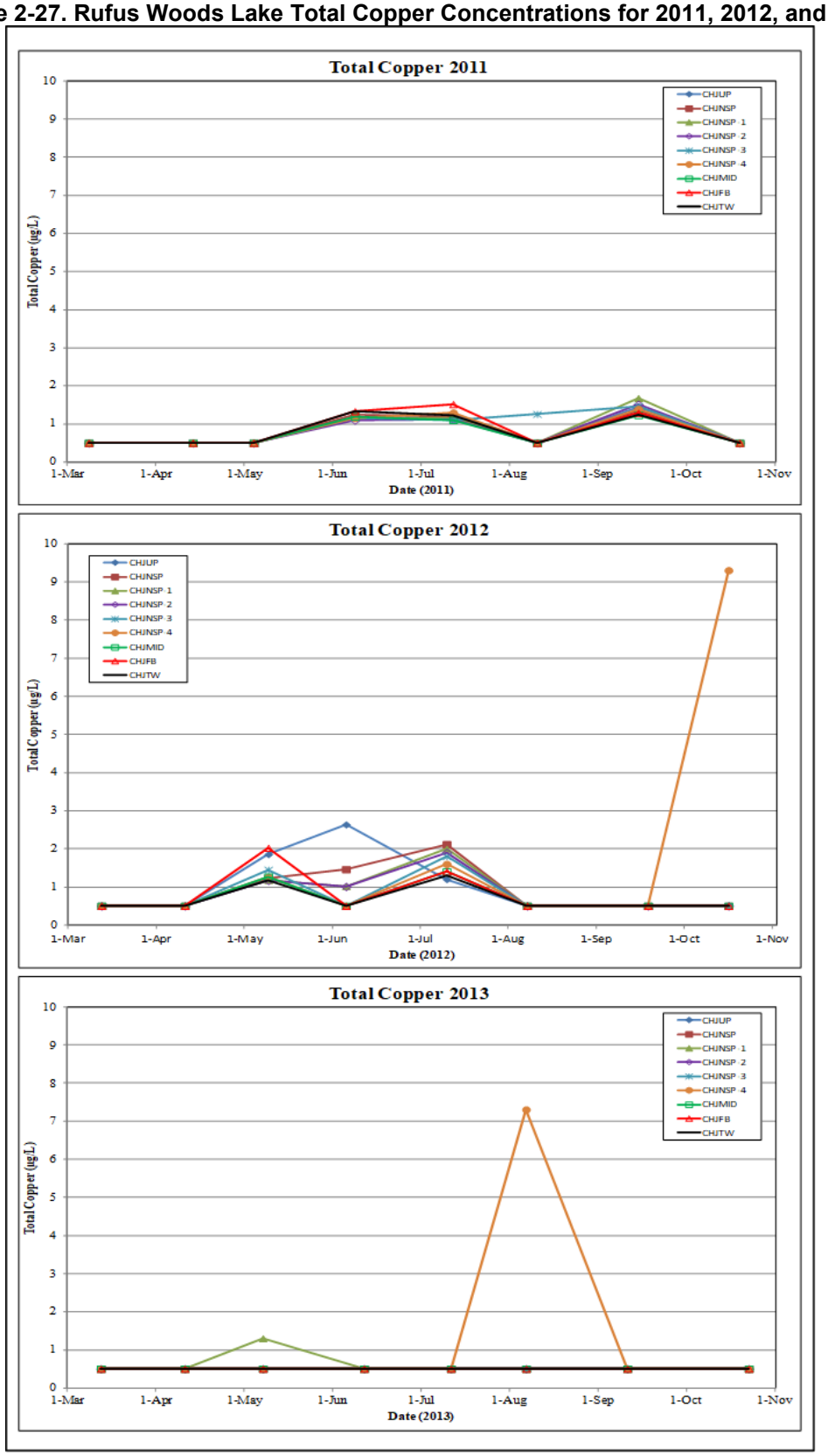
2.2.10 Trace Metals

Water column samples for trace metals were collected in 2011 and 2012 in conjunction with the quarterly anion/cation sampling at stations CHJUP, CHJMID, and CHJFB (see Table 2-1 to Table 2-3). These samples were analyzed for total aluminum, arsenic, cadmium, chromium, and lead. In addition to these quarterly metals samples, monthly sampling for total copper and zinc occurred in 2011, 2012, and 2013 at all stations in Rufus Woods Lake (see Table 2-1 to Table 2-3). Total copper and zinc samples were collected upstream and downstream of aquaculture facilities to determine if aquaculture practices were a source of these metals to Rufus Woods Lake.

Concentrations of the quarterly metals were all below the laboratory detection limits except for aluminum. Total aluminum concentrations were lowest in the late winter and early fall (March and October) samples and greatest during the spring and early summer (May and July) samples. Concentrations were similar between stations and ranged from about 5 µg/L in March 2011 to 83 µg/L in May 2012. The greater aluminum concentrations for the May samples during a period of high runoff, suggests that the major source of aluminum is likely suspended sediments from the watershed.

Total copper concentrations in Rufus Woods Lake were near or below the detection limit of 1 µg/L for all dates at all stations except CHJNSP-4 (Figure 2-27). Concentrations measured at CHJNSP-4 were elevated on October 17, 2012 (9.3 µg/L), and August 7, 2013 (7.3 µg/L), (see Table 2-1 to Table 2-3). Hardness was not measured on either occasion. However, hardness concentrations were estimated using a relatively strong relationship between alkalinity and hardness measured in Rufus Woods Lake during the study. Total copper concentrations were compared to Washington State water quality standards (see Table 1-8). Based on an estimated hardness of 56 mg $CaCO_3$/L on October 17, 2012, a copper concentration of 9.3 µg/L exceeded the Washington State chronic criteria of 7.2 µg/L but was less than the acute criteria of 10.3 µg/L. For an estimated hardness of 62 mg $CaCO_3$/L on August 7, 2013, a copper concentration of 7.3 µg/L was less than the state chronic criteria of 7.9 µg/L.

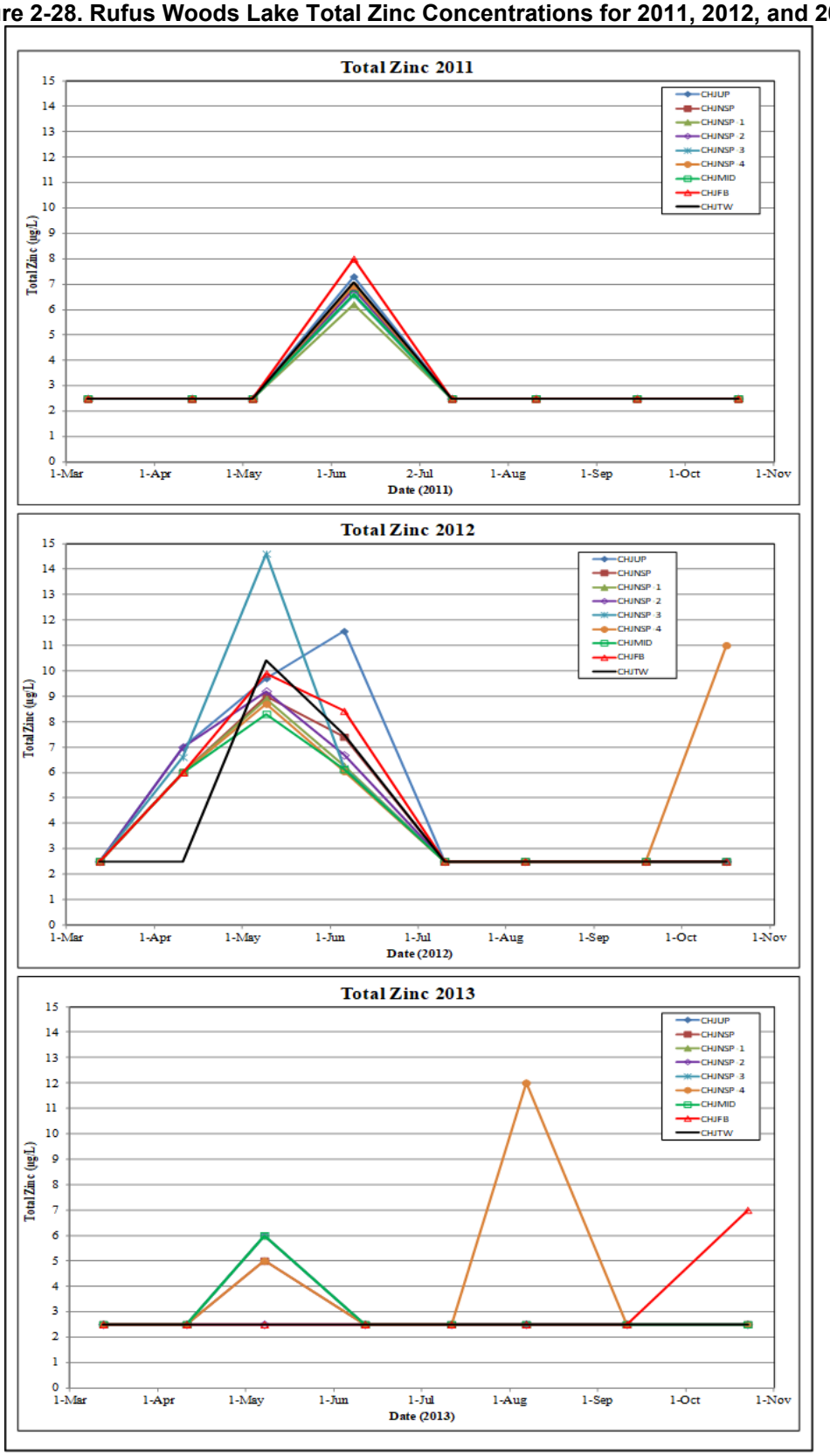
Figure 2-27. Rufus Woods Lake Total Copper Concentrations for 2011, 2012, and 2013



Total copper concentrations at station CHJNSP-4 were also compared to Colville Tribes water quality standards (see Table 1-7). Based on an estimated hardness of 56 mg $CaCO_3$/L on October 17, 2012, a copper concentration of 9.3 µg/L exceeded the Colville Tribes chronic criteria of 5.7 µg/L and the acute criteria of 8.1 µg/L. For an estimated hardness of 62 mg $CaCO_3$/L on August 7, 2013, a copper concentration of 7.3 µg/L exceeded the Colville Tribes chronic criteria of 6.2 µg/L but was less than the acute criteria of 8.9 µg/L.

Total zinc concentrations in Rufus Woods Lake were near or below the detection limit at all stations for the majority of samples collected from 2011 to 2013 (Figure 2-28). Zinc concentrations ranged from below the detection limit of 5 µg/L at all stations on numerous dates to 14.6 µg/L at CHJNSP-3 on May 10, 2012 (see Table 2-1 to Table 2-3). In general, zinc concentrations were greatest at all stations during the high runoff May and June time period, with the highest concentrations measured in 2012, slightly lower concentrations in 2011, and little to no measureable zinc in 2013 (Figure 2-28). The elevated zinc concentrations measured at all stations during the high runoff events of May and June 2011 and 2012 suggests that the major source of the zinc was from upstream suspended sediments transported through Rufus Woods Lake. Lower runoff measured in 2013 corresponds to lower zinc concentrations measured during May and June. Zinc concentrations at all stations were substantially less than the Washington State and Colville Tribes acute and chronic water quality standards (see Table 1-7).

Figure 2-28. Rufus Woods Lake Total Zinc Concentrations for 2011, 2012, and 2013



2.2.11 Fats, Oils, and Grease

Fats, oils, and grease (FOG) consists largely of oils and grease from animal and vegetable sources, as well as from hydrocarbon and petroleum sources. Oil and grease are of concern because elevated concentrations can coat fish gill surfaces and macroinvertebrates, leading to asphyxiation. Additionally, high levels of oil and grease in an aquatic ecosystem can increase the biological oxygen demand, leading to reduced dissolved oxygen concentrations. At aquaculture facilities, the principle source of oils and grease to the aquatic environment is from uneaten food particles.

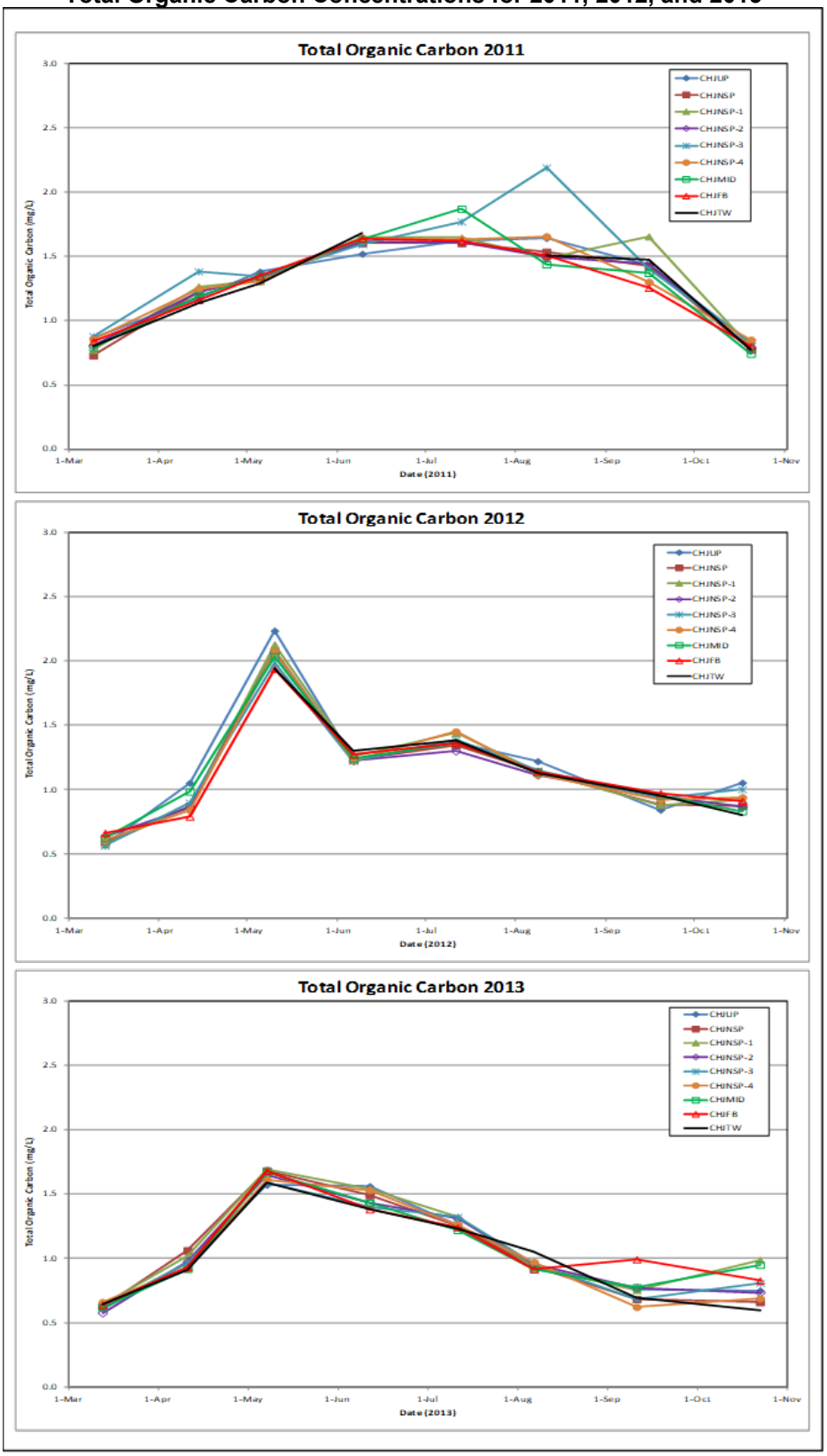
Fats, oils and grease was measured at site specific locations during the 2013 sampling season depending on the presence or absence of a surface oil sheen downstream of the aquaculture facilities. If a sheen was visible, FOG samples were collected at a background station located upstream of the aquaculture facilities (CHJNSP), as well as downstream at stations CHJNSP-1, CHJNSP-2, CHJNSP-3, and CHJNSP-4. If no sheen was visible, FOG samples were not collected. A surface oil sheen was visible downstream of the aquaculture facilities for every month except for March. FOG concentrations were less than the detection limit of 2 mg/L at background station CHJNSP every month that samples were collected. Downstream FOG samples were collected at CHJNSP-1, CHJNSP-2, CHJNSP-3, and CHJNSP-4. Concentrations ranged from less than the detection limit of 2 mg/L at all stations to 6.35 mg/L at CHJNSP-3 (see Table 2-1 to Table 2-3). Data collected during 2013 clearly show that the aquaculture sites were a source of oil and grease sheens floating on Rufus Woods Lake.

2.2.12 Total Organic Carbon

Organic matter is an important element of aquatic systems and can affect many biogeochemical processes occurring in the water such as nutrient cycling, biological availability of nutrients, and the chemical bonding, transport, and degradation of pollutants. Organic matter in aquatic systems can be either allochthones (derived from outside the system such as atmospheric deposition or via runoff) or autochthonous (derived from within the system such as plant matter and sediments). Organic matter can be measured as total organic carbon, which includes the dissolved and particulate forms of organic carbon.

Temporal variations in total organic carbon at all stations during 2011, 2012, and 2013 are shown in Figure 2-29. Total organic carbon concentrations were similar between all stations and ranged from about 0.6 mg/L to 2.2 mg/L, with the highest concentrations measured in May of 2012 (see Table 2-1 to Table 2-3). In general, total organic carbon concentrations varied seasonally, with peak concentrations occurring during the high runoff May to July time period and reduced concentrations during the lower flow March to April and August to October periods. One exception to the seasonal trend was seen in August 2011, where a spike in total organic carbon (2.2 mg/L) was measured at station CHJNSP-3. The increase in total organic carbon during the high runoff May to July time period suggests that most of the organic matter in Rufus Woods Lake is derived from outside the reservoir.

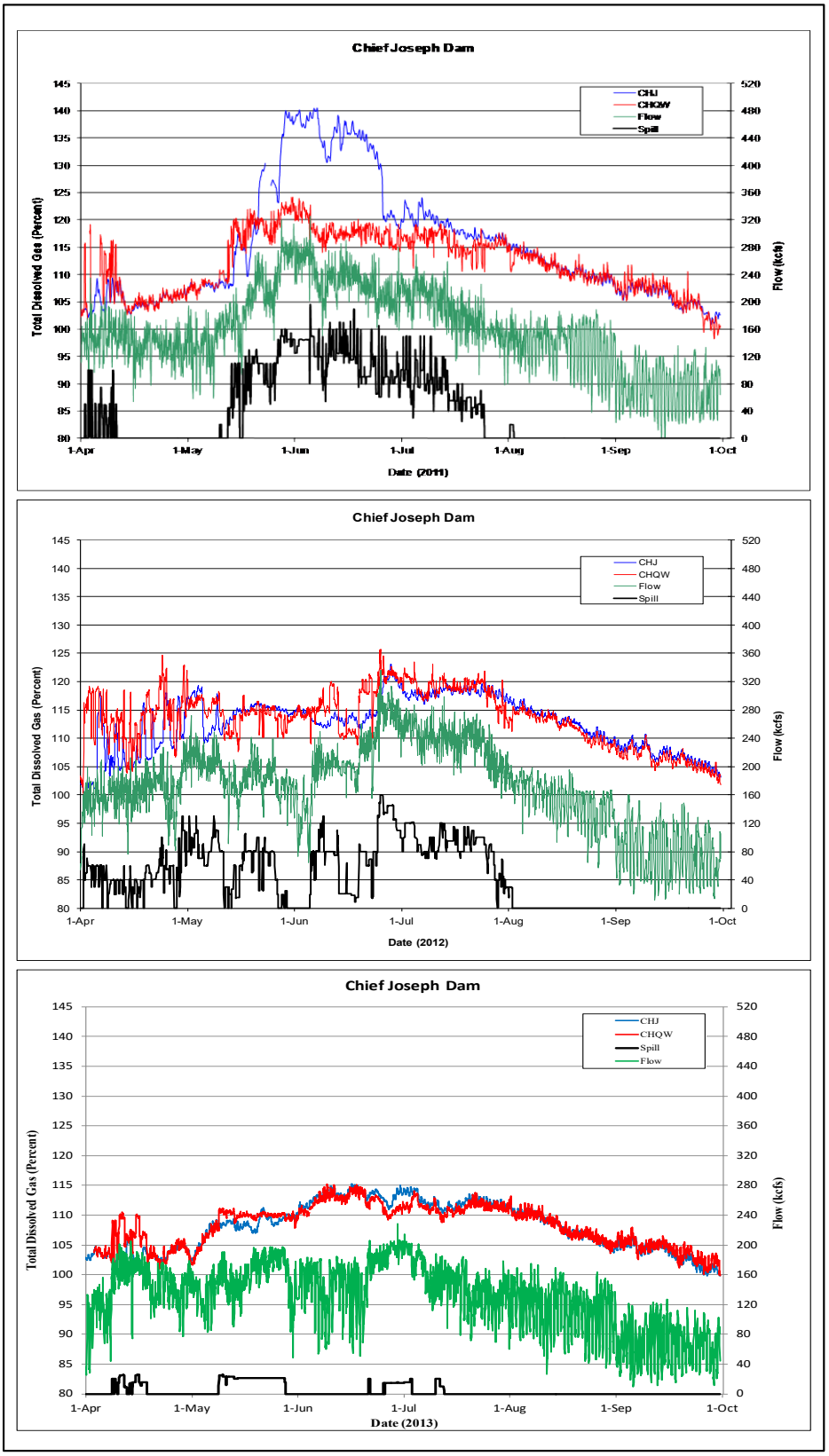
Figure 2-29. Rufus Woods Lake Temporal Variation in Total Organic Carbon Concentrations for 2011, 2012, and 2013



2.2.13 Total Dissolved Gas

Hourly percent TDG, river flows, and spillway flows at the Chief Joseph Dam forebay (station CHJ) and tailwater (station CHQW) fixed monitoring stations during the 2011 to 2013 study are presented in Figure 2-30. Columbia River flow and spill volumes were moderate to high during 2011 and 2012 with greatly diminished spill and flow volumes in 2013.

Figure 2-30. Rufus Woods Lake Temporal Variation in Total Dissolved Gas Saturations from 2011 to 2013



TDG at Chief Joseph Dam forebay station (CHJ) are is largely a function of the TDG saturations released upstream from Grand Coulee Dam because little degassing occurs in Rufus Woods Lake. Forebay TDG was greatest in 2011 with saturations exceeding 135 percent from about late May to late June, with a maximum forebay TDG saturation of about 140 percent measured in June. Rufus Woods Lake TDG saturations were lower in 2012 with the forebay station (CHJ) TDG exceeding 120 percent periodically from mid-June through July, while in 2013, forebay TDG saturations were even lower and did not exceed 115 percent. The large difference in TDG saturations measured in Rufus Woods Lake at the Chief Joseph Dam forebay station (CHJ) in 2011 and 2012 is largely a function of how Grand Coulee Dam spilled water. As previously noted, Grand Coulee spills water either via a series of outlet tubes (when forebay pool elevations are below 384 meters) or over the drum gates at times when forebay elevations are greater than 384 meters. TDG studies by Frizell (1997) show that spill from the outlet tubes increases TDG saturations in Rufus Woods Lake substantially more than spill over the drum gates. For 2011, the majority of spill was in late May and June via the outlet tubes, while in 2012, the majority of spill was in late June and July over the drum gates.

Columbia River TDG saturations as measured at the Chief Joseph Dam tailwater station (CHQW) were consistently lower than forebay TDG saturations in 2011, periodically exceeded forebay TDG in 2012, and were similar to forebay TDG in 2013. The installation of flow deflectors on the spillway at Chief Joseph Dam has resulted in reduced TDG saturations being generated by the dam during spillway operations. The periodic high TDG saturations measured in 2012 when compared to forebay saturations were largely due to several spill bays being out of service during 2012. Studies by Schneider (2009) showed that spill via all 19 spill bays resulted in the lowest TDG saturations, with increasing saturations when fewer spill bays are used

2.2.14 Statistical Analysis

2.2.14.1 *Mann-Whitney Test*

A non-parametric Mann-Whitney test was conducted between samples collected upstream of the aquaculture facilities (CHJUP and CHJNSP) and samples collected immediately downstream of the facilities (CHJNSP-1, CHJNSP-2, CHJNSP-3, and CHJNSP-4) during the summer months (June to October) to determine if any difference existed in water quality conditions. Water quality parameters used for the Mann-Whitney test included total phosphorus, soluble reactive phosphorus, total nitrogen, nitrate+nitrite-nitrogen, ammonia-nitrogen, chlorophyll a, and total organic carbon. To create a more robust dataset to compare, data for the upstream and downstream stations from 2011, 2012, and 2013 was combined, and a significance level of $p < 0.05$ was used to evaluate whether significant differences in a specific parameter existed. As seen in Table 2-7, significant differences between upstream and downstream stations existed for total phosphorus ($p = 0.00008$) and ammonia ($p = 0.0001$). In both cases, downstream concentrations were significantly greater than upstream concentrations, suggesting that the aquaculture facilities are a source of ammonia and phosphorus to Rufus Woods Lake. Although not significant at $p < 0.05$, soluble reactive phosphorus

and total nitrogen concentrations were also greater downstream with significance values of p = 0.0808 and p = 0.0893, respectively.

Table 2-7. Statistical Summary for Mann-Whitney Test Upstream and Downstream of Aquaculture Facilities in Rufus Woods Lake from 2011 to 2013

Locations	Number of Valid Samples	Mean Total Phosphorus (µg/L)	Mean Soluble Reactive Phosphorus (µg/L)	Mean Total Nitrogen (µg/L)	Mean Nitrate + Nitrite Nitrogen (µg/L)	Mean Ammonia (µg/L)	Mean Total Organic Carbon (mg/L)	Mean Chlorophyll a (µg/L)
Upstream (CHJUP, CHJNSP)	30	6.97	2.13	152.97	77.02	11.59	1.18	1.29
Downstream (CHJNSP-1, CHJNSP-2, CHJNSP-3, CHJNSP-4)	60	8.29	2.79	165.11	77.75	19.48	1.21	1.37
Mann Whitney U Test Z value	—	-3.95	-1.74	-1.69	-0.01	-3.82	-0.41	-0.23
Test Significance (ρ value)	—	**0..00008**	0.0808	0.0893	0.9898	**0.0001**	0.6812	0.8172

Notes:
Bold values **(0.0004)** indicate a significant difference at a ρ value of 0.05.

2.2.14.2 *Correlation Analysis*

Correlation of water quality data and phytoplankton data was conducted using the Kendall rank correlation (Kendall's tau) analysis. Summer (June to October) data from 2011, 2012, and 2013 was combined for all stations for the correlation analysis. A statistical significance level of $p < 0.05$ was used to identify relationships between two variables. The Kendall rank correlation coefficient can range from -1 to 1, with negative values indicating a negative relationship between the two parameters and positive values indicating a positive relationship. The farther the coefficient values are from 0, the stronger the relationship.

As would be expected, numerous significant relationships (both positive and negative) existed between several key water quality parameters (Table 2-8). Of particular interest was a strong negative relationship between transparency and chlorophyll a (-0.592) and a strong positive relationship between transparency and month (0.481). These results suggest that water clarity in Rufus Woods Lake is a factor of both phytoplankton growth and runoff. Additionally, chlorophyll a was correlated with all water quality parameters, with the strongest relationship with total phosphorus (0.321) and soluble reactive phosphorus (-0.559). This data suggests that phytoplankton biomass as measured by chlorophyll a was affected by phosphorus concentrations more than nitrogen concentrations in Rufus Woods Lake.

Table 2-8. Kendall Rank Correlation Coefficients for June to October Rufus Woods Lake Water Quality and Phytoplankton Data from 2011 to 2013

Kendall Tau Correlation Coefficients for Rufus Woods Lake Phytoplankton and Water Quality Data for 2011, 2012 and 2013

Variable	Station	Month	Year	Total Phyto Density	Total Phyto Biovolume	Total P	SRP	Ammonia	N03+N02	Total N	TN:TP Ratio	NO3:SRP Ratio	Transparency	Chl a
Station	1	0	0	-0.076527	-0.023726	0.151633	0.089003	0.250362	-0.006926	0.024147	-0.086776	-0.081197	0.027784	-0.075576
Month	0	1	0	-0.314481	-0.3403	-0.262088	0.609173	0.158648	-0.223373	-0.333513	-0.076365	-0.621828	0.481301	-0.585362
Year	0	0	1	-0.29726	-0.288333	-0.24998	-0.064309	0.148813	0.074678	-0.094522	0.124734	0.117811	0.225183	-0.195352
Total Phyto Density	-0.076527	-0.314481	-0.29726	1	0.553883	0.314199	-0.353952	-0.137058	-0.04132	0.118796	-0.178912	0.255728	-0.50102	0.530439
Total Phyto Biovolume	-0.023726	-0.3403	-0.288333	0.553883	1	0.233536	-0.412564	-0.113594	-0.134112	0.086819	-0.158403	0.240672	-0.506773	0.468502
Total P	0.151633	-0.262088	-0.24998	0.314199	0.233536	1	-0.116678	0.125608	0.124636	0.339145	-0.330662	0.136107	-0.394508	0.320714
SRP	0.089003	0.609173	-0.064309	-0.353952	-0.412564	-0.116678	1	0.195546	-0.040513	-0.11852	0.011584	-0.689629	0.467591	-0.558804
Ammonia	0.250362	0.158648	0.148813	-0.137058	-0.113594	0.125608	0.195546	1	-0.248137	-0.024479	-0.127404	-0.287022	0.034124	-0.218082
N03+N02	-0.006926	-0.223373	0.074678	-0.04132	-0.134112	0.124636	-0.040513	-0.248137	1	0.337138	0.213948	0.39489	0.022536	0.145029
Total N	0.024147	-0.333513	-0.094522	0.118796	0.086819	0.339145	-0.11852	-0.024479	0.337138	1	0.339037	0.25833	-0.290731	0.270647
TN:TP Ratio	-0.086776	-0.076365	0.124734	-0.178912	-0.158403	-0.330662	0.011584	-0.127404	0.213948	0.339037	1	0.090021	0.062748	-0.028158
NO3:SRP Ratio	-0.081197	-0.621828	0.117811	0.255728	0.240672	0.136107	-0.689629	-0.287022	0.39489	0.25833	0.090021	1	-0.327372	0.518629
Transparency	0.027784	0.481301	0.225183	-0.50102	-0.506773	-0.394508	0.467591	0.034124	0.022536	-0.290731	0.062748	-0.327372	1	-0.592078
Chl a	-0.075576	-0.585362	-0.195352	0.530439	0.468502	0.320714	-0.558804	-0.218082	0.145029	0.270647	-0.028158	0.518629	-0.592078	1
Blue Green %	0.038646	0.037428	0.228555	-0.060408	-0.135837	-0.028779	0.049031	0.035454	0.00817	-0.061586	-0.013717	-0.024005	0.063268	-0.095187
Chrysophyte %	-0.001798	-0.167666	0.106172	0.078652	0.007477	0.155539	-0.160939	0.290309	-0.149953	0.202283	0.07321	0.077432	-0.256869	0.097479
Cryptophyte %	-0.079872	-0.070919	0.518663	-0.05585	-0.227544	-0.100173	-0.126086	0.090225	0.053078	-0.020783	0.075971	0.129019	0.048418	-0.006039
Diatom %	0.083621	0.064082	-0.484463	0.040685	0.247928	0.081381	0.104296	-0.118042	-0.025163	0.003001	-0.087929	-0.100589	-0.039502	0.015401
Dinoflagellates %	0.006404	-0.081712	-0.035802	0.143419	0.102579	0.063762	-0.083225	-0.004409	-0.035344	0.052881	0.013215	0.041089	-0.072135	0.104073
Euglenoid %	-0.068371	-0.09572	0	-0.041145	-0.028321	-0.060087	-0.072787	-0.084986	0.067921	0.098913	0.102079	0.08605	-0.008131	0.042729
Green %	-0.019815	0.100933	0.062343	-0.080456	-0.144461	-0.074737	0.132361	0.001202	0.001686	-0.045897	0.04206	-0.092828	0.151387	-0.102464
Biovolume Blue Green	0.038995	0.03708	0.228555	-0.059429	-0.134204	-0.028448	0.048681	0.036453	0.006536	-0.062567	-0.014696	-0.025638	0.062936	-0.095518
Biovolume Chrysophyte	-0.033929	-0.209627	0.021701	0.225048	0.213017	0.194722	-0.274543	0.227146	-0.222988	0.173819	0.016531	0.119268	-0.393402	0.204916
Biovolume Cryptophyte	-0.075513	-0.149142	0.400705	0.133742	0.032096	-0.023952	-0.271369	0.107121	-0.090343	-0.005527	0.022156	0.180075	-0.11802	0.147394
Biovolume Diatom	-0.008374	-0.306805	-0.332302	0.493019	0.89267	0.211989	-0.355824	-0.112593	-0.147212	0.076233	-0.152621	0.197905	-0.454657	0.41341
Biovolume Dinoflagellates	0.004867	-0.080175	-0.038736	0.145821	0.104982	0.062301	-0.081679	-0.006858	-0.036787	0.052401	0.012734	0.039647	-0.072622	0.102614
Biovolume Euglenoid	-0.068371	-0.09572	0	-0.041145	-0.028321	-0.060087	-0.072787	-0.084986	0.067921	0.098913	0.102079	0.08605	-0.008131	0.042729
Biovolume Green	-0.036218	0.032327	-0.044648	0.066757	0.053506	-0.013196	0.036734	-0.038637	-0.044392	-0.044549	-0.011512	-0.05071	0.027566	0.011195

Variable	Blue Green %	Chrysophyte %	Cryptophyte %	Diatom %	Dinoflagellates %	Euglenoid %	Green %	Biovolume Blue Green	Biovolume Chrysophyte	Biovolume Cryptophyte	Biovolume Diatom	Biovolume Dinoflagellates	Biovolume Euglenoid	Biovolume Green
Station	0.038646	-0.001798	-0.079872	0.083621	0.006404	-0.068371	-0.019815	0.038995	-0.033929	-0.075513	-0.008374	0.004867	-0.068371	-0.036218
Month	0.037428	-0.167666	-0.070919	0.064082	-0.081712	-0.09572	0.100933	0.03708	-0.209627	-0.149142	-0.306805	-0.080175	-0.09572	0.032327
Year	0.228555	0.106172	0.518663	-0.484463	-0.035802	0	0.062343	0.228555	0.021701	0.400705	-0.332302	-0.038736	0	-0.044648
Total Phyto Density	-0.060408	0.078652	-0.05585	0.040685	0.143419	-0.041145	-0.080456	-0.059429	0.225048	0.133742	0.493019	0.145821	-0.041145	0.066757
Total Phyto Biovolume	-0.135837	0.007477	-0.227544	0.247928	0.102579	-0.028321	-0.144461	-0.134204	0.213017	0.032096	0.89267	0.104982	-0.028321	0.053506
Total P	-0.028779	0.155539	-0.100173	0.081381	0.063762	-0.060087	-0.074737	-0.028448	0.194722	-0.023952	0.211989	0.062301	-0.060087	-0.013196
SRP	0.049031	-0.160939	-0.126086	0.104296	-0.083225	-0.072787	0.132361	0.048681	-0.274543	-0.271369	-0.355824	-0.081679	-0.072787	0.036734
Ammonia	0.035454	0.290309	0.090225	-0.118042	-0.004409	-0.084986	0.001202	0.036453	0.227146	0.107121	-0.112593	-0.006858	-0.084986	-0.038637
N03+N02	0.00817	-0.149953	0.053078	-0.025163	-0.035344	0.067921	0.001686	0.006536	-0.222988	-0.090343	-0.147212	-0.036787	0.067921	-0.044392
Total N	-0.061586	0.202283	-0.020783	0.003001	0.052881	0.098913	-0.045897	-0.062567	0.173819	-0.005527	0.076233	0.052401	0.098913	-0.044549
TN:TP Ratio	-0.013717	0.07321	0.075971	-0.087929	0.013215	0.102079	0.04206	-0.014696	0.016531	0.022156	-0.152621	0.012734	0.102079	-0.011512
NO3:SRP Ratio	-0.024005	0.077432	0.129019	-0.100589	0.041089	0.08605	-0.092828	-0.025638	0.119268	0.180075	0.197905	0.039647	0.08605	-0.05071
Transparency	0.063268	-0.256869	0.048418	-0.039502	-0.072135	-0.008131	0.151387	0.062936	-0.393402	-0.11802	-0.454657	-0.072622	-0.008131	0.027566
Chl a	-0.095187	0.097479	-0.006039	0.015401	0.104073	0.042729	-0.102464	-0.095518	0.204916	0.147394	0.41341	0.102614	0.042729	0.011195
Blue Green %	1	0.04359	0.164715	-0.227919	-0.039554	-0.017596	-0.025884	0.995112	0.011276	0.079711	-0.19396	-0.039554	-0.017596	-0.071265
Chrysophyte %	0.04359	1	0.220839	-0.278008	0.033927	-0.026991	-0.089247	0.043927	0.788119	0.262524	-0.033563	0.032441	-0.026991	-0.115638
Cryptophyte %	0.164715	0.220839	1	-0.849685	0.040637	0.018944	0.032758	0.163061	0.156375	0.737004	-0.330516	0.038204	0.018944	-0.056757
Diatom %	-0.227919	-0.278008	-0.849685	1	-0.046845	-0.034733	-0.134468	-0.226286	-0.1993	-0.657441	0.355257	-0.044443	-0.034733	-0.035764
Dinoflagellates %	-0.039554	0.033927	0.040637	-0.046845	1	-0.011769	0.038828	-0.039554	0.084942	0.108285	0.098255	0.989418	-0.011769	0.06257
Euglenoid %	-0.017596	-0.026991	0.018944	-0.034733	-0.011769	1	0.076465	-0.017596	-0.0325	0.010284	-0.024046	-0.011769	1	0.061062
Green %	-0.025884	-0.089247	0.032758	-0.134468	0.038828	0.076465	1	-0.02622	-0.115523	-0.019791	-0.127281	0.038334	0.076465	0.796197
Biovolume Blue Green	0.995112	0.043927	0.163061	-0.226286	-0.039554	-0.017596	-0.02622	1	0.011613	0.079381	-0.192327	-0.039554	-0.017596	-0.071601
Biovolume Chrysophyte	0.011276	0.788119	0.156375	-0.1993	0.084942	-0.0325	-0.115523	0.011613	1	0.29487	0.163881	0.084446	-0.0325	-0.072231
Biovolume Cryptophyte	0.079711	0.262524	0.737004	-0.657441	0.108285	0.010284	-0.019791	0.079381	0.29487	1	-0.072865	0.106825	0.010284	-0.04743
Biovolume Diatom	-0.19396	-0.033563	-0.330516	0.355257	0.098255	-0.024046	-0.127281	-0.192327	0.163881	-0.072865	1	0.100657	-0.024046	0.068441
Biovolume Dinoflagellates	-0.039554	0.032441	0.038204	-0.044443	0.989418	-0.011769	0.038334	-0.039554	0.084446	0.106825	0.100657	1	-0.011769	0.062076
Biovolume Euglenoid	-0.017596	-0.026991	0.018944	-0.034733	-0.011769	1	0.076465	-0.017596	-0.0325	0.010284	-0.024046	-0.011769	1	0.061062
Biovolume Green	-0.071265	-0.115638	-0.056757	-0.035764	0.06257	0.061062	0.796197	-0.071601	-0.072231	-0.04743	0.068441	0.062076	0.061062	1

Correlation of water quality parameters to location, month, and year was also investigated. The majority of water quality parameters were significantly correlated to month and year affirming the importance of temporal variations in water quality at Rufus Woods Lake. However, only ammonia and total phosphorus showed a significant correlation to station location. A moderate relationship between station location and ammonia (0.250) was measured with a weaker relationship between station location and total phosphorus (0.151). These data suggest that the water quality parameters affected by location in Rufus Woods Lake were ammonia and total phosphorus.

2.3 LAKE BIOLOGICAL CONDITIONS

2.3.1 Phytoplankton

Phytoplankton are photosynthetic microorganisms that live free-floating in water. Phytoplankton are plant-like but are not plants. In general, most freshwater phytoplankton can be placed in two classes, algae and cyanobacteria. Numerous types of phytoplankton co-exist in freshwater ecosystems, including free-swimming, free-floating, colonial, and unicellular. Phytoplankton provides the base of the food chain in aquatic environments and support crucial food-web dynamics up the trophic level to more familiar aquatic organisms, such as fish. Seasonal changes in water temperature and light, as well as nutrient availability play important roles in the natural temporal variation in phytoplankton species and abundance found in freshwaters. Additionally, human-caused impacts such as increased nutrient inputs from both point and non-point sources can greatly impact the natural phytoplankton species composition and abundance found in freshwaters. Increased nutrients can result in blooms that will produce high concentrations of phytoplankton in the water column and on the water surface. Wind and currents can cause phytoplankton blooms to accumulate in certain areas of lakes, resulting in surface scums, floating mats, and nuisance conditions. Consequently, the abundance, taxonomic diversity, and productivity of phytoplankton are indicators of the health and sustainability of an aquatic ecosystem (Reynolds 1984).

Phytoplankton productivity (biomass and density) are typically highest in the spring and early summer because of warming water temperatures and the increased availability of nutrients. Phytoplankton levels often decline in the summer as nutrient supplies are depleted but can increase in early fall due to the breakdown of the thermocline making nutrients from the hypolimnion available to the epilimnion. Phytoplankton productivity levels and the dominant species composition are important when determining the general biological condition of a lake. For example, cyanobacteria can form blooms, scums, and mats and are most often associated with nuisance conditions. Additionally, numerous cyanobacteria species are capable of producing toxins (cyanotoxins) that are known to be harmful to pets, livestock, wildlife, and humans (DOH 2008). Phytoplankton blooms that produce toxins are often referred to as harmful algae blooms.

2.3.1.1 *Phytoplankton Characteristics*

Freshwater phytoplankton characteristics and traits are presented below by division.

Chlorophyta. Chlorophyta are also known as “green algae” and are a diverse group of algae commonly found in aquatic environments. Green algae are one of the most abundant algal groups in freshwater. Cells contain bright green pigments and can be either unicellular or filamentous. In general, most green algae species are considered part of a healthy aquatic ecosystem and a source of food for zooplankton. However, some filamentous green algae can create water quality problems by forming large slimy, stringy clouds of algae.

Cyanophyta. Cyanobacteria (commonly referred to as blue-green algae) are a bacteria, not algae. These unicellular, filamentous, motile, and colonial species are unique because they are a prokaryotic cell. Although they are prokaryotic, cyanobacteria have internal membranes that function in photosynthesis and contain chlorophyll a. Both filamentous and unicellular species occur in large colonies, all containing mucilaginous sheaths. Consequently, cyanobacteria are not a desirable food source for grazing zooplankton, can form nuisance algae blooms, and are generally considered a less desirable and noxious phytoplankton species. In addition, some species of cyanobacteria can produce cyanotoxins that can be harmful to mammals.

Bacillariophyta. Dominated by “diatoms,” bacillariophyta are very abundant single-celled organisms that are major photosynthetic producers. Most species of bacillariophyta are non-motile and are diverse in form. The primary characteristic of diatoms is a silicified cell wall. Although there are species that can produce harmful toxins, diatoms are generally considered valuable to the food chain and functionality of an ecosystem and are considered to be ecologically beneficial. Diatoms are commonly abundant during the spring and again during late summer and early autumn.

Cryptophyta. Commonly known as “cryptomonads,” cryptophyta are unicellular algae that usually contain two flagellates of two unequal lengths. This group of algae is very small in size, and little is understood about them. Cryptomonads are a desirable food source for zooplankton and are considered to be ecologically beneficial. When compared to other algae, cryptomonads can develop during colder periods with lower light intensities.

Chrysophyta. More commonly known as “golden algae,” this diverse algal group can be unicellular, colonial, and filamentous. Golden algae are characterized by their yellow-green coloration due to greater amounts of carotenoids versus chlorophylls in their cells. The majority of species possess two flagella.

Pyrrhophyta. Pyrrhophyta are known as “dinoflagellates” and are unicellular organisms with two flagella. Although most species are found in marine environments, there are a number of species found in freshwater systems. Dinoflagellates tend to bloom in temperate conditions toward the end of summer when stratification is stable and epilimnion nutrients are declining. In marine areas, some species can produce harmful toxins and are of particular concern to humans as they may cause red tides.

Euglenophyta. Commonly known as “euglenoids,” euglenophyta are a large and diverse group of phytoplankton commonly found in waters high in ammonia and organic

matter (Wetzel 1975). Most euglenoids are unicellular, lack a cell wall, and have up to three flagella.

2.3.1.2 *Phytoplankton Abundance and Composition*

Collectively, 178 species of phytoplankton representing 7 genera were identified in Rufus Woods Lake during the 2011 to 2014 study (Table 2-9). Of these 178 different species, there were 132 species of bacillariophyta (diatoms), 26 species of chlorophyta (green algae), 9 species of chrysophyta (golden algae), 7 species of cyanophyta (cyanobacteria), 2 species of cryptophyta (cryptomonads), and 1 species each of pyrrhophyta (dinoflagellates) and euglenophyta (euglenoids).

Table 2-9. Phytoplankton Species List for Rufus Woods Lake from 2011 to 2013

Bacillariophytes	Bacillariophytes (cont.)	Bacillariophytes (cont.)
Achnanthes clevei	*Fragilaria bicapitata*	*Nitzschia acicularis*
Achnanthes exigua	*Fragilaria capucina mesolepta*	*Nitzschia amphibia*
Achnanthes flexella	*Fragilaria construens*	*Nitzschia capitellata*
Achnanthes hauckiana	*Fragilaria construens venter*	*Nitzschia clausii*
Achnanthes lanceolata	*Fragilaria crotonensis*	*Nitzschia communis*
Achnanthes linearis	*Fragilaria leptostauron*	*Nitzschia constricta*
Achnanthes minutissima	*Fragilaria pinnata*	*Nitzschia dissipata*
Achnanthes sp.	*Fragilaria vaucheria*	*Nitzschia fonticola*
Amphipleura pellucida	*Frustulia rhomboides*	*Nitzschia frustulum*
Amphora coffeiformes	*Gomphoneis herculeana*	*Nitzschia fruticosa*
Amphora ovalis	*Gomphonema acuminatum*	*Nitzschia innominata*
Amphora perpusilla	*Gomphonema angustatum*	*Nitzschia linearis*
Anomoeoneis vitrea	*Gomphonema clevei*	*Nitzschia microcephala*
Asterionella formosa	*Gomphonema gracile*	*Nitzschia palea*
Caloneis ventricosa	*Gomphonema olivaceum*	*Nitzschia paleacea*
Caloneis ventricosa minuta	*Gomphonema sp.*	*Nitzschia recta*
Cocconeis disculus	*Gomphonema subclavatum*	*Nitzschia sinuata*
Cocconeis placentula	*Gomphonema tenellum*	*Nitzschia sp.*
Cyclotella atomus	*Gomphonema truncatum*	*Nitzschia volcanica*
Cyclotella comta	*Gyrosigma spencerii*	*Pinnularia sp.*
Cyclotella kutzingiana	*Hannaea arcus*	*Rhoicosphenia curvata*
Cyclotella meneghiniana	*Hantzschia amphioxys*	*Rhopalodia gibba*
Cyclotella ocellata	*Melosira ambigua*	*Stauroneis sp.*
Cyclotella sp.	*Melosira granulata*	*Stephanodiscus astraea*
Cyclotella stelligera	*Melosira granulata angustissima*	*Stephanodiscus astraea minutula*
Cymbella affinis	*Melosira italica*	*Stephanodiscus hantzschii*
Cymbella cesatii	*Melosira sp.*	*Stephanodiscus niagarae*
Cymbella cistula	*Melosira varians*	*Surirella linearis*
Cymbella cymbiformes	*Meridion circulare*	*Surirella ovata*
Cymbella microcephala	*Navicula anglica*	*Synedra cyclopum*
Cymbella minuta	*Navicula capitata*	*Synedra delicatissima*
Cymbella muelleri	*Navicula cascadensis*	*Synedra mazamaensis*
Cymbella naviculiformis	*Navicula cryptocephala*	*Synedra parasitica*
Cymbella sinuata	*Navicula cryptocephala veneta*	*Synedra radians*
Cymbella sp.	*Navicula decussis*	*Synedra rumpens*
Cymbella tumida	*Navicula graciloides*	*Synedra socia*
Cymbellonitzschia diluviana	*Navicula gregaria*	*Synedra sp.*
Denticula elegans	*Navicula minima*	*Synedra tenera*
Diatoma tenue	*Navicula minuscula*	*Synedra ulna*
Diatoma tenue elongatum	*Navicula pseudoscutiformis*	*Tabellaria fenestrata*
Diatoma vulgare	*Navicula pupula*	
Diploneis elliptica	*Navicula radiosa*	
Diploneis smithii	*Navicula sp.*	
Epithemia sorex	*Navicula tripunctata*	
Eunotia pectinalis	*Navicula viridula*	
Eunotia sp.	*Neidium sp.*	

Table 2-9. Phytoplankton Species List for Rufus Woods Lake from 2011 to 2013 (continued)

Cryptophytes
- *Cryptomonas erosa*
- *Rhodomonas minuta*

Chlorophytes
- *Ankistrodesmus falcatus*
- *Characium sp.*
- *Chlamydomonas sp.*
- *Chodatella wratislawiensis*
- *Cladophora sp.*
- *Closteriopsis longissima*
- *Closterium sp.*
- *Cosmarium sp.*
- *Crucigenia quadrata*
- *Dictyosphaerium ehrenbergianum*
- *Gloeocystis ampla*
- *Mougeotia sp.*
- *Nephrocytium sp.*
- *Oocystis lacustris*
- *Oocystis pusilla*
- *Pediastrum boryanum*
- *Scenedesmus abundans*
- *Scenedesmus denticulatus*
- *Scenedesmus quadricauda*
- *Schroderia sp.*
- *Selenastrum minutum*
- *Sphaerocystis schroeteri*
- *Spirogyra sp.*
- *Staurastrum gracile*
- *Tetraedron minimum*
- *Ulothrix sp.*

Chrysophytes
- *Chromulina sp.*
- *Chrysococcus rufescens*
- *Dinobryon sertularia*
- *Kephyrion littorale*
- *Kephyrion obliquum*
- *Kephyrion sp.*
- *Kephyrion spirale*
- *Mallomonas sp.*
- *Rhizosolenia eriensis*

Cyanophytes
- *Anabaena flos-aquae*
- *Anabaena planctonica*
- *Anabaena sp.*
- *Aphanizomenon flos-aquae*
- *Microcystis aeruginosa*
- *Oscillatoria limosa*
- *Oscillatoria sp.*

Euglenophytes
- *Trachelomonas scabra*

Pyrrhophyta
- *Glenodinium sp.*

Temporal variations in phytoplankton biomass volume and density at all stations in Rufus Woods Lake during the 2011 to 2013 study are presented in Figure 2-31 and Figure 2-32. Phytoplankton density is a measure of the total number of organisms of

each species per milliliter in a sample. Phytoplankton biovolume is a measure of the total volume of organisms of each species in a sample. Because biovolume measurements incorporate both cell numbers and size, they can be very different from density measurements depending on the size of the phytoplankton species. For example, cryptomonads are very small in size and may have large density numbers but small bio-volume numbers. Conversely, diatoms which are generally large in size, may have low densities but high biovolumes.

Phytoplankton biovolume was greatest in 2011 and lowest in 2013 (Figure 2-31). In 2011, biovolume at each station was similar with a large peak in May that was dominated by the diatom *Asterionella formosa*, and a second smaller peak in July that was dominated by several diatom species including *Asterionella formosa*, *Cyclotella* spp., and *Synedra* spp. Biovolumes were moderate in March and April and lowest in August, September, and October. For 2012, biovolume was low from March through June, with a small peak in July and August dominated by *Tabellaria fenestrate* and *Fragilaria crotonensis*, and lower volumes in September and October. Interestingly, the large peak in biovolume measured in July 2012 occurred only at station CHJNSP with much smaller biovolume concentrations measured in July at all other stations. Biovolume concentrations in 2013 were substantially lower at all stations throughout the entire year, with little to no temporal variation.

Figure 2-31. Rufus Woods Lake Temporal Variation in Phytoplankton Biovolume and Density from 2011 to 2013

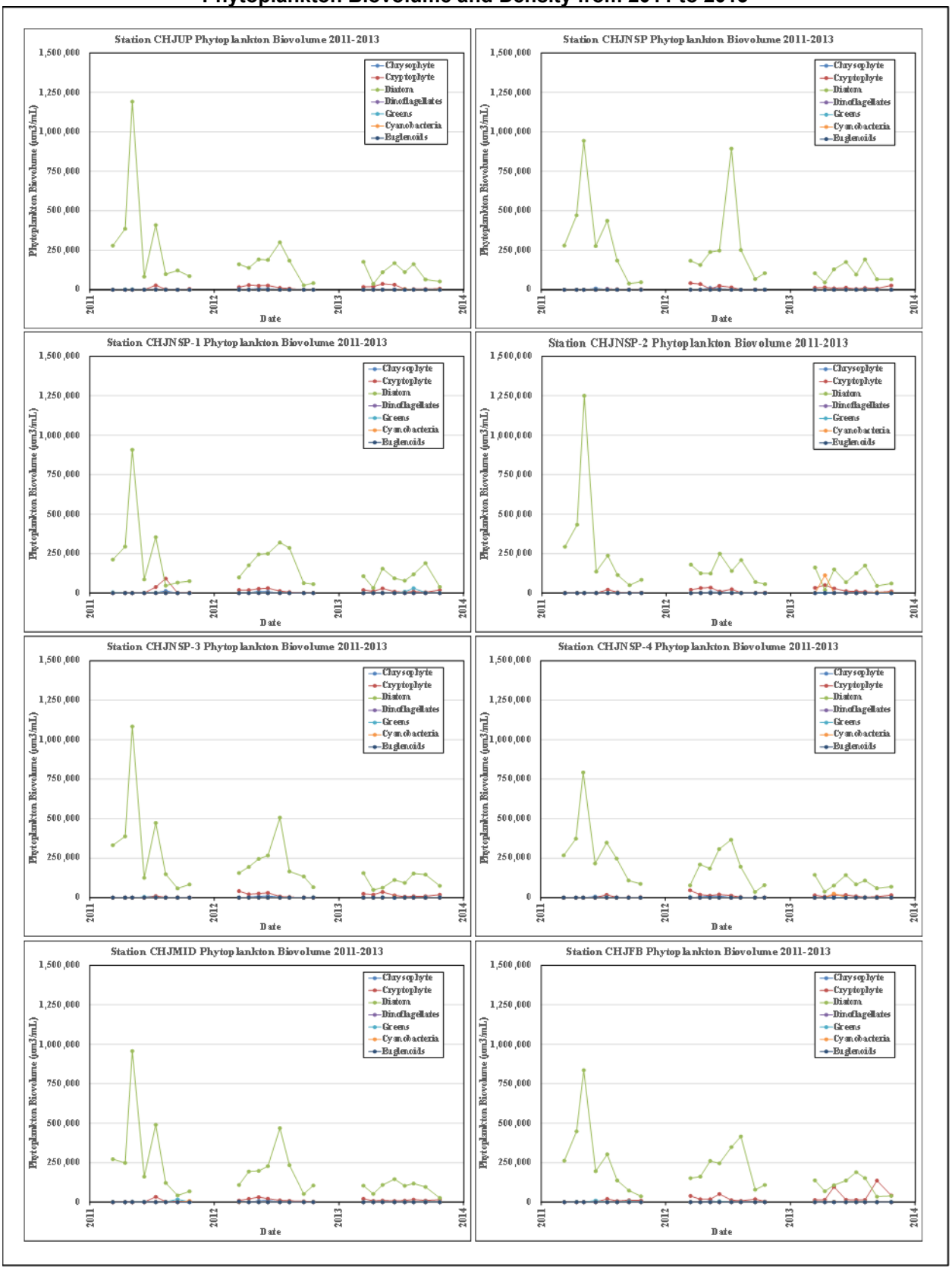
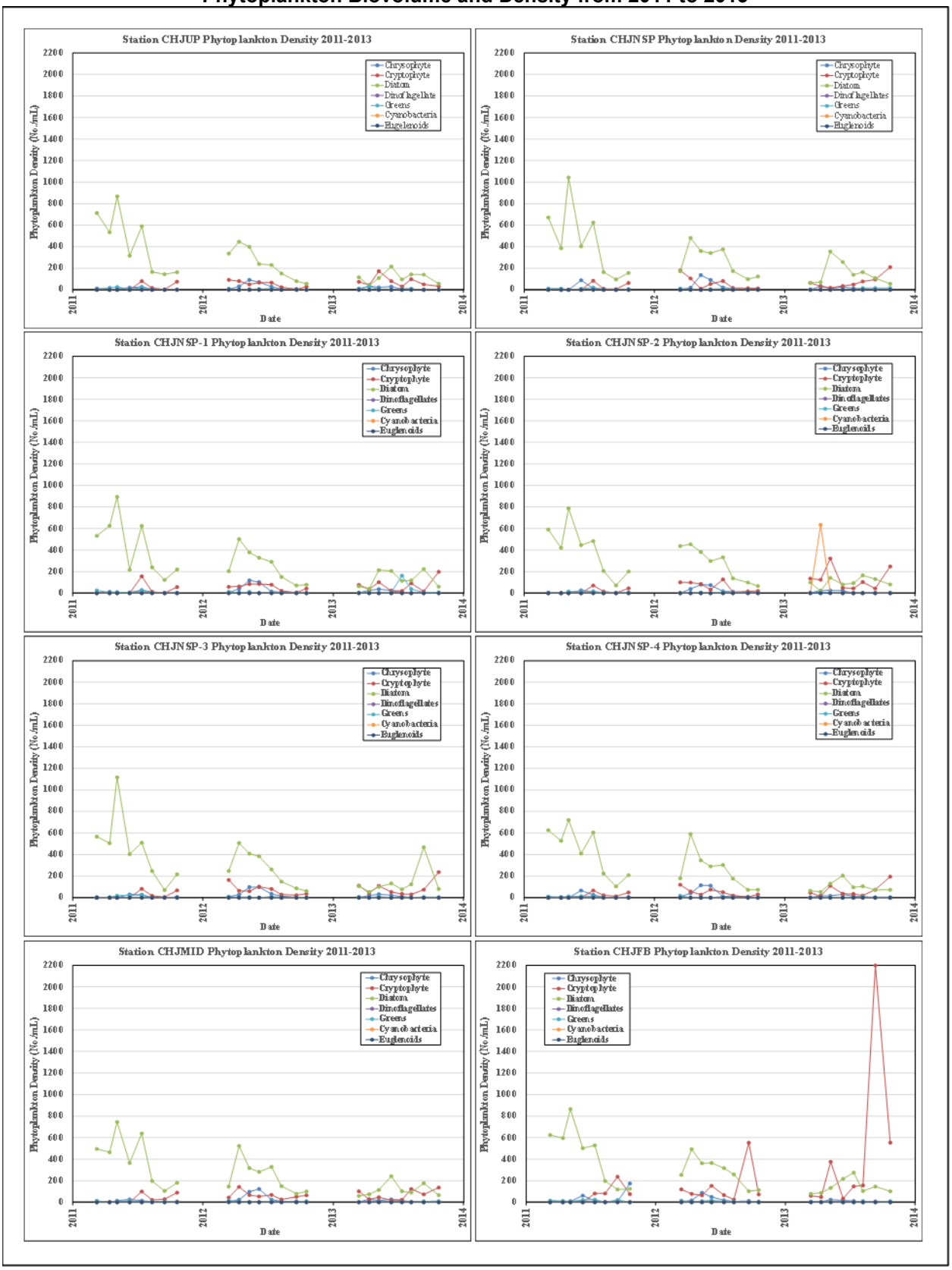


Figure 2-32. Rufus Woods Lake Temporal Variation in Phytoplankton Biovolume and Density from 2011 to 2013

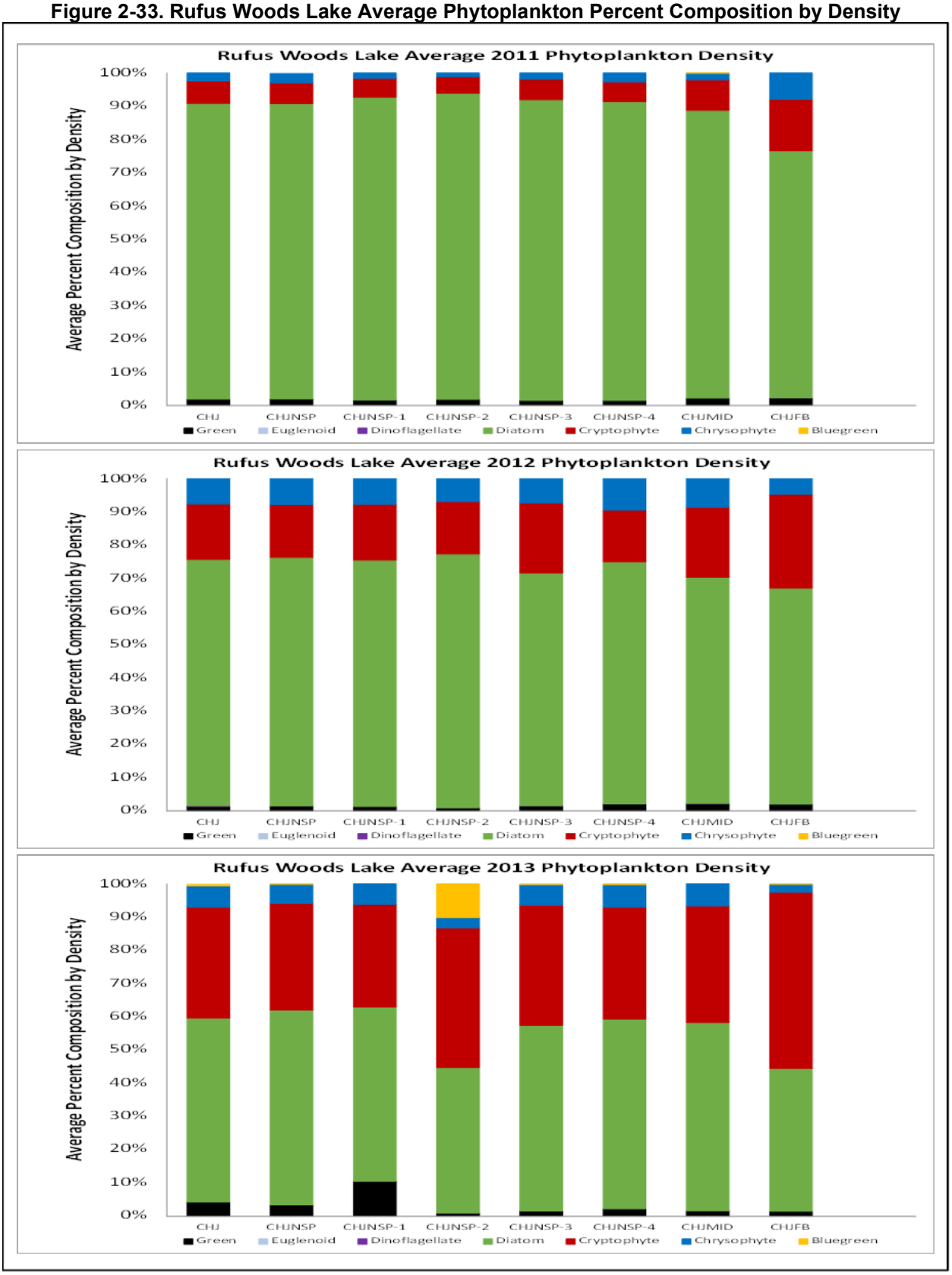


Phytoplankton density followed a similar pattern as biovolume in 2011, with peak densities measured in May and July dominated by *Asterionella formosa*, Cyclotella spp., and *Synedra* spp., and lower densities at all other times of the year (Figure 2-31). One exception was a small peak in phytoplankton density measured at CHJFB in September 2011, which was dominated by the cryptomonad *Rhodomonas minuta*. For 2012, phytoplankton density had a small peak in April and May dominated by *Asterionella formosa*, and a gradual decline throughout the rest of the summer to a low in September and October. An exception was a large peak in phytoplankton density measured at the forebay station CHJFB in September. This sample was dominated by the cryptomonad *Rhodomonas minuta*. Phytoplankton densities in 2013 were slightly less than in 2012 but followed a similar pattern of a small peak in April and May, and low densities for the rest of the year except for a large density spike of *Rhodomonas minuta* measured at CHJFB in September. The phytoplankton density peak in April was measured only at station CHJNSP-2 and was dominated by the cyanobacteria *Microcystis aeruginosa*, while the small peak in May was seen at most stations and dominated by the cryptomonads *Rhodomonas minuta* and *Cryptomonas erosa*. Because cryptomonads are extremely small in size, peaks in phytoplankton density due to this group are typically not seen when classifying phytoplankton on a volumetric basis.

Rufus Woods Lake water column phytoplankton populations were dominated by diatoms and cryptomonads at all stations throughout most of the 2011 to 2013 study (Figure 2-33 and Figure 2-34). In general, diatoms accounted for about 60 to 100 percent of phytoplankton composition by biovolume and about 40 to 95 percent by total density. Cryptomonads were the next most abundant species, accounting for about 5 to 15 percent by biovolume and from about 10 to 50 percent by density. Phytoplankton abundance dominance by diatoms was greatest in 2011 for both biovolume and density measurements, with substantial percentages of other phytoplankton (cryptomonads, green algae, and cyanobacteria) only measured periodically at CHJNSP-1, CHJMID, and CHJFB. Based on biovolume, diatoms were the dominant algae at every station for every month in 2011, except for August at station CHJNSP-1, where cryptomonads were dominant. Based on density, diatoms dominated at all stations except CHJFB in September and October when cryptomonads and crysophytes dominated.

Figure 2-32. Rufus Woods Lake Average Phytoplankton Percent Composition by Biovolume

Figure 2-33. Rufus Woods Lake Average Phytoplankton Percent Composition by Density



Diatom dominance continued in 2012; however a greater percentage of cryptomonads were measured during nearly all months at every station in Rufus Woods Lake. This increase in cryptomonads was clearly seen when accounting for phytoplankton abundance by density. Using density, both cryptomonads and crysophytes accounted for about 30 percent of phytoplankton abundance at all stations in Rufus Woods Lake, with the greatest densities measured in September and October. In 2013, diatoms were still the dominant phytoplankton group by biovolume but were nearly equal in dominance with cryptomonands by density (Figure 2-).

The shift in phytoplankton composition seen in Rufus Woods Lake from nearly total diatom dominance in 2011 and 2012 to co-dominance by diatoms and cryptomonads in 2013 is interesting. Numerous studies have shown diatom dominance in lakes related to increased water column mixing, lower water temperatures, and high concentrations of silica and phosphorus (Harris and Piccinin 1980; Zhang and Prepas 1996). The greater dominance by diatoms in 2011 and 2012 when compared to 2013 may be related to the higher runoff and flows in Rufus Woods Lake and the Columbia River during those 2 years, resulting in greater water column mixing, cooler water temperatures, and higher phosphorus concentrations. Because silica was not analyzed during the study, it is uncertain if variations in silica in Rufus Woods Lake was a cause for the change in algal dominance from 2011 to 2013.

Very little cyanobacteria was detected in water column phytoplankton samples collected during 2011 and 2012, with slightly greater populations detected in 2013. In 2011, *Aphanizomenon flos-aquae* was detected only at station CHJMID in October, while in 2012, no cyanobacteria were detected in water column samples collected in Rufus Woods Lake. In 2013, several different species of cyanobacteria were detected in the lake, including *Aphanizomenon flos-aquae*, *Anabaena flos-aquae*, *Anabaena* sp., *Anabaena planctonica*, *Oscillatoria* sp., *Oscillatoria limosa*, and *Microcystis aeruginosa*. The majority of the cyanobacteria noted in 2013 were detected at stations CHJNSP-2 and CHJNSP-4.

Phytoplankton Correlation Analysis. Correlation of water quality data and phytoplankton data was conducted using the Kendall rank correlation coefficient (Kendall's tau) analysis. Phytoplankton data from 2011, 2012, and 2013 was combined for all stations for the correlation analysis. A statistical significance level of $p < 0.05$ was used to identify relationships between two variables. The Kendall rank correlation coefficient can range from -1 to 1, with negative values indicating a negative relationship between the two parameters and positive values indicating a positive relationship. The farther the coefficient values are from 0, the stronger the relationship.

Total phytoplankton biovolume was strongly correlated to transparency (-0.507), chlorophyll a (0.469), and soluble reactive phosphorus (-0.413), and moderately correlated to month (-0.340), year (-0.288), and total phosphorus (0.234) (see Table 2-8). Total phytoplankton biovolume was strongly correlated to diatom biovolume (0.893) and moderately correlated to chrysophyte biovolume. Phytoplankton populations of chrysophytes, cryptophytes, and diatoms were correlated with most water quality

parameters while populations of cyanobacteria, dinoflagellates, euglenoids, and green algae showed little correlation with any water quality parameter.

2.3.2 Periphyton

Periphyton refers to algae attached to an aquatic substrate, and includes both benthic algae attached to the bottom substrate, and epiphytic algae attached to other plants. In most freshwater habitats, periphyton assemblages are dominated by cyanobacteria (Cyanophyta), diatoms (Bacillariophyta), and green algae (Chlorophyta) (Stevenson 1996). Periphyton are an important part of an aquatic ecosystem, and can be a major contributor to the primary productivity of a water body. Periphyton are often considered good indicators of the overall water quality and condition of an ecosystem because, unlike phytoplankton, which can move through a system, periphyton remain attached and thus better reflect ecosystem changes. For example, changes in nutrient inputs, temperature, light availability, and flow may cause changes in periphyton growth and assemblages (Shilling et al. 2005). As such, changes in the periphytonstructure, species composition, and biomass is an indicator of the overall ecological condition of a water body.

2.3.2.1 *Periphyton Abundance and Composition*

Periphyton samples were collected from cobble scrapes in Rufus Woods Lake between Grand Coulee Dam and Chief Joseph Dam at 10 stations (see Figure 1-4). Collectively, 41 distinct periphyton taxa representing 3 genera were identified for samples collected in Rufus Woods Lake on July 11, 2011 (Table 2-10). Of these 41 different taxa, there were 28 species of diatoms, 9 species of green algae, and 4 species of cyanobacteria. Only one sample collected near Rocky Flats at Site 2 included the potentially toxic cyanobacteria *Oscillatoria*. In general, periphyton abundance measured from the July 11, 2011, samples were dominated by diatoms, with *Fragilaria*., *Melosira*, and *Staurosira* being the dominant species at all locations except Station 4 (Table 2-10). For Site 4 located near Rocky Flats, the nuisance green algae *Spirogyra* dominated.

Table 2-10. Periphyton Data for July 11, 2011, Rufus Woods Lake Samples

Water Body	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	Rufus Woods Lake	
Site	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
Latitude	**47.995129°**	**48.066496°**	**48.066496°**	**48.066496°**	**48.093495°**	**48.060505°**	**48.128754°**	**48.129105°**	**48.115351°**	**48.048128°**	
Longitude	**-119.627259°**	**-119.430224°**	**-119.430224°**	**-119.430224°**	**-119.020256°**	**-119.015819°**	**-119.042744°**	**-119.177104°**	**-119.299882°**	**-119.339209°**	
Collection Date	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	**07-11-2011**	
Volume Received (ml)	**15**	**30**	**50**	**40**	**15**	**15**	**35**	**25**	**15**	**35**	
Percent Counted	**0.00082%**	**0.00053%**	**0.00048%**	**0.00144%**	**0.00087%**	**0.00017%**	**0.00042%**	**0.00039%**	**0.00021%**	**0.00033%**	
EcoAnalysts Sample ID	**5792.1-1**	**5792.1-2**	**5792.1-3**	**5792.1-4**	**5792.1-5**	**5792.1-6**	**5792.1-7**	**5792.1-8**	**5792.1-9**	**5792.1-10**	
LIVE DIATOM TAXA											
Achnanthidium sp.	4	2	0	0	2	24	4	4	10	4	diatom
Amphora sp.	0	0	0	0	0	0	1	0	1	1	diatom
Asterionella formosa	0	2	0	0	0	7	2	1	1	2	diatom
Asterionella sp.	2	0	0	0	0	0	0	0	0	0	diatom
Aulacoseira sp.	16	6	27	0	37	3	0	2	0	6	diatom
Cocconeis pediculus	0	0	0	0	0	0	0	0	0	8	diatom
Cocconeis sp.	2	0	0	1	0	1	2	0	0	0	diatom
Cyclotella sp.	1	1	1	0	1	0	0	0	0	0	diatom
Cymatopleura sp.	0	0	0	0	3	0	0	1	0	0	diatom
Cymbella sp.	6	5	14	0	10	19	6	10	11	5	diatom
Diatoma sp.	0	0	0	0	0	33	0	4	24	26	diatom
Encyonema sp.	8	0	10	0	11	5	1	5	2	1	diatom
Epithemia sp.	1	0	0	0	0	0	1	0	0	0	diatom
Fragilaria crotonensis	0	35	0	0	10	10	9	20	0	7	diatom
Fragilaria sp.	129	113	187	37	165	180	169	151	180	177	diatom
Frustulia sp.	0	0	1	0	1	0	0	0	0	0	diatom
Gomphonema sp.	5	1	2	0	0	1	5	1	0	10	diatom
Melosira varians	53	15	26	1	11	20	62	48	12	45	diatom
Navicula sp.	2	1	3	0	8	2	2	1	0	0	diatom
Nitzschia sp.	10	6	3	0	5	7	11	17	3	4	diatom
Rhoicosphenia sp.	0	0	0	0	0	0	0	0	0	5	diatom
Rhopalodia sp.	0	0	1	0	0	0	1	0	0	1	diatom
Staurosira sp.	17	75	8	27	12	0	14	45	32	11	diatom
Surirella sp.	1	0	1	0	0	1	0	0	0	0	diatom
Synedra sp.	8	5	7	2	10	6	5	6	6	12	diatom
Tabellaria sp.	0	0	0	0	0	6	0	0	0	2	diatom
unknown centric sp.	10	2	3	0	3	1	1	3	1	2	diatom
unknown pennate diatom	32	9	28	0	13	3	3	9	8	6	diatom
LIVE DIATOM SUB TOTAL	**307**	**278**	**322**	**68**	**302**	**329**	**299**	**328**	**291**	**335**	
SOFT BODY TAXA											
Ankistrodesmus falcatus	0	0	0	0	0	0	4	0	0	0	green
Calothrix sp.	0	0	0	0	0	0	1	0	0	0	blue-green
Merismopedia sp.	0	1	0	0	0	0	0	0	0	0	blue-green
Microspora sp.	0	0	0	0	0	0	0	0	1	0	green
Mougeotia sp.	0	3	0	0	0	4	0	0	2	5	green
Oedogonium sp.	3	1	0	1	0	1	1	0	9	1	green
Oscillatoria sp.	0	1	0	0	0	0	0	0	0	0	blue-green
Pediastrum boryanum	0	0	1	0	0	1	0	0	0	0	green
Phormidium sp.	1	0	1	0	4	0	0	1	0	1	blue-green
Scenedesmus ecornis	1	1	0	0	0	0	0	0	1	2	green
Spirogyra sp.	0	27	0	238	0	0	4	0	1	0	green
Ulothrix zonata	1	0	0	0	0	0	1	0	1	1	green
Zygnema sp.	0	3	0	0	0	0	0	0	3	0	green
SOFT BODY SUB TOTAL	**6**	**37**	**2**	**239**	**4**	**6**	**11**	**1**	**18**	**10**	
GRAND TOTAL	**313**	**315**	**324**	**307**	**306**	**335**	**310**	**329**	**309**	**345**	

More extensive sampling of periphyton in Rufus Woods Lake was conducted by EcoAnalysts during the summer in 2010 and 2011 (Richards, Rensel, and Siegrist 2011). Samples were collected from both cobble scrapes and tiles at several littoral locations in Rufus Woods Lake between Grand Coulee Dam and Chief Joseph Dam. During the 2-year study, 76 distinct periphyton taxa were identified. In general, the periphyton assemblages were dominated by diatoms, with *Fragilaria*, *Achnanthes*, *Cocconeis*, *Cymbella* , *Gomphonema*, *Navicula*, and *Melosira* being the dominant diatom species. In addition, these periphyton samples contained several potentially noxious green algae species, such as *Spirogyra* and *Cladophora*, as well as the potentially toxic cyanobacteria *Oscillatoria*. Those stations located farthest upstream in Rufus Woods Lake (several kilometers downstream of Grand Coulee Dam) tended to have the most soft-bodied algae, such as *Oscillatoria*, *Spirogyra*, and *Cladophora* (Richards, Rensel, and Siegrist 2011). Similar periphyton abundance results were noted in Lake Pateros, the reservoir formed by Wells Dam located immediately downstream of Chief Joseph Dam, during a 2005–2006 study. Periphyton assemblages were dominated by the diatoms *Cymbella*, *Fragilaria*, *Gomphoneis*, and *Tabellaria*., with the cyanobacteria *Oscillatoria* present in nearly every sample collected (EES Consultants 2006).

The EcoAnalysts study measured chlorophyll a concentrations and ash free dry mass, and calculated the autotrophic index (ratio of chlorophyll a to ash free dry mass) for periphyton samples collected in Rufus Woods Lake. Periphyton chlorophyll a concentrations ranged from near 0 to about 50 milligrams per square meter (mg/m^2), with a mean concentration of 12.8 mg/m^2. Chlorophyll a concentrations were greatest at the farthest upstream stations (several kilometers downstream of Grand Coulee Dam), lowest in the middle sections of the reservoir, and moderate at the stations farthest downstream (several kilometers upstream of Chief Joseph Dam) (Richards, Rensel, and Siegrist 2011). For comparative purposes, a water year 2000 study at Rocky Reach Reservoir (two reservoirs below Chief Joseph Dam) measured a mean chlorophyll a concentration of 89.7 mg/m^2 (Parametrix 2001). Thus, mean chlorophyll a concentrations in Rufus Woods Lake were lower than previously measured downstream in the Columbia River but were within the range of concentrations measured from other rivers in the Pacific Northwest (Richards, Rensel, and Siegrist 2011).

The autotrophic index was calculated in 2010 and 2011 for Rufus Woods Lake by EcoAnalysts from the ratio of chlorophyll a to ash free dry mass as a percentage (Richards, Rensel, and Siegrist 2011). The autotrophic index determines the trophic nature of the periphytic community. Chlorophyll a concentrations give an estimate of the autotrophic component (e.g., photosynthetic) of the periphyton, while ash free dry mass gives an estimate of the organic matter in the sample including all autotrophs (algae, cyanobacteria) and heterotrophs (organisms that cannot create their own food such as bacteria, fungi, and invertebrates). In general, the data from 2010 and 2011 show that Rufus Woods Lake periphyton assemblages were dominated by autotrophic algal production.

2.3.3 Harmful Algae Blooms

Numerous cyanobacteria species are capable of producing toxins (cyanotoxins) that are known to be harmful to pets, livestock, wildlife, and humans (DOH 2008). Phytoplankton blooms that produce toxins are often referred to as harmful algae blooms. Harmful algae bloom cyanotoxins include hepatotoxins (liver toxins) and neurotoxins (nerve toxins) (DOH 2008, Oregon Public Health Department [OPHD] 2015). The most widespread cyanotoxins are microcystin (liver toxin) and anatoxin-a (nerve toxin) (EPA 2012b). Several cyanobacteria genera that have been identified as species of concern in Washington State, including *Microcystis*, *Anabaena*, *Aphanizomenon*, *Gloetrichia*, *Oscillatoria*, *Cylindrospermopsis*, *Lyngbya*, and *Nostoc* (DOH 2008). Washington State Department of Health recreational guidelines for microcystin and anatoxin-a concentrations are 6 µg/L and 1 µg/L, respectively.

Harmful algae blooms were investigated in Rufus Woods Lake and upstream reservoirs (e.g., Lake Roosevelt and Banks Lake) during the 2011, 2012, and 2013 sampling seasons. As described in the previous section, Rufus Woods Lake's photic zone phytoplankton biovolume was dominated by diatoms and cryptomonads with very few cyanobacteria. Although little to no cyanobacteria species were present in the water column (see phytoplankton section), free-floating phytoplankton mats containing cyanobacteria occurred in Rufus Woods Lake during the 2011, 2012, and 2013 seasons. Indeed, all harmful algae bloom samples collected in Rufus Woods Lake were from these free-floating surface mats or clumps of phytoplankton. The floating mats and clumps of phytoplankton were a mixture of cyanobacteria, diatoms and green algae, that were dominated by diatoms and cyanobacteria. In general, the dominant cyanobacteria found in all floating mats and clumps was *Oscillatoria*. Other cyanobacteria occasionally found in the mats were *Anabaena* and *Aphanizomenon*.

2.3.3.1 *Temporal and Spatial Variability*

Pronounced and prolonged harmful algae blooms occurred in Rufus Woods Lake during the summer in 2011, 2012, and 2013 (Figure 2-35). During each year, the blooms consisted of free-floating clumps and mats of phytoplankton that were located throughout Rufus Woods Lake from station CHJUP upstream of the aquaculture sites downstream to station CHJFB in the forebay (see Figure 1-3). These mats were present in Rufus Woods Lake from early June through September 2011, from early July through September 2012, and from early May through September 2013. Numerous environmental variables (water temperature, flow, flushing rate, zooplankton abundance, water column stability, and nutrient availability) varied from year to year and are likely responsible for the slight temporal variability of floating mat start/end dates that were seen between years.

Figure 2-34. Photos of Rufus Woods Lake Harmful Algae Bloom in Forebay During 2011

For each year, the location, aerial extent and coverage of the harmful algae mats were not uniform throughout the lake and were extremely patchy in nature. This patchiness of the floating mats resulted in substantial spatial variability based on wind direction and wave action. In general, small algal clumps were observed floating downstream in the middle of the river channel and tended to build up in sheltered nearshore areas with the largest mats forming farthest downstream in Rufus Woods Lake near the forebay (stations CHJFB and CHJFB-BR) and Bridgeport State Park (stations CHJSP-BR and CHJSP-SB) (See Figure 1-3). During calm days, small floating clumps of toxic algae were present throughout the majority of the 80-kilometer Rufus Woods Lake, from Buckley Bar near station CHJUP downstream to the forebay station CHJFB. Wind and wave action periodically resulted in breaking up the algal mats and mixing the algae clumps down into the water column, thereby creating an apparent absence of any floating algae on the lake until environmental conditions allowed for the reformation of the mats.

Although harmful algae blooms are most often caused by planktonic species in eutrophic waters, benthic (periphyton) mats in oligotrophic waters have been known to cause problems (Mez, Hanselmann, and Preisig 1998; World Health Organization [WHO] 2003). Studies have shown that benthic mats in lakes and rivers can break free from the bottom by either physical activities (e.g., increased flows, boating, changing reservoir elevations) or photosynthetic activities (e.g., production of oxygen-forming bubbles) that can loosen parts of the mats and float them to the surface (Mez, Hanselmann, and Preisig 1998; St. Croix Watershed Research Station 2011; Komarek and Johansen 2015). Often when these detached mats float to the surface, they are transported by the current and wind, tending to build up along the shore in windward locations.

The floating algal mats containing *Oscillatoria* in Rufus Woods Lake are likely derived from a benthic source. The fact that plankton samples collected from the water column in Rufus Woods Lake contained little to no *Oscillatoria* while periphyton samples contained this blue-green algae points to a benthic source of the floating algal mats. Moreover, numerous studies have shown that the planktonic genera *Anabaena*, *Aphanizomenon*, and *Microcystis* form surface scums, and the benthic genus *Oscillatoria* forms mats of high algal biomass that can produce toxins (Codd et al. 2005).

2.3.3.2 *Abundance and Composition*

Algal mat abundance and composition were determined both qualitatively and quantitatively. Qualitative algal mat analysis identified 50 distinct taxa representing 7 genera (Table 2-11). Of these 50 different taxa, there were 19 species of diatoms, 16 species of green algae, 8 species of blue-green algae, 3 species of golden algae, 1 cryptomonad, 1 euglenoid, and 1 fungus. Quantitative algal mat analysis identified 95 distinct taxa representing 4 genera (Table 2-12). Of these 95 different taxa, there were 83 species of diatoms, 7 species of green algae, 3 species of blue-green algae, and 2 species of golden algae.

Table 2-11. Harmful Algae Bloom Qualitative Analysis Species List for Rufus Woods Lake from 2011 to 2013

Blue-green algae

- Anabaena: trichome irregularly twisted
- Aphanizomenon sp.
- Arthrospira sp.
- Lyngbya sp.
- Merismopedia sp.
- Oscillatoria sp.
- Pseudoanabaena sp.
- Woronichinia sp.

Cryptomonads

- Cryptomonas sp.

Diatoms

- Asterionella
- Aulacoseira sp.
- Cocconeis sp.
- Cymbella sp.
- Eunotia sp.
- Fragilaria sp.
- Gomphonema sp.
- Gyrosigma sp.
- Melosira sp.
- Navicula sp.
- Nitzschia sp.
- Pinnularia sp.
- Rhizosolenia sp.
- Sphaerocystis sp.
- Stephanodiscus sp.
- Surirella sp.
- Synedra sp.
- Tabellaria sp.
- Undetermined Centric Diatom
- Undetermined Pennate Diatom

Euglenoids

- Euglena sp.

Fungus

- Microspora Sp.

Golden algae

- Dinobryon sp.
- Mallomonas sp.
- Ophiocytium sp.

Green algae

- Ankistrodesmus sp.
- Botryococcus sp.
- Closteriopsis sp.
- Closterium sp.
- Coelastrum sp.
- Cosmarium sp.
- Oedogonium sp.
- Oocystis sp.
- Pediastrum sp.
- Scenedesmus sp.
- Spirogyra sp.
- Ulothrix sp.
- Unicellular Green 1-3 microns
- Unicellular Green 4-7 microns
- Unicellular Green 8-10 microns
- Zygnema sp.

Table 2-12. Harmful Algae Bloom Quantitative Analysis Species List for Rufus Woods Lake from 2011 to 2013

Blue-green algae
- Anabaena sp.
- Oscillatoria limosa
- Oscillatoria sp.

Cryptophyte
- Cryptomonas erosa
- Rhodomonas minuta

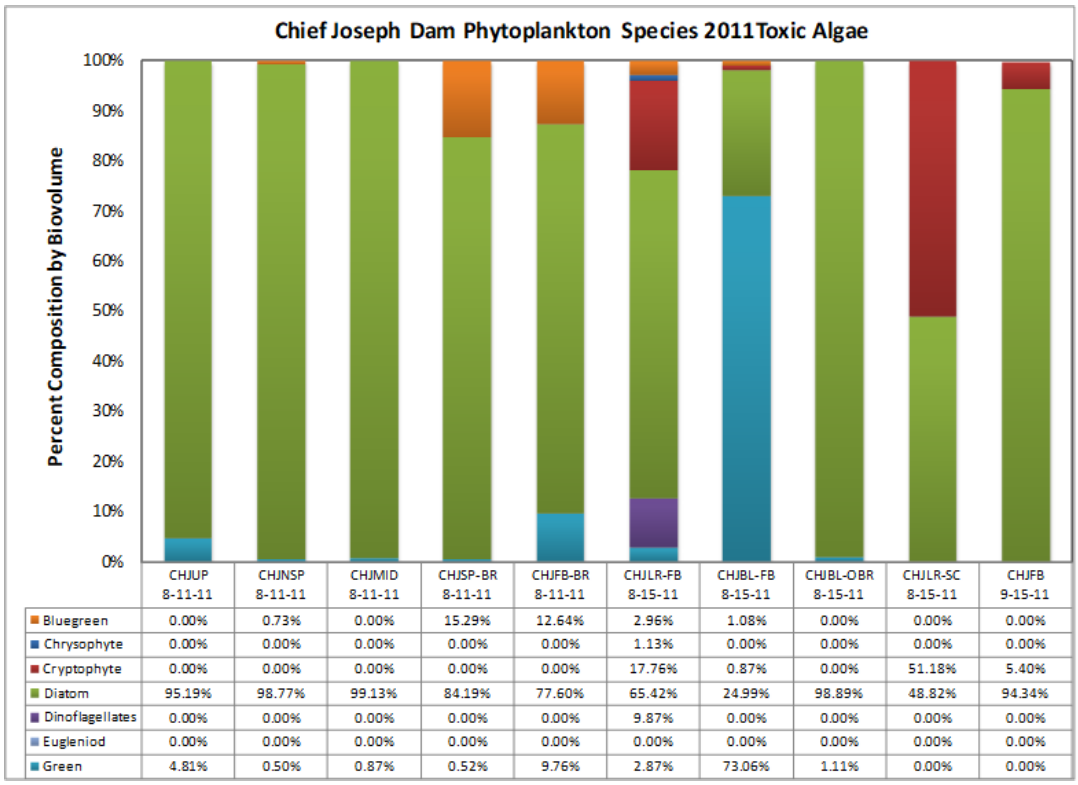
Diatom
- Achnanthes clevei
- Achnanthes exigua
- Achnanthes hauckiana
- Achnanthes lanceolata
- Achnanthes linearis
- Achnanthes minutissima
- Achnanthes recurvata
- Amphipleura pellucida
- Amphora perpusilla
- Asterionella formosa
- Cocconeis placentula
- Cyclotella comta
- Cyclotella kutzingiana
- Cyclotella meneghiniana
- Cyclotella ocellata
- Cyclotella stelligera
- Cymatopleura solea
- Cymbella affinis
- Cymbella cesatii
- Cymbella cistula
- Cymbella cymbiformes
- Cymbella microcephala
- Cymbella minuta
- Cymbella muelleri
- Cymbella sinuata
- Cymbella sp.
- Cymbella tumida
- Denticula elegans
- Diatoma tenue
- Diatoma tenue elongatum
- Diatoma vulgare
- Diploneis elliptica
- Fragilaria capucina mesolepta
- Fragilaria construens
- Fragilaria construens venter
- Fragilaria crotonensis
- Fragilaria leptostauron
- Fragilaria pinnata
- Fragilaria vaucheria
- Gomphoneis herculeana
- Gomphonema acuminatum
- Gomphonema angustatum

Diatom (continued)
- Gomphonema clevei
- Gomphonema gracile
- Gomphonema subclavatum
- Gomphonema truncatum
- Hannaea arcus
- Melosira ambigua
- Melosira granulata
- Melosira italica
- Melosira varians
- Navicula anglica
- Navicula capitata
- Navicula cascadensis
- Navicula cryptocephala
- Navicula cryptocephala veneta
- Navicula decussis
- Navicula graciloides
- Navicula sp.
- Navicula tripunctata
- Navicula viridula
- Nitzschia acicularis
- Nitzschia amphibia
- Nitzschia capitellata
- Nitzschia dissipata
- Nitzschia frustulum
- Nitzschia linearis
- Nitzschia microcephala
- Nitzschia palea
- Nitzschia paleacea
- Nitzschia sp.
- Pinnularia sp.
- Stephanodiscus astraea minutula
- Stephanodiscus hantzschii
- Surirella linearis
- Synedra mazamaensis
- Synedra parasitica
- Synedra radians
- Synedra rumpens
- Synedra socia
- Synedra tenera
- Synedra ulna
- Tabellaria fenestrata

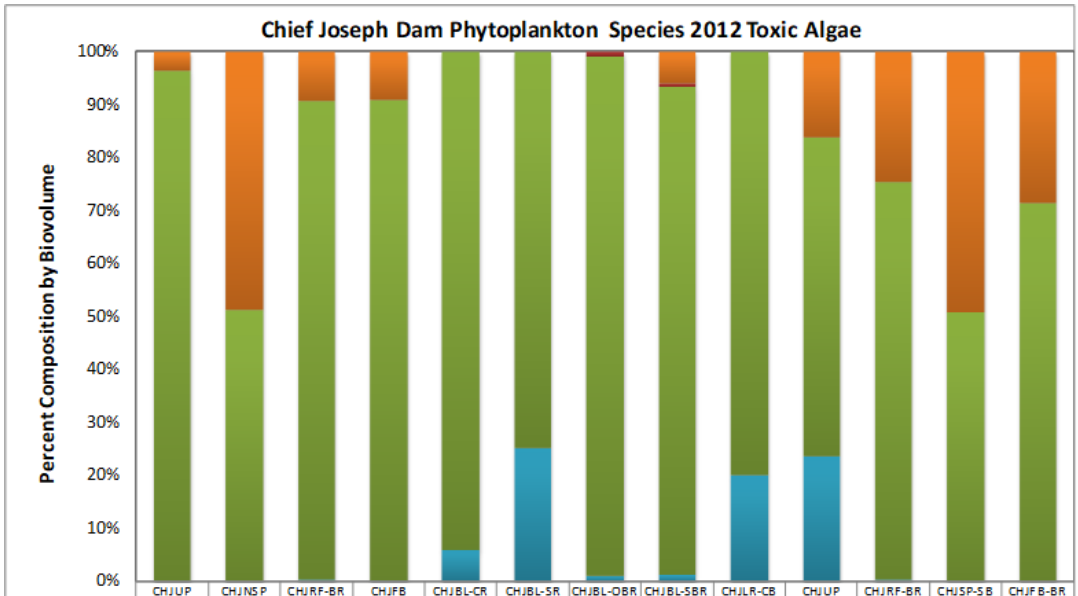
Green algae
- Ankistrodesmus falcatus
- Cladophora sp.
- Mougeotia sp.
- Nephrocytium sp.
- Scenedesmus quadricauda
- Spirogyra sp.
- Ulothrix sp.

Quantitative and qualitative analysis determined harmful algae bloom floating mats sampled in Rufus Woods Lake from 2011 to 2013 to be a mixture of filamentous cyanobacteria intertwined with diatoms and green algae (Figure 2-36). In general, diatoms dominated most floating mat samples, with *Achnanthes* spp., *Cymbella* spp., *Fragilaria* spp., *Melosira* spp., *Synedra* spp., and *Tabellaria* spp. the most abundant. Cyanobacteria were the next most abundant algal type detected in the floating mats, with *Oscillatoria limosa* and *Oscillatoria* sp. being the dominant cyanobacteria. Green algae species were detected in a majority of floating mat samples, with *Spirogyra* sp. the dominant green algal type.

Figure 2-35. Rufus Woods Lake Harmful Algae Bloom Algal Percent Composition by Biovolume for 2011 and 2012



	CHJUP 8-11-11	CHJNSP 8-11-11	CHJMID 8-11-11	CHJSP-BR 8-11-11	CHJFB-BR 8-11-11	CHJLR-FB 8-15-11	CHJBL-FB 8-15-11	CHJBL-OBR 8-15-11	CHJLR-SC 8-15-11	CHJFB 9-15-11
Bluegreen	0.00%	0.73%	0.00%	15.29%	12.64%	2.96%	1.08%	0.00%	0.00%	0.00%
Chrysophyte	0.00%	0.00%	0.00%	0.00%	0.00%	1.13%	0.00%	0.00%	0.00%	0.00%
Cryptophyte	0.00%	0.00%	0.00%	0.00%	0.00%	17.76%	0.87%	0.00%	51.18%	5.40%
Diatom	95.19%	98.77%	99.13%	84.19%	77.60%	65.42%	24.99%	98.89%	48.82%	94.34%
Dinoflagellates	0.00%	0.00%	0.00%	0.00%	0.00%	9.87%	0.00%	0.00%	0.00%	0.00%
Eugleniod	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Green	4.81%	0.50%	0.87%	0.52%	9.76%	2.87%	73.06%	1.11%	0.00%	0.00%



	CHJUP 7-11-12	CHJNSP 7-11-12	CHJRF-BR 7-11-12	CHJFB 7-11-12	CHJBL-CR 7-25-12	CHJBL-SR 7-25-12	CHJBL-OBR 7-25-12	CHJBL-SBR 7-25-12	CHJLR-CB 7-25-12	CHJUP 7-26-12	CHJRF-BR 7-26-12	CHJSP-SB 7-26-12	CHJFB-BR 7-26-12
Bluegreen	3.54%	48.77%	9.34%	9.04%	0.00%	0.00%	0.00%	6.11%	0.00%	16.28%	24.60%	49.12%	28.63%
Chrysophyte	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cryptophyte	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.99%	0.58%	0.00%	0.00%	0.00%	0.00%	0.00%
Diatom	96.46%	51.23%	90.33%	90.72%	94.11%	74.93%	97.92%	91.98%	80.04%	60.07%	75.04%	50.88%	71.37%
Dinoflagellates	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Eugleniod	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Green	0.00%	0.00%	0.33%	0.24%	5.89%	25.07%	1.09%	1.33%	19.96%	23.65%	0.36%	0.00%	0.00%

2.3.3.3 *Harmful Algae Bloom Toxicity*

Microcystin (liver toxin) and anatoxin-a (nerve toxin) are the two most widespread cyanotoxins detected in North America (EPA 2012). Concentrations of cyanotoxins (microcystin and anatoxin-a) measured in floating algal mats and the surrounding water column from various locations in Rufus Woods Lake for 2011 to 2013 are presented in Table 2-13 to Table 2-15. Station locations are shown in Table 1-3 to Table 1-5 and Figure 1-4. Washington State Department of Health recreational guidelines for microcystin and anatoxin-a concentrations are 6 µg/L and 1 µg/L, respectively (DOH 2008).

Table 2-13. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2011

Station Name	Station Location	Date	Sample Type	Anatoxin-a (µg/L)	MDL (µg/L)	Microcystin (µg/L)	MDL (µg/L)	Oscillatoria Abundance
CHJFB-BR	Forebay Boat Ramp	7/13/2011	Algal Mat	**5.26**	0.0185	<MDL	0.05	ND
CHJFB	Forebay	7/13/2011	Algal Mat	**4.75**	0.0185	<MDL	0.05	P
CHJFB	Forebay	7/26/2011	Algal Mat	**37.4**	0.0185	—	—	NA
CHJFB-BR	Forebay Boat Ramp	7/26/2011	Algal Mat	**21.6**	0.0185	—	—	NA
CHJFB-BR	Forebay Boat Ramp	8/11/2011	Algal Mat	**8.73**	0.0185	<MDL	0.05	NA
CHJFB-BR	Forebay Boat Ramp	8/11/2011	Open Water	<MDL	0.0185	<MDL	0.05	NA
CHJSP-SB	State Park Swim Beach	8/11/2011	Algal Mat	**32.7**	0.0185	<MDL	0.05	NA
CHJSP-SB	State Park Swim Beach	8/11/2011	Open Water	<MDL	0.0185	<MDL	0.05	NA
CHJNSP	Mouth Nespelum River	8/11/2011	Algal Mat	**5.05**	0.0185	<MDL	0.05	NA
CHJUP	Downstream Buckley Bar	8/11/2011	Algal Mat	**2.31**	0.0185	<MDL	0.05	NA
CHJSP-SB	State Park Swim Beach	8/17/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	NA
CHJRF-BR	Rocky Flats Boat Ramp	8/17/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	NA
CHJLP	Lone Pine Island	8/17/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	NA
CHJSP-BR	State Park Boat Ramp	8/25/2011	Algal Mat	**1.46**	0.0185	<MDL	0.05	NA
CHJSP-SB	State Park Swim Beach	8/25/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	NA
CHJSP-BR	State Park Boat Ramp	8/31/2011	Algal Mat	0.025	0.0185	<MDL	0.05	P
CHJSP-SB	State Park Swim Beach	8/31/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	ND
CHJSP-SB	State Park Swim Beach	9/15/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	NA
CHJSP-BR	State Park Boat Ramp	9/15/2011	Algal Mat	0.111	0.0185	<MDL	0.05	NA
CHJFB	Forebay	9/15/2011	Algal Mat	<MDL	0.0185	<MDL	0.05	P

Notes:

1.1	Exceeds Washington Department of Health recreational guidance for anatoxin-a of 1 µg/L
MDL	Method Detection Limit
NA	Not Analyzed
D, S, P, ND	Dominant, Sub-Dominant, Present, Not Detected

Table 2-14. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2012

Station Name	Station Location	Date	Sample Type	Anatoxin-a (µg/L)	MDL (µg/L)	Microcystin (µg/L)	MDL (µg/L)	Oscillatoria Abundance
CHJRF-BR	Rocky Flats Boat Ramp	7/11/2012	Algal Mat	**11.2**	0.0185	2.13	0.05	NA
CHJUP	Downstream of Buckley Bar	7/11/2012	Algal Mat	**30.7**	0.0185	0.148	0.05	NA
CHJNSP	Mouth Nespelem River	7/11/2012	Algal Mat	**8.87**	0.0185	<MDL	0.05	NA
CHJFB	Forebay	7/11/2012	Algal Mat	**73**	0.0185	<MDL	0.05	NA
CHJFB	Forebay	7/11/2012	Open Water	<MDL	0.0185	<MDL	0.05	NA
CHJFB-BR	Forebay Boat Ramp	7/26/2012	Algal Mat	**110**	0.0185	0.246	0.05	P
CHJFB-BR	Forebay Boat Ramp	7/26/2012	Open Water	0.065	0.0185	<MDL	0.05	P
CHJSP-BR	State Park Boat Ramp	7/26/2012	Algal Mat	**10**	0.0185	<MDL	0.05	P
CHJSP-BR	State Park Boat Ramp	7/26/2012	Open Water	<MDL	0.0185	<MDL	0.05	ND
CHJUP	Downstream of Buckley Bar	7/26/2012	Algal Mat	**63.2**	0.0185	0.072	0.05	P
CHJUP	Downstream of Buckley Bar	8/8/2012	Algal Mat	0.129	0.0185	<MDL	0.05	P
CHJSP-BR	State Park Boat Ramp	8/8/2012	Algal Mat	0.622	0.0185	<MDL	0.05	P
CHJSP-BR	State Park Boat Ramp	8/8/2012	Open Water	<MDL	0.0185	<MDL	0.05	ND
CHJFB	Forebay	8/8/2012	Algal Mat	**22.8**	0.0185	0.051	0.05	P
CHJFB	Forebay	8/8/2012	Open Water	0.025	0.0185	<MDL	0.05	P
CHJNSP	Mouth Nespelem River	8/8/2012	Algal Mat	**2.82**	0.0185	<MDL	0.05	P
CHJFB-BR	Forebay Boat Ramp	8/30/2012	Algal Mat	**2.99**	0.0185	<MDL	0.05	S
CHJFB-BR	Forebay Boat Ramp	8/30/2012	Open Water	0.358	0.0185	<MDL	0.05	D
CHJSP-BR	State Park Boat Ramp	8/30/2012	Algal Mat	**1.65**	0.0185	<MDL	0.05	P
CHJSP-BR	State Park Boat Ramp	8/30/2012	Open Water	0.04	0.0185	<MDL	0.05	ND
CHJSP-BR	State Park Boat Ramp	9/19/2012	Algal Mat	0.019	0.0185	0.061	0.05	ND
CHJFB	Forebay	9/19/2012	Algal Mat	**50.1**	0.0185	<MDL	0.05	D
CHJMID	Mid Reservoir Location	9/19/2012	Algal Mat	**1.34**	0.0185	0.165	0.05	D

Notes:

1.1	Exceeds Washington Department of Health recreational guidance for anatoxin-a of 1 µg/L
MDL	Method Detection Limit
NA	Not Analyzed
D, S, P, ND	Dominant, Sub-Dominant, Present, Not Detected

Table 2-15. Harmful Algae Bloom Cyanotoxin Data for Rufus Woods Lake 2013

Station Name	Station Location	Date	Sample Type	Anatoxin-a (µg/L)	MDL (µg/L)	Microcystin (µg/L)	MDL (µg/L)	Oscillatoria Abundance
CHJSP-BR	State Park Boat Ramp	5/8/2013	Algal Mat	**1.4**	0.02	<MDL	0.05	D
CHJFB-BR	Forebay Boat Ramp	5/8/2013	Algal Mat	0.9	0.02	<MDL	0.05	S
CHJMID	Mid Reservoir Location	5/8/2013	Algal Mat	**3.03**	0.02	<MDL	0.05	S
CHJSP-BR	State Park Boat Ramp	6/12/2013	Algal Mat	**38.8**	0.01	<MDL	0.05	D
CHJSP-BR	State Park Boat Ramp	6/12/2013	Open Water	0.01	0.01	<MDL	0.05	ND
CHJNSP-4	Downstream Fish Farms	6/12/2013	Algal Mat	**61.5**	0.01	<MDL	0.05	D
CHJUP	Downstream of Buckley Bar	6/12/2013	Algal Mat	**11.7**	0.01	<MDL	0.05	D
CHJUP	Downstream of Buckley Bar	7/12/2013	Algal Mat	**37.5**	0.01	<MDL	0.16	D
CHJFB-BR	Forebay Boat Ramp	7/12/2013	Open Water	<MDL	0.01	<MDL	0.16	ND
CHJFB-BR	Forebay Boat Ramp	7/12/2013	Algal Mat	**12**	0.01	0.171	0.16	D
CHJMID	Mid Reservoir Location	7/12/2013	Algal Mat	**7.43**	0.01	<MDL	0.16	D
CHJNSP-4	Downstream Fish Farms	8/7/2013	Algal Mat	0.12	0.01	<MDL	0.16	D
CHJMID	Mid Reservoir Location	8/7/2013	Algal Mat	0.51	0.01	<MDL	0.16	D
CHJFB	Forebay	8/7/2013	Algal Mat	**12**	0.01	<MDL	0.16	D
CHJFB	Forebay	8/7/2013	Open Water	<MDL	0.01	<MDL	0.16	ND
CHJUP	Downstream of Buckley Bar	9/11/2013	Algal Mat	**60.9**	0.01	<MDL	0.16	D
CHJFB	Forebay	9/11/2013	Algal Mat	**6.08**	0.01	<MDL	0.16	D
CHJFB	Forebay	9/11/2013	Open Water	0.013	0.01	<MDL	0.16	ND

Notes:

1.1	Exceeds Washington Department of Health recreational guidance for anatoxin-a of 1 µg/L
MDL	Method Detection Limit
NA	Not Analyzed
D, S, P, ND	Dominant, Sub-Dominant, Present, Not Detected

Samples for anatoxin-a and microcystin analysis were collected from the algae mat and from the surrounding water. Anatoxin-a concentrations in floating mat samples collected in Rufus Woods Lake from 2011 to 2013 ranged from less than detection (0.0185 µg/L) to 110 µg/L (Table 2-13 to Table 2-15). Anatoxin-a was the most prevalent cyanotoxin measured in algal mats from Rufus Woods Lake and was detected in 11 of 18 samples in 2011, 16 of 16 samples in 2012, and 14 of 14 samples in 2013. Microcystin concentrations were low in the algal mats (range from less than detection to 2.13 µg/L), with the majority of samples collected below the detection limit of 0.05 µg/L. Cyanotoxins were periodically detected at low concentrations in the water column surrounding the algal mats, suggesting that the harmful algae bloom toxicity in Rufus Woods Lake was largely isolated in the floating mats with little transfer of toxin from the algal mats to the open waters.

Anatoxin-a concentrations measured in algal mat samples were greater than the recreational guideline of 1 µg/L at numerous locations on multiple dates in 2011 to 2013. The cyanobacteria *Oscillatoria* was present in all algal mat samples that exceeded the 1 µg/L recreational guideline and was generally present in all algal mat or open water samples where anatoxin-a was detected (Table 2-13 to Table 2-15). These

results suggest that *Oscillatoria* sp. was the primary anatoxin-a producer in Rufus Woods Lake during the 2011 to 2013 study period.

2.3.3.4 *Harmful Algae Bloom Sources*

Floating algal mats had not been observed in Rufus Woods Lake prior to 2010 (Robert Fisher Personal Communication 2011). Chief Joseph Dam Natural Resource staff travel the lake by boat nearly every day in the summer and had never observed floating algal mats or clumps during the previous 30 years. Consequently, it appears that the floating algal mats are a fairly recent water quality issue on Rufus Woods Lake. A source-tracking study was conducted in 2011 and 2012 to attempt to (1) determine if the floating mats were derived from an upstream source, (2) determine if the mats were derived from a source within Rufus Woods Lake, and (3) determine if the algal mats were upstream or only downstream of aquaculture facilities.

As outlined in a previous section, small floating clumps of harmful algae were present throughout the majority of the 80-kilometer Rufus Woods Lake from the farthest upstream station (CHJUP), located 10 km downstream of Grand Coulee Dam near Buckley Bar, downstream to the forebay station (CHJFB). In 2011 and 2012, several areas located upstream of Grand Coulee Dam in Lake Roosevelt and Banks Lake were investigated (see Figure 1-4). Few floating algal clumps were present at the locations sampled in Lake Roosevelt and Banks Lake, and no floating algal clump was visually similar to those found in Rufus Woods Lake. For Lake Roosevelt and Banks Lake, algal clumps were dominated by the diatoms *Achnanthes*, *Fragilaria*, *Synedra*, *Tabellaria* and the green algae *Ulothrix*. The only cyanobacteria present were *Anabaena flos-aquae* and *Aphanizomenon flos-aquae* in minor amounts. The cyanobacteria *Oscillatoria*was not detected in any sample collected from Lake Roosevelt or Banks Lake during 2011 and 2012. This data suggests an in-reservoir source of the cyanobacteria *Oscillatoria* in Rufus Woods Lake. In addition, sampling results from 2011, 2012, and 2013 consistently detected *Oscillatoria* in floating algal mats upstream of any aquaculture facilities, suggesting that the aquaculture facilities were not a source of the floating algal mats in Rufus Woods Lake.

2.3.4 Zooplankton

Zooplankton are microscopic animals found in the water column that are important to the trophic structure of an ecosystem because they feed on phytoplankton and, in turn, are consumed by fish. Zooplankton can be either herbivorous (feeds on phytoplankton), carnivorous (feeds on other zooplankton), or omnivorous (feeds on both phytoplankton and zooplankton). Water quality conditions can be assessed from the numbers and types of zooplankton species present in the water (Gannon and Stemberger 1978). For example, the presence of certain zooplankton species relative to other species may serve as an indicator of the biological productivity of a water body. However, this generalization may or may not be indicative of site-specific water quality conditions, such as those found in Rufus Woods Lake. Consequently, zooplankton density and species information should be used in conjunction with phytoplankton data, physical data, and chemical data to determine the overall trophic condition of a lake.

Freshwater zooplankton are usually dominated by three main groups: the Rotifers and two subclasses of the Crustacea: Cladocera and Copepods. Zooplankton are classified by size, developmental stage, grazing techniques, reproductive characteristics, and/or morphology. The traits of these three main zooplankton are explained below.

2.3.4.1 *Cladocera*

Commonly known as water fleas, these organisms are filter feeders and generally range in size from 0.2 to 3.0 millimeters. These filter feeders are identifiable by the presence of a large eye and two-valved carapace. Cladocera are an important part of the freshwater ecosystem as they graze on phytoplankton and are a prime source of food for fish. Cladocera have the ability to migrate vertically in the water column on a daily basis. Herbivorous species dominate, although some carnivorous species of Cladocera exist in freshwaters.

2.3.4.2 *Copepod*

The second major group of crustacean zooplankton, adult members grow slightly larger than Cladocerans, and range in size from 0.5 to 5.0 millimeters. These organisms are identifiable by their long teardrop-shaped body and antennae. No filtration mechanism exists for feeding, and food is seized by mouthparts and brought to the mouth. Both herbivorous and carnivorous species of Copepods exist in freshwater. Some species of Copepods have the ability to migrate vertically in the water column on a daily basis.

2.3.4.3 *Rotifers*

A large group of soft-bodied plankton, they are among the smallest of the zooplankton, ranging in size from .002 to 0.2 millimeters in adult form. The majority of rotifers have an elongated body shape with distinguishable head, trunk, and foot regions. Characterized by the division of their body, rotifers are identified by their wheel-shaped corona. Herbivorous species dominate, although some carnivorous species of Rotifers exist in freshwaters.

2.3.4.4 *Zooplankton Abundance and Composition*

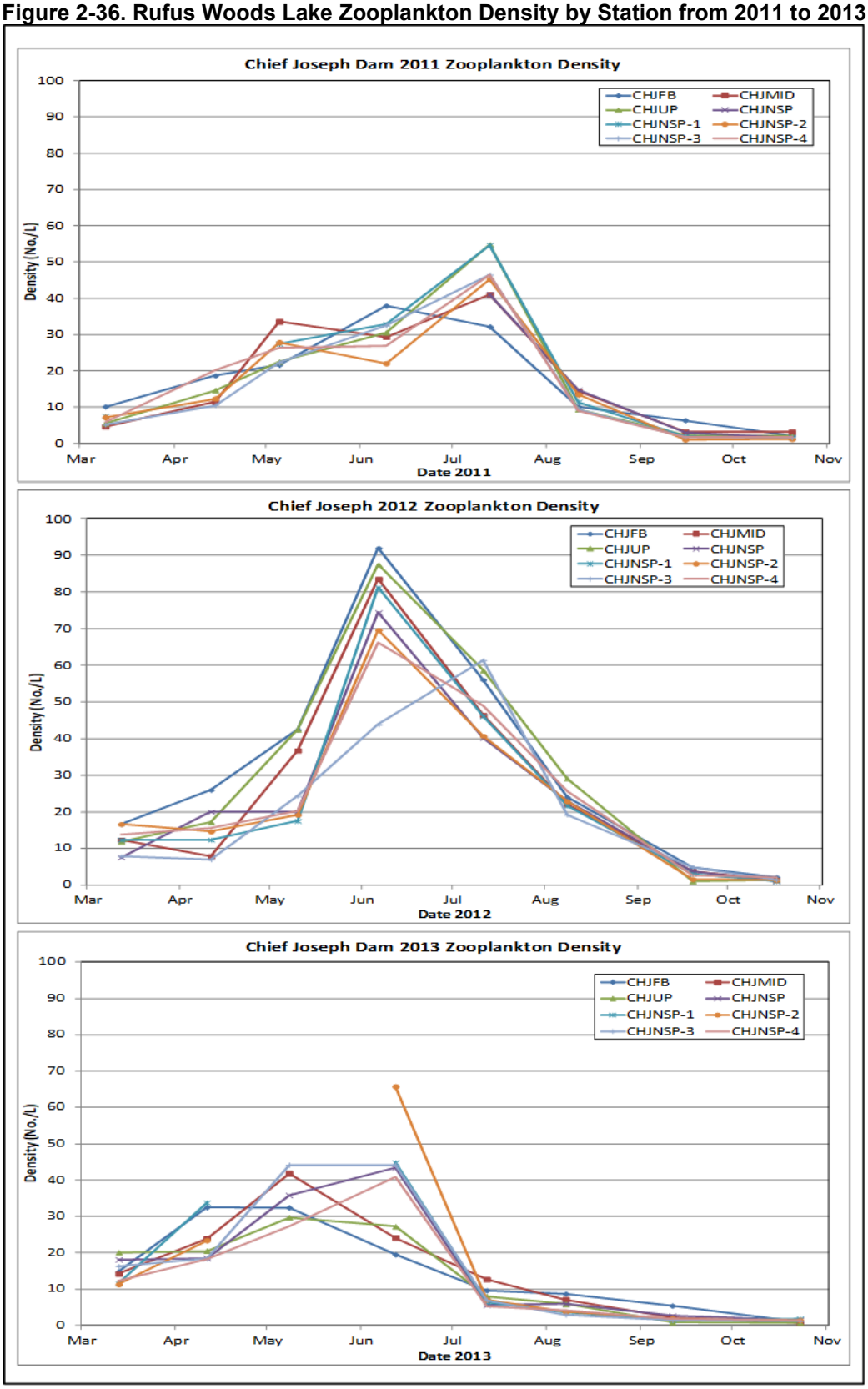
Collectively, 56 species of zooplankton were identified in Rufus Woods Lake during the 2011 to 2013 study (Table 2-16). Of these 56 different species, there were 28 species of Rotifers, 17 species of Cladocera, and 11 species of Copepods.

Table 2-16. Zooplankton Species List for Rufus Woods Lake from 2011 to 2013

Cladocera	Rotifer
Alonella sp.	*Anuraeopsis sp*
Bosmina longirostris	*Ascomorpha sp*
Camptocerus sp	*Asplanchna sp*
Ceriodaphnia quadrangula	*Brachionus sp*
Chydorus sp	*Collotheca sp*
Daphnia sp.	*Conochilus sp*
Daphnia galeata mendotae	*Euchlanis sp*
Daphnia pulicaria	*Filinia sp*
Diaphanosoma birgei	*Gastropus sp*
Eurycercus sp	*Hexarthra sp*
Holopedium gibberum	*Kellicottia longispina*
Leptadora kindti	*Keratella cochlearis*
Macrothrix sp	*Keratella longispina*
Polyphemus pediculus	*Keratella loricate*
Scapholoberis sp	*Keratella quadrata*
Sida crystallina	*Keratella sp*
Unknown	*Lecane sp*
	Monostyla sp
Copepod	*Notholca sp*
Calanoid sp.	*Platyias sp*
Cyclopoid sp.	*Ploesoma sp*
Diacyclops sp	*Polyarthra sp*
Epischura nevadensis	*Proales sp*
Harpaticoida	*Rotifer Eggs*
Hesperodiaptomus	*Synchaeta sp*
Leptodiaptomus aslandi	*Trichocerca sp*
Leptodiaptomus minutus	*Trichotria sp*
Macrocyclops sp	*Unknown*
Nauplii	
Unknown	

Temporal variations in zooplankton density at all stations in Rufus Woods Lake from 2011 through 2013 are presented in Figure 2-36. Zooplankton density was measured as the total number of organisms of each species per liter in a sample. Total zooplankton densities were greatest in 2012, and similar in 2011 and 2013. In general, zooplankton densities were greatest from March through June or July, depending on the year, with substantially reduced densities in August, September, and October. Rotifers dominated density measurements at all stations for all years.

Figure 2-36. Rufus Woods Lake Zooplankton Density by Station from 2011 to 2013



The composition of zooplankton was similar between stations and between years; however, within-year seasonal differences were apparent. From March through July, rotifers were the dominant zooplankton group, accounting for about 75 to 95 percent of the total density throughout Rufus Woods Lake, with copepods accounting for about 5 to 20 percent of the density, and cladocerans from about 0 to 5 percent (Figure 2-). However, from August through October, copepods were the dominant zooplankton group accounting for about 60 to 70 percent of the density, rotifers accounted for about 20 to 35 percent of the density, and cladocerans accounted for about 5 to 10 percent. For all three sampling years, rotifers were dominated by *Keretella* sp. and *Synchaeta* sp.; copepods were dominated by *Nauplii*, *Cyclopoid* sp., and *Diacyclops* sp.; and *cladocerans* were dominated by *Daphnia* sp. and *Bosmina longirostris*.

Figure 2-37. Rufus Woods Lake Whole Lake Zooplankton Density and Percent Composition from 2011 to 2013

The seasonal succession in zooplankton species seen in Rufus Woods Lake is likely in response to food source availability, changes in temperature, and upstream population dynamics in Lake Roosevelt. Many zooplankton populations are low over the winter and begin to increase in the spring as food supplies (e.g., phytoplankton) increase and water temperatures rise. As phytoplankton species shift in dominance during the spring, summer, and fall, the zooplankton populations will cycle in response to the quality and size of the food (with some phytoplankton species being more palatable than others) as well as due to predation by other zooplankton species (Wetzel 1975).

SECTION 3 - CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

Harmful algae blooms have been occurring annually in Rufus Woods Lake, the reservoir formed by Chief Joseph Dam, since 2010. An annual water quality monitoring program on Rufus Woods Lake and the Columbia River was started by the Corps in 2011. This comprehensive program is designed to assess the current physical, chemical, and biological conditions within Rufus Woods Lake. Data collected from 2011 to 2013 was evaluated for this summary report. Evaluation of these physical, chemical, and biological data yielded the following conclusions and recommendations:

In general, the water quality of Rufus Woods Lake is good. Rufus Woods Lake would be classified as oligotrophic on the basis of both summer TSI values and annual OCED concentrations for total phosphorus, transparency, and chlorophyll a.

Small differences in annual total phosphorus concentrations in Rufus Woods Lake existed between sampling stations. The greatest phosphorus concentrations were measured downstream of the aquaculture facilities. This data suggests that the aquaculture facilities may be a source of phosphorus to Rufus Woods Lake.

Ammonia concentrations in Rufus Woods Lake were greatest during the June to October time period, with the highest concentrations measured downstream of the aquaculture facilities. The increased ammonia concentrations downstream of the aquaculture facilities are likely due to this nutrient being released directly to the water column by fish excretion, as well as the decomposition of feed and feces.

The TN:TP ratios at all stations in Rufus Woods Lake suggests that phosphorus concentrations likely limit algal growth in Rufus Woods Lake. Although no station's TN:TP ratio was less than 10, indicating nitrogen limitation, several stations were between 10 and 17, suggesting that either nitrogen or phosphorus could be limiting, or that both nitrogen and phosphorus are limiting (co-limitation).

Nitrogen (TN and NO_2+NO_3) concentrations in Rufus Woods Lake were similar between stations for each sampling season. In general, nitrogen followed similar seasonal patterns for each year with moderate concentrations in March, peak concentrations in April, a decline in May and June/July, and slightly increasing concentrations from July/August through October.

Total copper concentrations in Rufus Woods Lake were near or below the detection limit of 1 µg/L for all dates at all stations except for two samples collected at CHJNSP-4 located 300 meters downstream of Aquaculture Site 1. Concentrations measured at CHJNSP-4 were elevated on October 17, 2012, (9.3 µg/L) and August 7, 2013, (7.3 µg/L). The 9.3 µg/L concentration exceeded DOE chronic criteria and Colville Tribes acute criteria, while the 7.3 µg/L concentration exceeded the Colville Tribes chronic criteria.

A non-parametric Mann-Whitney test conducted on summer (June to October) samples determined that the aquaculture facilities are a possible source of ammonia and phosphorus to Rufus Woods Lake.

Rufus Woods Lake water column phytoplankton populations were dominated by diatoms and cryptomonads at all stations throughout most of the 2011 to 2013 study. In general, diatoms accounted for about 60 to 100 percent of phytoplankton composition by biovolume and about 40 to 95 percent by total density. Cryptomonads were the next most abundant species, accounting for from about 5 to 15 percent by biovolume and from about 10 to 50 percent by density. Very little cyanobacteria was detected in water column phytoplankton samples.

The composition of zooplankton was similar between stations and years; however, seasonal differences were apparent. From March through July, rotifers were the dominant zooplankton group, accounting for about 75 to 95 percent of the total density with copepods accounting for about 5 to 20 percent and cladocerans from about 0 to 5 percent. From August through October, copepods were the dominant zooplankton group accounting for about 60 to 70 percent of the density, with rotifers accounting for about 20 to 35 percent, and cladocerans accounting for about 5 to 10 percent.

Harmful algae blooms occurred in Rufus Woods Lake during the summer in 2011, 2012, and 2013. These blooms were floating algal mats composed of a mixture of filamentous cyanobacteria intertwined with diatoms and green algae. In general, diatoms dominated most floating mat samples, with *Achnanthes, Cymbella, Fragilaria*, *Melosira*, *Synedra*, and *Tabellaria*. the most abundant phytoplankton. Cyanobacteria were the next most abundant phytoplankton type detected in the floating mats, with *Oscillatoria* being the dominant cyanobacteria. Green algae species were detected in a majority of floating mat samples, with *Spirogyra* the dominant green algal type.

Anatoxin-a concentrations in harmful algae bloom floating mat samples collected in Rufus Woods Lake from 2011 to 2013 ranged from less than detection (0.0185 µg/L) to 110 µg/L. The cyanobacteria *Oscillatoria* was present in all algal mat samples that exceeded the 1 µg/L recreational guideline and was generally present in all samples where anatoxin-a was detected, suggesting that *Oscillatoria* was the primary anatoxin-a producer in Rufus Woods Lake. Microcystin concentrations were low in the algal mats with the majority of samples collected below the detection limit of 0.05 µg/L.

Harmful algae samples collected upstream of Rufus Woods Lake in Lake Roosevelt and Banks Lake in 2011 and 2012 did not detect an upstream source of *Oscillatoria* or algal mats visually similar to those found downstream in Rufus Woods Lake. This data suggests an in-reservoir source of the cyanobacteria *Oscillatoria* in Rufus Woods Lake.

3.2 RECOMMENDATIONS

Annual physical, chemical, and biological water quality sampling of Rufus Woods Lake should continue at current sampling locations. An additional water quality station located downstream of the newest aquaculture facility (Pacific Aquaculture Inc. Site 3) should

be sampled. Contaminants such as antibiotics, pesticides, herbicides, and fungicides should be sampled in the water column upstream and downstream of aquaculture facilities to monitor if any of these compounds are being released to Rufus Woods Lake. In addition, a more comprehensive and detailed periphyton sampling program should be conducted in Rufus Woods Lake to determine the possible source(s) of harmful algae blooms measured in the lake.

SECTION 4 - REFERENCES

Azevedo, P. A., C. L. Podemski, R. H. Hesslein, S. E. M. Kasian, D. L. Findlay, and D. P. Bureau. 2011. “Estimation of Waste Outputs by a Rainbow Trout Cage Farm Using a Nutritional Approach and Monitoring of Lake Water Quality.” Aquaculture 311(1–4):175–186.

Beveridge, M. 2004. Cage Aquaculture. 3rd edition. Oxford, United Kingdom: Blackwell Publishing.

Black, K. D. 2008. “Environmental Aspects of Aquaculture.” In Aquaculture, Innovation and Social Transformation. K. Culver, D. Castle, eds. Chapter 7:97–113.

Briggs, J. C., and J. F. Ficke. 1977. Quality of Rivers of the United States, 1975 Water Year – Based on the National Stream Quality Accounting Network. U.S. Geological Survey Open-File Report 78-200.

BPA (Bonneville Power Administration). 2003. Lake Roosevelt Fisheries Evaluation Program: Limnological and Fisheries Monitoring, 2000 Annual Report. BPA Project No. 199404300.

———. 2006. Lake Roosevelt Fisheries Evaluation Program: Limnological and Fisheries Monitoring, 2004-2005 Annual Report. BPA Project No. 199404300.

Carlson, R. E. 1977. “A Trophic State Index for Lakes.” Limnology and Oceanography 22:361¬–369.

Codd G. A., Morrison L. F., Metcalf J. S. (2005). “Cyanobacterial toxins: risk management for health protection.” Toxicology and Applied Pharmacology 203:264–272.

Cornel, G. E., and F. G. Whoriskey. 1993. “The Effects of Rainbow Trout (Onchorhynchus mykiss) Cage Culture on the Water Quality, Zooplankton, Benthos and Sediments of Lac du Passage, Quebec.” Aquaculture 109:101–117.

Corps (U.S. Army Corps of Engineers). 2009. Chief Joseph Dam, Columbia River, Washington Water Control Manual. Seattle District.

———. 2011. Chief Joseph Dam Water Quality Sampling and Analysis Plan, 2011. Seattle District, Hydraulics and Hydrology Branch.

———. 2012. Chief Joseph Dam Water Quality Sampling and Analysis Plan, 2012. Seattle District, Hydraulics and Hydrology Branch.

———. 2013. Chief Joseph Dam Water Quality Sampling and Analysis Plan, 2013. Seattle District, Hydraulics and Hydrology Branch.

Dean, R. J., T. M. Shimmield, and K. D. Black. 2007. “Copper, Zinc and Cadmium in Marine Cage Fish Farm Sediments: An Extensive Survey.” Environmental Pollution 145:84–95.

DFO (Department of Fisheries and Oceans Canada). 2006. State of Knowledge Presentation for the Special Committee on Sustainable Aquaculture of the British Columbia Legislature. November 30, 2006.

DOH (Washington State Department of Health Division of Environmental Health). 2008. Washington State Recreational Guidance for Microcystins (Provisional) and Anatoxin-a (Interim/Provisional).

Ecology (Washington State Department of Ecology). 2018. Washington State Water Quality Assessment. https://fortress.wa.gov/ecy/approvedwqa/ApprovedSearch.aspx.Ecology 2011. Water quality standards for surface waters of the State of Washington. Chapter 173-201A WAC Ammended May 9, 2011. Publication No. 06-10-091.

EES Consulting. 2006. Comprehensive Limnological Investigation Wells Dam Hydroelectric Project. FERC NO. 2149. Bellingham, WA.

Environment Canada. 2009. Organic Waste and Feed Deposits on Bottom Sediments from Aquaculture Operations: Scientific Assessment and Guidance. Report No. 1-14. Ecosystem Health: Science-Based Solutions.

EPA (U.S. Environmental Protection Agency). 1983. Methods for Chemical Analysis of Water and Wastes. EPA-600/4-79-020. Environmental Monitoring and Support Laboratory. Cincinnati, OH.

———. 1984. Guidelines Establishing Test Procedures for the Analysis of Pollutants under the Clean Water Act; Final Rule and Interim Final Rule. CFR Part 136. Friday, October 26, 1984.

———.1989. Ambient Water Quality Criteria for Aluminum – 1988. Office of Water Regulations and Standards. EPA 4405-86-008.

———. 1992. NPDES [National Pollutant Discharge Elimination System] Stormwater Sampling Guidance Document. EPA 833-B-92-001. U.S. Office of Water. Washington, D.C.

———. 1998. Guidance for Quality Assurance Project Plans. EPA-QA/G-5. Office of Research and Development. Washington D.C.

———. 2012b. Cyanobacteria and Cyanotoxins: Information for Drinking Water Systems. United States Environmental Protection Agency Office of Water. EPA Report EPA-810F11001.

EPA 2008. Upper Columbia River work plan for the remedial investigation and feasibility study. Modified by U.S. Environmental Protection Agency, Region 10, Seattle, WA. Based on draft work provided by Teck Cominco American Incorporated. December 2008.EPA 2012a. Authorization to Discharge under the National Pollutant Discharge Elimination System, Pacific Aquaculture, Inc. – Site 3 Columbia River Mile 576.4, United States Environmental Protection Agency, Region 10, Seattle, WA.

Fisher, Robert, 2011. Personal communication with Kent Easthouse. May 11, 2011.

Forsberg, C., and S. O. Ryding, 1980. “Eutrophication Parameters and Trophic State Indices in 30 Swedish Waste Receiving Lakes.” Archiv fur Hydrobiologie 89:189¬207.

Frizell, K. H. and Vermeyen, T. B., 1997, “Investigative Trip to Grand Coulee Dam Prior to Performing Total Dissolved Gas Tests in the River,” U. S. Bureau of Reclamation, TR-97-16, Denver CO, March 1997.

Gannon, J. E. and R. S. Stemberger. 1978. Zooplankton (especially crustaceans and rotifers) as indicators of water quality. Transactions of the American Microscopical Society. 97:16-35.

G3 Consulting. 2001. Assessment of Columbia River receiving waters, final report. Prepared for Teck Cominco Ltd., Trail, British Columbia. December 2008.

Greenberg, A. E., A. D. Eaton, and L. S. Clesceri, eds. 1992. Standard Methods for the Examination of Water and Wastewater. 18th edition. American Public Health Association, American Water Works Association, and Water Environment Federation.

_____. 2000. Standard Methods for the Examination of Water and Wastewater. 20th edition. American Public Health Association, American Water Works Association, and Water Environment Federation.

Harris, G. P., and B. Piccinin. 1980. “Physical Variability and Phytoplankton Communities. IV. Temporal Changes in the Phytoplankton Community of a Physically Variable Lake.” Arch. Hydrobiol. 89: 447–473.

Helsel, D. R., and R. M. Hirsch. 2002. Statistical Methods in Water Resources Techniques of Water Resource Investigations. Book 4, Chapter A3. U.S. Geological Survey.

Komarek, J., and J. R. Johansen. 2015. Filamentous Cyanobacteria. Freshwater Algae of North America: Ecology and Classification. 2nd edition. San Diego, CA: Academic Press.

MacDonald Environmental Sciences Ltd. 1997. Lower Columbia River from Birchbank to the International Border: Water Quality Assessment and Recommended Objectives. Technical report. Prepared for Environment Canada.

Mekebri A., G. J. Blondina, and D.B. Crane. 2009. “Method Validation of Microcystins in Water and Tissue by Enhanced Liquid Chromatography Tandem Mass Spectrometry.” J. Chromatography A, 1216(15):3147–55.

Mez, K., K. Hanselmann, and H. R. Preisig. 1998. “Environmental Conditions in high Mountain Lakes Containing Toxic Benthic Cyanobacteria.” Hydrobiologia 368:1–15.

Mills, J.W. 1977. Zinc and lead ore deposits in carbonate rocks, Stevens County, Washington. State of Washington Department of Natural Resources. Bulletin No. 70.

Mugg, J., A. Serrano, A. Liberti, and M. A. Rice. 2007. Aquaculture Effluents: A Guide for Water Quality Regulators and Aquaculturists. Publication No. 00-003. Northeast Regional Aquaculture Center.

OECD (Organization for Economic Co-Operation and Development). 1982. Eutrophication of Waters: Monitoring, Assessment and Control. Paris, France.

Oehrle, S.A., B. Southwell, J. Westrick. 2010. “Detection of Various Freshwater Cyanobacterial Toxins Using Ultra-Performance Liquid Chromatography Tandem Mass Spectrometry.” Toxicon 55(5): 965–72.

OPHD (Oregon Public Health Division). 2015. Oregon Harmful Algae Bloom Surveillance (HABS) Program. Center for Health Protection, Environmental Public Health Section. Updated June 19, 2015.

Parametrix. 2001. Water Quality Monitoring Report Rocky Reach Reservoir Water Year 2000. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Podemski, C. L., and P. J. Blanchfield. 2006. Overview of the Environmental Impacts of Canadian Freshwater Aquaculture. Fisheries and Ocean Canada 2006–Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems: Volume 5. Canadian Technical Reports of Fisheries and Aquatic Sciences 2450.

Reynolds, C. S. 1984. The Ecology of Freshwater Phytoplankton. Cambridge University Press.

Richards, D. C., J. Rensel, and Z. Siegrist. 2011. Rufus Woods Lake–Columbia River Reservoir Morphometrics, Initial Food Web and Rainbow Trout Fishery Studies. Prepared for The Colville Confederated Tribes Fish and Wildlife Department.

Rooney, R. C., and C. L. Podemski. 2010. “Freshwater Rainbow Trout (Oncorhynchus mykiss) Farming Affects Sediment and Pore-Water Chemistry.” Marine and Freshwater Research 61:513–526.

Ryding, S. O., and W. Rast. 1989. Control of Eutrophication in Lakes and Reservoirs. Programme on Man and the Biosphere. Cambridge University Press.

Shilling, F., S. Sommarstrom, R. Kattelmann, B. Washburn, J. Florsheim, and R. Henly. 2005. California Watershed Assessment Manual: Volume I. May 2005. Prepared for the California Resources Agency and the California Bay-Delta Authority. http://cwam.ucdavis.edu.

St. Croix Watershed Research Station. 2011. Blue-Green Algal Mats in the St. Croix River. St. Croix Watershed Research Station Fact Sheet 2011-01. St. Croix, MN.

Stevenson, R. J. 1996. An Introduction to Algal Ecology in Freshwater Benthic Habitats. Algal Ecology: Freshwater Benthic Ecosystems. R. J. Stevenson, M. I. Bothwell, and R. L. Lowe, eds. San Diego, CA: Academic Press.

Troell, M., and H. Berg. 1997. “Cage Fish Farming in the Tropical Lake Kariba, Zimbabwe: Impact and Biogeochemical Changes in Sediment.” Aquaculture 28(7):527¬–544.

USGS (U.S. Geological Survey). 1994. Sediment Quality Assessment of Franklin D. Roosevelt Lake and the Upstream Reach of the Columbia River, Washington, 1992. U.S. Geological Survey Open-File Report 94-315.

Washington State DNR (Washington Department of Natural Resources) 2004. The Geology of Washington. http://www.dnr.wa.gov/geology/geolofwa.htm. Olympia, WA.

Wetzel, R. G. 1975. Limnology. Philadelphia, PA: W. B. Saunders Company.

Weitkamp, D.E. and M. Katz 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society, 109:659-702.

Weitkamp, D.E., Sullivan, R.D., Swant, T., and J. DosSantos 2002. Gas bubble disease in resident fish of the Lower Clark Fork River. Report prepared for Avista Corporation by Parametrix, Inc.

WHO (World Health Organization). 2003. Guidelines for Safe Recreational Water Environments: Volume 1, Coastal and Fresh Waters. Geneva, Switzerland.

Zar. 1984. Biostatistical Analysis, 2nd edition. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Zhang, Y. and E.E. Prepas. 1996. Regulation of the dominance of planktonic diatoms and cyanobacteria in four eutrophic hardwater lakes by nutrients, water column stability, and temperature. Canadian Journal of Fisheries and Aquatic Sciences, 53(3) 621-633.

Zivic, I., Z. Markovic, Z. Filipovic-Rojka, and M. Zivic. 2009. “Influence of a Trout Farm on Water Quality and Macrozoobenthos Communities of the Receiving Stream.” International Review Hydrobiology 94:673–687.